LIST OF DR. V. SARABHAI'S PAPER

YEAR	AUTHOR	TITLE	REPRI NO.
1942	Sarabhai,V.	Time distribution of cosmic rays	E_1
1944	Sarabhai, V.	Method of shower anticoincidences for measuring the meson component of cosmic radiation.	E_2
1945	Sarabhai,V.	Semidiurnal variation of meson intensity	E_3
1947	Sarabhai,V.& Nicolson,P.	Semi-diurnal variation in Meson intensity	E_4
19[illegible]	Sarabhai,V. ~~etal~~	Variation of cosmic ray intensity at low latitudes and its relationships with meteorological factors.	
1953	Sarabhai,V. etal	Daily variation of meson intensity and its possible solar origin.	E_5
1953	Sarabhai,V. etal	Meteorological and extraterrestrial causes of the daily variation of cosmic ray intensity.	E_6
1953	Sarabhai,V. & Kane,R.P.	World-wide effects of continuous Emission of cosmic rays from the sun.	E_7
1953	Sarabhai,V. & Kane,R.P.	Effects at Godhavn and lower latitudes of changes in energy and composition of solar cosmic rays.	E_8
1953	Sarabhai,V.	Report of the committee on standardisation of cosmic rays continuous recording equipment.	E_9
1954	Sarabhai,V.	ATIRA - Ahmedabad Textile Industry's Association.	
1954	Sarabhai,V. etal	Cycle of world-wide changes in the Daily changes in the daily variation of meson intensity.	E_{10}
1955	Sarabhai,V.	Organisation of research for the textile industry.	
1955	Sarabhai,V. etal	Study of the anisotropy of cosmic rays with narrow angle telescopes.	E_{13}

1955	Sarabhai,V. etal	Solar influence on the anisotropy of primary cosmic radiation. I: Studies at low latitudes.	E_{14}
1955	Sarabhai,V. etal	Changes in the daily variation of Meson intensity.	E_{14}
1956	Sarabhai,V.	Co-operative research laboratories industry.	
1956	Sarabhai,V. &Nerurkar, N.W.	Time variations of primary cosmic rays.	E_{15}
1956	Sarabhai,V. etal	Solar flare type increase in cosmic rays at low latitudes.	E_{28}
1956	Sarabhai,V.	Anisotropy of primary cosmic radiation and the electromagnetic state in interplanetary space.	E_{92} E_{97} E_{19}
1958	Sarabhai,V.	Changes of solar anisotropy and of the intensity of cosmic radiation.	E_{18}
1959	Sarabhai,V. &Palmeira,R.	North-South Anisotropy and anticipatory increase of intensity associated with the cosmic-ray storm of February 11, 1958.	E_{2}
1959	Sarabhai,V. etal	Anisotropy and the origin of the Solar daily variation of cosmic ray intensity.	E_{2}
1959	Sarabhai,V.	Role of Science in Industry.	E_{9}
1959	Sarabhai,V. & SatyaPrakash	Variations of intensity and anisotropy of cosmic rays measured at the geomagnetic equator.	E_{2}
1960	Sarabhai,V. &Chitnis,E.V.	Arrival directions of cosmic-ray Air showers from the equatorial sky.	E
1960	Sarabhai,V.A. & Rao, U.R.	Anisotropy and non-meteorological local source responsible for solar daily variation of cosmic ray intensity.	E_{1}
1961	Sarabhai,V.A. &Rao,U.R.	Time variations of directional cosmic ray intensity and low latitudes. III: Interpretation of solar daily variation and changes of east-west asymmetry.	E_{3}
1962	Sarabhai,V.A.	Cosmic rays and interplanetary space.	E_{3}

1962	Sarabhai, V.A. etal.	Anisotropy and changes of energy spectrum during cosmic ray storms.	E_4
1962	Sarabhai, V.A. etal.	Cosmic ray effects associated with polar cap absorption events.	E_4
1962	Sarabhai, V.A.	Review of cosmic ray daily variation and geomagnetic effects.	E_4
1962	Sarabhai, V.A. & Gottlieb, B.	Time variation of cosmic ray intensity from North and South directions at low latitudes.	E_5
1963	Sarabhai, V.A.	Asymmetric interaction of the magnetosphere with solar plasma.	C_1
1963	Sarabhai, V.A.	Some consequences of nonuniformity of solar wind velocity.	E_3
1963	Sarabhai, V.A. &Pai, G.L.	Intensity of green coronal emission and the velocity of Plasma wind.	E_7
1963	Sarabhai, V.A. &Subramanian, G.	Modulation of Galactic cosmic rays by interplanetary Plasma.	E_9
1963	Sarabhai, V.A.	Modulation of galactic cosmic rays in the solar system.	E_9
1963	Sarabhai, V.A. &Subramanian, G.	Nature of the daily variation of cosmic ray intensity during the period 1958-1962	E_9
1964	Sarabhai, V.A. &Pai, G.L.	Periodic fluctuations in the Geomagnetic field during magnetic storms.	E_1
1964	Sarabhai, V.A.	Probing interplanetary space with cosmic rays.	E_1
1965	Sarabhai, V.A. &Subramanian, G.	Characteristics of anisotropy of galactic cosmic rays during the solar cycle.	E_3 E_5
1965	Sarabhai, V.A.	Modulation II.	E_6
1965	Sarabhai, V.A. &Subramanian, G.	Galactic cosmic rays in the solar system.	E_7 &
1965	Sarabhai, V.A. etal	Sector structure of solar activity and the electromagnetic conditions of interplanetary space.	E_7

1965	Sarabhai, V.A. &Subramaniam, G.	Changes in the characteristics of the anisotropy of galactic cosmic rays with solar activity.	E_8
1965	Sarabhai, V.A., Pai, G.L. & Wada, M.	Interplanetary magnetic field and the anisotropy of galactic cosmic rays.	E_5
1966	Sarabhai, V.A. etal	Geomagnetic disturbance, plasma wind and solar activity.	E_1
1966	Sarabhai, V.A. &Subramaniam, G.	Galactic cosmic rays in the solar system.	E_6 & E_8
1966	Sarabhai, V.A. etal	Characteristics and the anisotropy of galactic cosmic rays during IQSY - a day to day analysis.	E_1 &E_1
1966	Sarabhai, V.A.	Value of space activity for developing countries.	G
1967	Subramanian, G. &Sarabhai, V.A.	Consequences of the distributions of galactic cosmic-ray density in the solar system.	E
1967	Sarabhai, V.A. &Sukkx Dhanju, M.S.	Short-period variations of cosmic-ray intensity	E
1967	Sarabhai, V.A. & Nair, K.N.	Experimental determination of temperature effect on Masone recorded at Trivandrum.	E
1967	Patel, D., Sarabhai, V.A., &Subramaniam, G.	Gradient of galactic cosmic rays normal to the solar equatorial Plane.	E
1967	Sarabhai, V.A., Patel, D.& Subramanian, G.	Anisotropies of galactic cosmic rays.	
1968	Patel, D., Sarabhai, V.A. &Subramaniam, G.	Anisotropies of galactic cosmic rays in the Solar system.	E
1969	Sarabhai, V.A.	Television for Development.	E
1969	Sarabhai, V.A. &Nair, K.N.	Geomagnetic field - A measure of kinetic energy density of solar wind.	C

1969	Sarabhai,V.A. & Nair,K.N.	Daily variation of the Geomagnetic field and the deformation of the Magnetosphere.	C
1969	Sarabhai,V.A. &Nair,K.N.	Geomagnetic Plasma Probe for solar wind.	C_{2} E_{1}
1969	Sarabhai,V.A. &Dhanju,M.S.	Characteristics of cosmic ray fluctuations in the frequency range of 10^{-6} to $4.15x10^{-3}$ cycle per second.	E_{1}
1970	Sarabhai,V.A. &Dhanju,M.S.	Short-period fluctuations of cosmic ray intensity at the geomagnetic equator and their solar and terrestrial relationship.	E_{1}
1970	Pathak,P.N.& Sarabhai,V.A.	Study of the long-term modulation of galactic cosmic ray intensity.	E_{17}
1970	Sarabhai,V.A. etal	Daily variation of the Geomagnetic field at the Dip Equator.	E_{2}
1971	Sarabhai,V.A. & Nair,K.N.	Morphology of the geomagnetic field variations and a study of the interplanetary magnetic field fluctuations in relation to the daily variation of the geomagnetic field at low latitudes.	C_{2}
1971	Sarabhai,V.A.	Music and Noise	C_{2}
1972	Sarabhai,V.A.	Vikram A Sarabhai, Scientist-Educationist. - Sketched by Ramanathan, M.R. - 2 copies.	G
1972	Sarabhai,V.A. &Thomas,K.T.	Nuclear Power in Agricultural development	G
1973	Pratap,R., Sarabhai,V.A. &Nair,K.N.	Three dimensional dynamo theory in the	C
1973	Chowdhury,K. &Sarabhai, V.A.	Organization for developmental Takks: Atomic Energy Commission of India. -TWO COPIES.	G

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THE TIME DISTRIBUTION OF COSMIC RAYS

BY

VIKRAM SARABHAI

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THE TIME DISTRIBUTION OF COSMIC RAYS

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1. *Introduction*

THE problem of the probability distribution of α-particles emitted during radioactive decay has for long attracted the attention of workers in the field of nuclear physics. An experimental verification of the distribution law to be expected from complete time-randomness had an importance not only for the light it would throw on the basic decay mechanism at work, but also for introducing suitable correction for the finite resolving time of counting devices of nuclear particles. Most of the early experiments were done on the α-particles from polonium; the technique consisted in observing the particles by the scintillations produced on a suitable screen, and recording the instants of observation on a chronograph tape. The results were then analysed by either one of two methods. In that due to Bateman,[1] the fluctuations of the number 'n' of particles observed in small equal intervals of time were determined; whereas in that due to Marsden and Barratt,[2] the probabilities for the occurrence between successive arrivals of time intervals of duration greater than any particular 't' were calculated.

The earliest investigations made by Rutherford and Geiger,[3] by Marsden and Barratt,[2] and by Curie[4] all went to show that the α-particles from polonium obeyed the probability law to be expected from a complete time-randomness of the disintegrations. However, certain experiments of Kutzner[5] and later of Pokrowski[6] seemed to indicate that the concentration of the source investigated might have some effect on the statistics of the measured counts. These effects were later found to have no significance as far as the fundamental process of decay was concerned. Indeed Feather[7] who repeated some of the experiments of these two workers found " no evidence to show that the Marsden-Barratt distribution formula was not completely valid under the conditions obtaining ".

While therefore the position with respect to ordinary nuclear phenomenon seems now to be firmly established, a direct experimental test of the time distribution of cosmic rays does not appear to have been made. It has of course been assumed, perhaps reasonably, that the arrivals of cosmic rays follow a perfectly random law; and indeed all counter experiments on cosmic rays have been corrected for the finite resolving time of the apparatus by using this assumption. But the fact that most of the cosmic ray particles at low levels are secondaries, and that often two or more particles from the same primary are present and capable of detection by the recording apparatus, makes it at least conceivable that the complete time-randomness of the arrivals of the particles may be disturbed. With this in view the present experiment was undertaken; and the question whether or not it was possible with the arrangement used to detect such an effect will be discussed in detail at a later stage.

2. *Theory of Random Fluctuations*

A very general treatment of the subject has been given by Ruark and Devol[8]; and several other authors have considered the various aspects of the problem. It can easily be shown that for perfectly random arrivals, the chance that 'n' particles arrive in a time 't' is given by the well-known formula of Bateman, *viz.*,

$$w_n(0, t) = \frac{x^n}{n!} e^{-x} \tag{1}$$

where '$x = ft$' is the mean number of particles that arrive in the interval t. fdt, the probability that one particle would arrive in time dt, is naturally independent of 't' in the case considered. When we have a distribution of this kind, the standard deviation is $x^{\frac{1}{2}}$; and therefore the Lexian ratio Q^2, or the ratio of the (standard deviation)^2 and the mean is unity. The value of Q^2 gives us a quantitative measure of how far any given distribution agrees with the Bateman law. The dispersion is called supernormal or subnormal according to whether Q^2 is greater or less than unity. A subnormal dispersion indicates the we have in the distribution a larger number of small intervals than would be expected from the normal law. The value of making a Bateman analysis, *i.e.* to study how the number of particles in any given small time interval fluctuates about the mean number expected, is that we thereby get a quantitative measure of the goodness of fit between experimental results and the theory.

For the Marsden-Barratt analysis we have to know the theoretical probability for the occurrence between successive particles of time intervals of duration greater than any t. This can easily be derived from the Bateman formula (1) by considering the case where $n = 0$. The required probability is then:

$$\rho_t = e^{-ft} \tag{2}$$

We have here only made the arbitrary instant, at which we start the Bateman interval, coincide with the occurrence of each successive arrival. Thereby no fallacy is introduced into the argument as the probability $f(dt)$ is independent of time. If N_0 be the total number of intervals between the random arrivals, then the number of intervals N_s of duration greater than t_s is given by

$$N_s = N_0 \, e^{-\frac{t_s}{\bar{T}}}, \tag{3}$$

where $\bar{T}$ is the mean time interval and is equal to $1/f$. By taking logarithms we therefore get the linear relation

$$\log N_s = \log N_0 - \frac{t_s}{\bar{T}} \log e. \tag{4}$$

This is of a very suitable form for comparison with experimental data, because all the measured values of log N_s when plotted against t_s should fall on a straight line.

3. *Experimental*

In the present series of experiments, cosmic rays were detected by means of Geiger-Müller counters. All the counters used were of the Trōst fast self-quenching type; and the treatment of the counter copper cylinders was done according to the method described by Neher.[9] The counters were filled with a mixture of argon and petrol-ether; and when operated at a potential of about 1200 volts, they possessed plateaux of 150–200 volts. The efficiency of the counters, as experimentally found from a comparison of double and triple coincidences according to the usual method, came to greater than 95%.

Recently Driscoll *et al.*[10] have studied Geiger counter statistics by means of a completely electrical arrangement for discriminating between time intervals of varying durations. On using γ-rays from a sealed radium source to operate their counter tubes, they found that argon filled counters gave a time distribution of pulses in excellent agreement with fluctuation theory; a hydrogen filled counter however showed marked deviation. The use of argon filled counters in the present case was therefore expected to bring out faithfully the true statistics of cosmic ray arrivals. For, though Driscoll has not used alcohol vapour counters, the presence of the vapour should have no effect on the experiment so long as spurious discharges are not present to any appreciable extent. The existence of a fairly good plateaux in the counters used goes to show that this mechanism can be neglected.

The high voltage for the counter was obtained from an electronic voltage regulator[11] fed by a 2000 volt transformer. The central wire of the Geiger-Müller tube was directly connected to the grid of the first amplifier valve and the subsequent connections are shown in Fig. 1. For the purpose of discriminating between time intervals of different duration it would have been possible to use the electrical method given by Driscoll, or the more elegant apparatus of Roberts[12] who has studied the statistical operation of various Geiger counter quenching circuits. But in the present case it was thought desirable to employ the more direct method of registering the arrivals of cosmic rays on a chronograph tape and then make both a Marsden-Barratt and a Bateman analysis of the record. Such a procedure, though laborious has obvious advantages; specially as it can with quite good accuracy reach the same order of small time intervals as the interval meter developed by Driscoll. The record from electrical time interval meters does not lend itself to a Bateman analysis and hence a quantitative criterion of goodness of fit, namely the value of Q^2 cannot be found. Besides, in experiments with cosmic rays we usually deal with much lower counting rates than in the case of nuclear disintegration phenomenon; and consequently the number of counts missed due to the finite resolving time of the recorder is also small.

The pulse from the Geiger counter was so fast that it was necessary to lengthen it before it could operate the chronograph pen. It was first tried to work the pen from the output current of a multivibrator circuit operating a telephone call counter (see Fig. 1 B). A resolving time of 1/15 second was attained in this way but there were two objections for using this method. It was thought that a multivibrator circuit, though operating normally for regular pulses, might have a tendency under certain circumstances to count double. This was in fact observed; and in some experiments done with this method, a larger number of small intervals was obtained than what we should expect from a random law. The second objection to this was that the call counter formed the limit for the resolving power, while the pen by itself was capable of registering much quicker pulses. Hence the method that was finally adopted consisted in a lengthening of the Geiger counter pulse by the use of high resistances and capacitances in the amplifier. This explains the unconventional values of some of the components shown in Fig. 1 A. The moving coil operating the pen of the chronograph was connected in series with the plate resistor r_6 of the second stage 57 tube; and the size of the deflection of the pen could be controlled by changing the cut-off bias voltage V_1 on this tube. A value of 10 volts for the bias was found to be suitable for most of the experiments undertaken. The object of the plate resistor r_6 was to generate a sufficient voltage pulse to operate the multivibrator counting unit shown in Fig. 1 B. The simultaneous running of this unit along with the chronograph pen was found to be very helpful in order to know the progress of the experiment. From the total counts registered by the call counter, it was immediately possible to have an idea of the satisfactory operation of the apparatus during a run. The Fig. 1 A shows the arrangement as used for measuring double coincidences between Geiger counters; but when a single Geiger counter was under investigation it was only necessary to remove one of the two Rossi tubes from its socket and use the other singly.

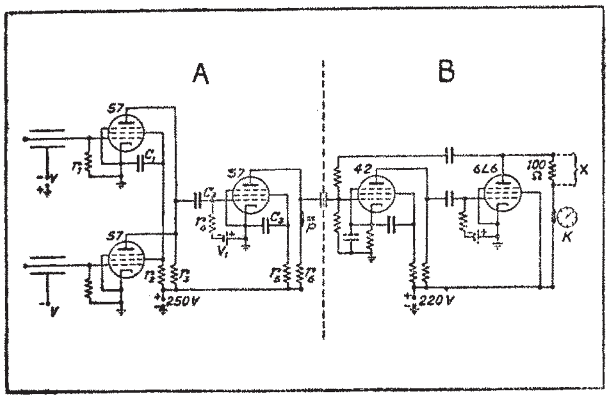

FIG. 1

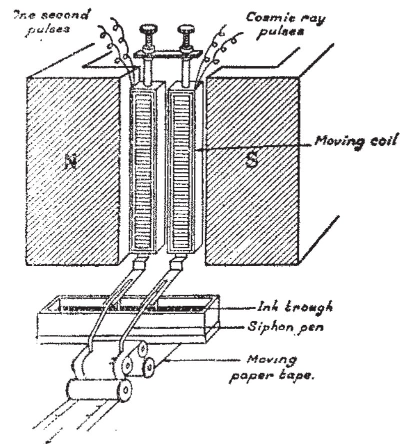

FIG. 2

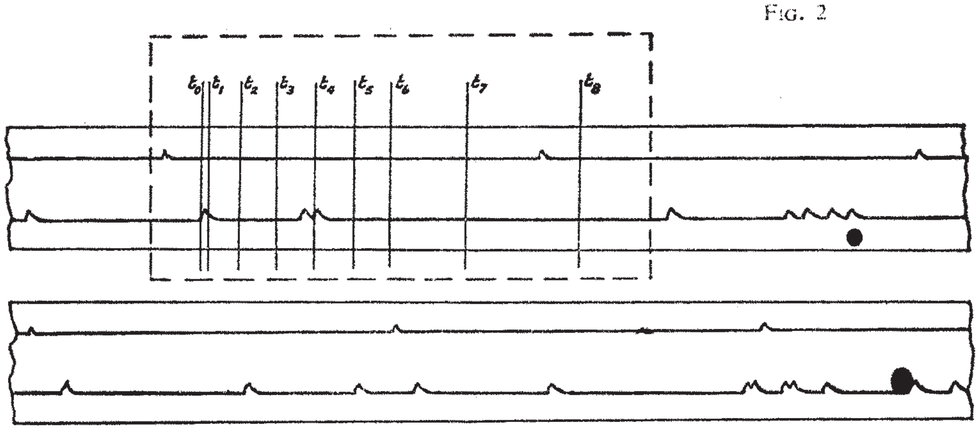

FIG. 3

FIG. 1. Circuit diagram showing A, the double coincidence set and amplifier operating the chronograph pen P; and B, the multivibrator working the telephone call counter K. X shows the points to which the coil of P was first connected. The constants are $r_1=10$ meg. Ω, $r_2=75000\,\Omega$, $r_3=100000\,\Omega$, $r_4=250000\,\Omega$, $r_5=50000\,\Omega$, $r_6=12000\,\Omega$, $C_1=\cdot 05\,\mu F$, $C_2=\cdot 5\,\mu F$, and $C_3=\cdot 02\,\mu F$.

FIG. 2. Diagram of Chronograph recorder.

FIG. 3. Typical tape record of cosmic ray and one second pulses. Scale for making Marsden-Barratt analysis is also shown (Actual size).

A diagrammatical view of the chronograph recording device is shown in Fig. 2. Two moving coils are sensitively suspended in a strong magnetic field produced by a permanent magnet. Each coil bears an arm at the lower end, and special capillary pens are attached by wax to these arms. The pens dip at one end in a small trough filled with ink and rest on a moving paper tape drawn at a uniform rate past them by an electric motor. The pressure of the pens on the paper could be adjusted by the moving coil suspension screws. The motor was operated from a battery set, and during the experiment the speed remained constant to within 2%. The speed of the moving tape could be easily changed by shifting the gears attached to the motor. The speed was adjusted after taking into consideration the counting rate and the likely duration of each particular experiment. One of the pens was made to register the arrival of cosmic rays as already described before. The other pen simultaneously marked uniform pulses arriving at intervals of 1 second. These pulses were obtained from a synchronous clock operated by a 1000 cycle standard valve maintained tuning fork. The time scale given by this arrangement was of an accuracy for surpassing that achieved in the rest of the experiment.

Fig. 3 shows a portion of a typical record. The resolving time of the pen as estimated from a record of uniform pulses fed from a pulse generator came to about 1/60th of a second. This value only forms a rough estimation, and hence it has not been used in the comparison of experimental data with theory. The length of the tape corresponding to one second in time was determined separately for each experiment by measuring accurately the lengths of a known interval of time at a number of places along the tape record, and taking a mean.

4. *Marsden-Barratt Analysis*

For making a Marsden-Barratt analysis of the tape record, a scale was made as shown in Fig. 3; having vertical lines ruled at distances from a fixed index line corresponding to certain fractions t_1, t_2 $\cdots\cdots$ of a second. The lines were ruled on the emulsion side of a transparent photographic plate with a fine needle fixed in a microtome; and the scratches were made more visible by rubbing rouge into them. After ruling, the distances between the various lines and the index line were again accurately measured to better than 1% accuracy. Thus the scale was marked out into different regions 1, 2, $\cdots$ etc., corresponding to various time intervals t_1, t_2 $\cdots$ etc. from the index line t_o. The procedure then consisted in placing the tape under the scale so that one particular cosmic ray pulse coincided with line t_o. If the next pulse was in the region between, say, lines t_4 and t_3, it was noted down as having belonged to group 4, *i.e.* of duration from between t_3 and t_4 seconds. The penultimate pulse was then made to coincide with t_0, and the time interval between the two pulses was similarly noted into the appropriate group. In this way the intervals between the arrivals of the cosmic ray particles were classified into one or other of nine groups, the last group containing intervals larger than t_8.

There are however two difficulties in this method of analysis. One is the inaccuracy of making a pulse on the tape exactly coincide with the vertical index line on the scale. Then again the second pulse may not lie in between the lines bordering any range but might fall just on one particular line. A decision has then to be made whether the interval lies in the range to the right or to the left of the line in question. Though perhaps this might be expected to introduce considerable inaccuracies in tabulation, specially when the sizes of some of the small ranges are only about a millimetre in length; it is possible with the help of a reading lens, and a suitable convention for deciding ambiguous cases to arrive at surprisingly consistent results. An estimate can be formed of the extent of inaccuracy that can thus be introduced by considering the thickness of the lines on the scale; and it would be safe to put a value of 5% as the upper limit for the error in the smallest ranges. The second difficulty arises when two cosmic ray arrivals come so close to each other that the pen mark no longer shows two distinct deflections. It was found however, that the shape of the deflection showed a marked change even when two arrivals followed so closely that the pen had not been fully deflected after the first arrival. But such an estimation, though possible, would introduce considerable errors. It was therefore decided to draw the t_1 line of the scale at just such a distance from t_0 that all particles that would lie in group 2 (between t_1 and t_2) would be unambiguously resolved; which amounted to the condition that the distance between t_0 and t_1 should be just larger than the distance between the start of a deflection and the position of its peak.* All particles that lay in group 1 were noted but not taken into consideration for the final comparison of experimental data with theory. In the particular experiment where double coincidences due to cosmic rays were measured, a further complication was introduced by the fact that though a majority of the deflections were similar and of equal magnitude, there were in between a not inconsiderable number of deflections of varying sizes. These latter were attributed to false coincidences, and it was legitimate to assume that their occurrence was due to two independent arrivals striking individually the separate counter trays within the resolving time of the coincidence discriminating circuit. Hence in the analysis of this record a further convention had to be made; namely

* In Expt. 1, this practice was not carried out and t_1 was taken as equal to half t_2.

that we should neglect all deflections smaller than an arbitrary fixed magnitude, which was taken as just less than the height of the majority of deflections attributed to true coincidences.

The data so obtained directly gives us the total number of intervals which lie in the groups 1, 2 · · · 9, *i.e.* which had a duration between t_r to t_1, t_1 to t_2 · · · and t_8 to $\propto$ (t_r being the resolving time of the pen, naturally forms the lower limit for the measurement of time intervals). From this we can immediately calculate the number N_s of intervals larger than any particular t_s. This data collected for the several experiments is shown in Tables I and II. The first column indicates the groups that were excluded in order to arrive at N_s; and under the column 't_s seconds' is given the value of the corresponding 't_s'. The logarithm of N_s is also given and is plotted against t_s in Fig. 4. As explained earlier the curves should be linear. But to make a proper comparison with the theoretical expression (4), we need to know the value of the total number of intervals N_0 that would have been recorded had the resolving time of the apparatus been not t_r, but infinitely smaller. It is of course possible to extrapolate N_0 from any set of values N_s, t_s by assuming that the theoretical law (4) is valid. As however the resolving time t_r is not accurately known, the extrapolation from the 1st group would not be accurate. This group was therefore excluded and the mean N_0 was calculated from the extrapolated values obtained from all the other sets of N_s and t_s, as explained below.

TABLE I

Group	Expt. 1			Expt. 2		
	t_s sec.	N_s	log N_s	t_s sec.	N_s	log N_s
r*	·0166	8688	3·9389	·0166	9653	3·9847
1	·0510	8013	3·9038	·0208	8908	3·9498
2	·1021	7122	3·8526	·1022	6168	3·7902
3	·2042	5747	3·7594	·2044	3922	3·5935
4	·3063	4688	3·6710	·3070	2463	3·3915
5	·4084	3754	3·5745	·4095	1564	3·1942
6	·5105	3008	3·4783	·5113	982	2·9921
7	·7147	1944	3·2887	·7161	401	2·6031
8	1·021	1018	3·0077	1·023	125	2·0899

	t_s sec.	log N_s (theo.)	t_s sec.	log N_s (theo.)
Theoretical Values from eq. (4)	0	3·9533	0	3·9929
	·3	3·6747	·3	3·4152
	·6	3·3961	·6	2·8374

TABLE II

Group	Expt. 3			Expt. 4		
	t_s sec.	N_s	log N_s	t_s sec.	N_s	log N_s
r*	·0166	9234	3·9654	·0166	9028	3·9556
1	·0211	8677	3·9384	·0244	8516	3·9302
2	·1037	6270	3·7973	·1014	6955	3·8423
3	·2074	4216	3·6249	·2030	5394	3·7319
4	·3113	2781	3·4442	·3062	4153	3·6184
5	·4153	1856	3·2686	·4073	3263	3·5136
6	·5186	1253	3·0979	·5094	2517	3·4009
7	·7263	559	2·7474	·7137	1517	3·1810
8	1·0371	163	2·2122	1·0244	685	2·8357

	t_s secs.	log N_s (theo.)	t_s sec.	log N_s (theo.)
Theoretical Values ..	0	3·9812	0	3·9519
From eq. ..	·3	3·4703	·3	3·6279
(4) ..	·6	2·9594	·6	3·3040

TABLE III

t_s	Expt. 1		Expt. 2		Expt. 3		Expt. 4	
	R_s	R_0	R_s	R_0	R_s	R_0	R_s	R_0
t_1 ..	114·5	127·5	241·0	264·0	213·2	231·2	141·9	150·8
t_2 ..	101·7	126·2	166·9	259·2	154·1	229·0	115·9	149·4
t_3 ..	82·4	126·9	106·1	242·0	103·6	228·5	89·9	148·6
t_4 ..	67·0	129·9	66·6	281·5	68·3	249·0	69·2	145·6
t_5 ..	53·6	129·0	42·3	273·2	45·6	239·5	54·4	148·0
t_6 ..	43·0	130·4	26·6	273·8	30·8	235·5	41·9	150·2
t_7 ..	27·8	128·7	10·8	269·0	13·7	234·5	25·3	149·3
t_8 ..	14·5	127·9	..	..	..	..	11·4	151·6
Mean R_0	128·3		266·1		235·3		149·2	
Total Time Minutes	70		36·97		40·70		60	
N_0	8981		9838		9577		8951	
$\bar{T}$. secs.	·4676		·2255		·2550		·4022	

By dividing in any particular experiment the values of N_s by the total time T_s of the experiment, we arrive at the corresponding values for R_s, the rate per minute of intervals larger than t_s. Values for R_s are tabulated in Table III for each experiment. Now, eq. (4) can be written in terms of R_s as

$$\log R_s = \log R_0 - \frac{t_s}{T} \log e.$$

But as $\bar{T} = \frac{60}{R_0}$ seconds, we have the identity

$$\log R_0 - \log R_s = \frac{R_0}{60} t_s \log e. \quad (5)$$

The solution for R_0 for any particular set R_0, t_s is easily found graphically by plotting separately the two sides of this equation against R_0. The extrapolated value in each case is given in Table III under column R_0. From the mean of R_0, we can immediately get N_0 and the true value of the mean interval $\bar{T}$. Both these quantities should to a large extent be free from errors of finite sampling. These values of N_0 and $\bar{T}$ have been used in eq. (4) to get the theoretical log. N_t as tabulated in Tables I and II; and these theoretical values for each experiment have been drawn as continuous lines in Fig. 4 for direct comparison with the experimental points. The consistency of the value of R_0 obtained from the different values of R_s is itself a good indication as to how far the distribution obeys the random law expressed by eq. (4). Fig. 5 shows the variation of both R_0 and R_s against t_s. While theoretically R_0 should remain constant, the value of R_s should diminish exponentially.

5. *Experimental Results*

The investigation of the time distribution of cosmic rays was carried out in three different experiments; while a fourth experiment was undertaken to verify whether it was possible to confirm with the same apparatus and under almost similar conditions the distribution of time intervals for a radioactive source. The various experiments were:—

(1) *Experiment* 1.—Cosmic ray investigation with a small Geiger counter having a cylinder 4 inches long, operating singly. The counting rate per minute was 128·3. The speed of the chronograph tape was 2·496 cm. sec.$^{-1}$

(2) *Experiment* 2.—Cosmic ray investigation with a large counter having a cylinder 8 inches long, operating singly. The counting rate per minute was 266·1. The speed of the chronograph tape was 4·858 cm. sec.$^{-1}$

(3) *Experiment* 3.—γ-Ray investigation with a midget Geiger counter having a cylinder 1 inch long. The background count of the counter was 23·7 and this was increased by a radioactive thorium source to 235·3 counts per minute. The speed of the chronograph tape was 4·779 cm. sec.$^{-1}$

(4) *Experiment* 4.—Cosmic ray investigation with a double coincidence Geiger-counter arrangement. Four counters having cylinders 12 inches long, were stacked two over two; and coincidences between the upper and the lower pairs were registered. With the very wide solid angle subtended by this arrangement, and a sensitive area of about 25 sq. inches for each pair, it was possible to get a counting rate of 149·2 counts per minute. The speed of the chronograph tape was 2·994 cm. $sec.^{-1}$

The proper functioning of the apparatus in each experiment was checked by noting during the Marsden-Barratt analysis, the number of cosmic ray intervals that successively occurred in a certain fixed time period, say 10 minutes. The fluctuations of the number of these intervals about the mean number expected in the same time period, give us an indication as to whether the experimental conditions remained constant during the run. If there is no variation in the efficiency of the apparatus, then the probable error calculated from the residuals should be smaller than the probable error taken from the total number of counts. This condition was well satisfied in each of the four experiments; showing that there was consistency not only in the functioning of the apparatus but also in the system of analysis with the scale.

A glance at Figs. 4 and 5 immediately makes it obvious that judged from all the criteria discussed before, the time distribution of cosmic rays as investigated in Experiments 1 and 4 agrees remarkably well with what we should expect from the random law. The very good fit with theory for the double coincidence experiment is specially significant, as we have here a detecting device sensitive only to cosmic rays as against terrestrial radioactive sources. For both experiments, what little variation there is in the value of the extrapolated R_0 (this amounts to 2% for the largest deviation from the mean) can be explained entirely by the estimated experimental error. In Experiment 2 however the fit between experimental points and the theory is not so good. Whether or not this deviation has any physical significance can be judged by considering the results in relation to those obtained in Experiment 3. The experimental conditions in these two experiments correspond closely to each other as far as the counting rate and the speed of the chronograph tape are concerned; and the same scale was used for making the Marsden-Barratt analysis in both cases. But while in Experiment 2 the counting rate was predominantly due to cosmic rays, in Experiment 3 the conditions were reversed so that cosmic rays only played a negligible role and the measured rate was mostly due to radioactivity. A comparison of the results of these two experiments therefore directly indicates the position in cosmic rays *vis-a-vis* radioactivity. It is important

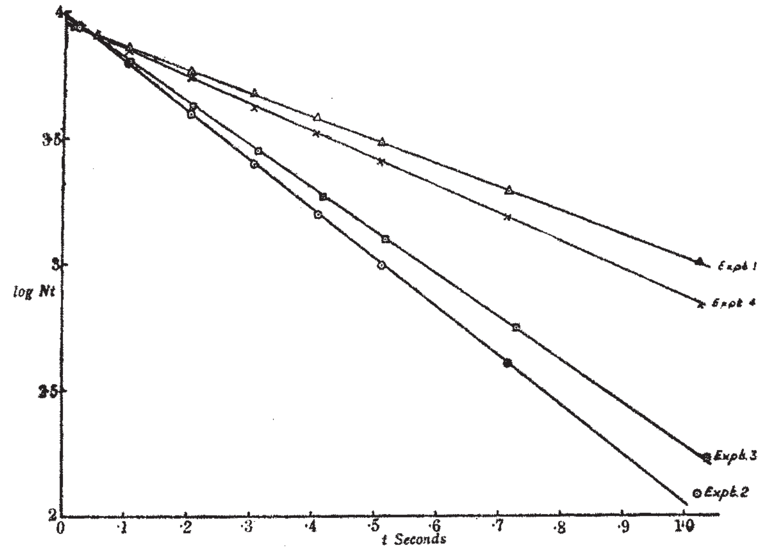

FIG. 4

△ Expt. points for cosmic rays with small counter.
⊙ ,, cosmic rays with large counter.
⊡ ,, radio-activity with Midget counter.
× ,, cosmic rays. Double coincidences.

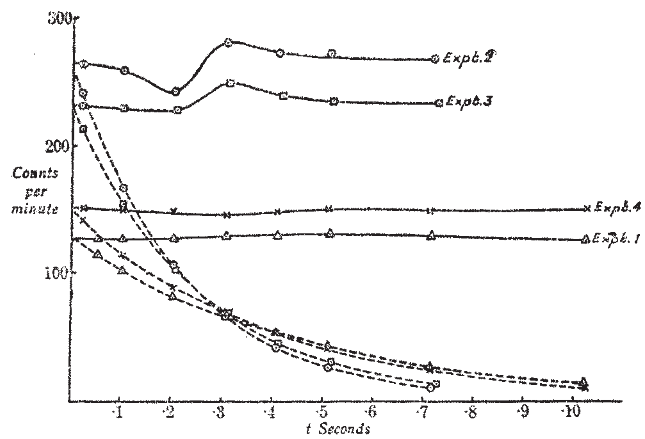

FIG. 5

Curves showing variation of R_s (dashed curves) and of the extrapolated values of R_0 (continuous lines).

to notice that for these two experiments the curves showing the variations in R_0 follow the same general trend; and indeed the maximum deviation from the mean R_0 occurs in both cases at t_4 and amounts to 6%. Though the magnitude of the error is slightly larger than what would be estimated from experimental inaccuracy, it is highly probable that it is due to some peculiarity of the scale, possibly the ruling of the particular line t_4. Besides, the all round poorer fit with theory for these experiments is very probably due to the higher counting rates used. But in so far as this is present for both these experiments, it is justifiable to say that the lack of agreement is not due to any departure in the cosmic rays from the random law.

6. *Bateman Analysis*

A confirmatory check of the results obtained above was made by means of Bateman analysis of the chronograph tape records of all the four experiments. The number 'f' of intervals of some fixed duration 't' having 'n' particles in each of them, was found for various values of 'n'. This only required the counting of the number of cosmic ray pulses in successive intervals of 't' seconds as indicated by the one second pulses on the tape. No attempt was made to artificially eliminate the very small intervals where only a change in the shape of the deflection had occurred. The results of the analysis therefore cannot be taken as very accurate for the small ranges. In the case of Experiment 4 however, the same convention regard-

TABLE IV

n	f			
	Expt. 1	Expt. 2	Expt. 3	Expt. 4
1	1	0	0	5
2	9	0	0	27
3	17	0	7	59
4	48	3	11	110
5	79	3	6	152
6	139	5	33	205
7	177	22	59	221
8	172	39	64	179
9	122	46	73	143
10	124	72	92	105
11	95	78	86	75
12	74	82	94	36
13	41	102	72	32
14	31	91	44	10
15	18	74	44	4
16	15	62	36	1
17	7	45	21	3
18	3	28	14	0
19	1	19	6	0
20	4	13	4	0
21	0	3	2	0
22	0	3	1	0
23	0	1	0	0
t	4 secs.	3 secs.	3 secs.	3 secs.
Σf	1177	791	769	1367
Σnf	10236	10243	8524	9922
$\Sigma n^2 f$	98502	141025	103264	81602
Q^2	0·928	1·03	0·817	0·966

ing the elimination of small deflections (due to false coincidences) was adopted as in the Marsden-Barratt analysis.

The results of the analysis are presented in Table IV for all the four experiments. The mean number of particles $\bar{n}$ that arrive in the interval 't' is obtained by dividing the total number of particles Σnf by the total number of intervals Σf. But the square of the standard deviation is:—

$$6^2 = \frac{\Sigma f\,(n-\bar{n})^2}{\Sigma f} = \frac{\Sigma fn^2}{\Sigma f} - \bar{n}^2$$

Hence dividing by $\bar{n} = \frac{\Sigma fn}{\Sigma f}$ we get

$$Q^2 = \frac{\Sigma fn^2}{\Sigma fn} - \frac{\Sigma fn}{\Sigma f}.$$

The values of Q^2 are tabulated for each experiment. Experiments 2 and 4 show a normal distribution as the deviation of the value of Q^2 from unity is small and may easily be due to errors of random sampling. Experiments 1 and 3 show slightly sub-normal distributions; and this is very probably due to the errors in the marking of small intervals as already explained before. The number of small time intervals must obviously have been overestimated; and in any case, as this has happened to the largest degree in the experiment on radioactivity, no importance need be attached to this subnormality for the purpose of our investigation.

7. *Discussion*

The time distribution of any radiation depends basically on the mechanism by which the emission takes place. The random law as we observe it in the case of nuclear phenomenon is only an expression of the fact that every atom in a radioactive material has the same chance to disintegrate. However it is well known that when a chain of radioactive elements has a member with a short life time, comparable to the time intervals experimentally measured, a departure from the time randomness is in fact observed. Indeed a good way of detecting the existence of a short life product is by studying the time distribution of the emitted radiation. But such departures from time-randomness can only be studied by observing the total emitted radiation, so that the space randomness does not mask the effect.

While the origin and the mechanism of the production of cosmic rays is still a matter of conjecture, it is not possible to anticipate what would be the time distribution in a primary beam of radiation. Even if there were any departures from time randomness in this beam, it is very likely that in any terrestrial measurement of the distribution, the effect would be completely masked by space randomness. However we do know that there are numerous processes by which secondary particles are produced in our atmosphere by the primary beam of cosmic rays. Whenever such a production takes place at high energy, the product or products have a great tendency to keep the original direction of the primary particle without suffering much angular divergence. In such a case we would be able to register not only one, but several related particles in the same detecting device, provided the exposed sensitive area of the latter is large enough. The time difference in the arrivals of these related particles (and we need not assume that the primary particle must be absent from the group) depends on the distance from the detector at which the particles are produced, and the individual velocities of the particles. Considering the high velocities of the majority of cosmic ray particles (electrons, positrons and mesons), it is not likely that the time difference would be large if the production of secondary radiation can take place only in our own atmosphere. The interval would be probably of the order of microseconds, and hence quite outside the range of the present investigation. For heavier particles like the neutron, a larger time interval might be expected because of the much lower velocities compared with those of electrons and mesons. To detect such an effect, it would be necessary to use not the ordinary Geiger counter but an apparatus sensitive to both slow neutrons and the high energy ionising component of the cosmic radiation.

The very good agreement between the experimental and theoretical time distribution of cosmic rays as investigated here, certainly goes to show that upto intervals as small as one-fiftieth of a second, there is no appreciable lack of time randomness of the radiation. The size of the detecting area also seems to have no effect on the extent of agreement. It might nevertheless be worthwhile to investigate the time distribution for much smaller intervals using an electrical time interval meter like the one developed by Roberts. The use of a much larger sensitive area, having a bias for the vertical direction of incidence would also help in detecting any deviation, if indeed it does exist.

In conclusion it is a pleasure to acknowledge the unfailing support and guidance that Prof. Sir C. V. Raman has given throughout this investigation. I am deeply grateful to Prof. K. Aston for having whole-heartedly placed at my disposal the chronograph recording device without which the investigation would have been impossible.

8. *Summary*

An experimental test of the time distribution of cosmic rays has been made using different Geiger counter arrangements. The distribution given

by cosmic rays has been compared with that due to radioactivity. It is found that at least upto the small time intervals ($\frac{1}{50}$ sec.) reached in the experiment, the arrivals of cosmic rays follow a law to be expected from complete time randomness; and their behaviour is therefore similar to that shown by radiations from radioactive sources. The possibility of detecting deviations from time randomness in the case of cosmic rays has been discussed.

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THE METHOD OF SHOWER ANTI-COINCIDENCES FOR MEASURING THE MESON COMPONENT OF COSMIC RADIATION

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THE METHOD OF SHOWER ANTI-COINCIDENCES FOR MEASURING THE MESON COMPONENT OF COSMIC RADIATION

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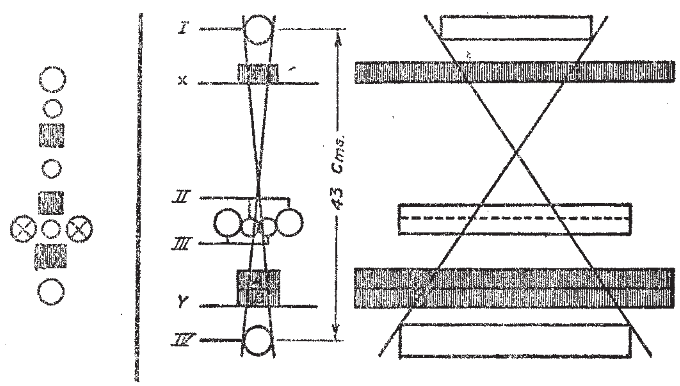
1. *Introduction*

IT is comparatively simple enough to distinguish between ionising particles of electronic and of heavier mass in the Wilson Chamber as long as the energy of the particles is not too high. In experiments with Geiger counters however, there is no direct and simple way for identification of the type of the particles, and so far the criterion of penetrability has been the one most widely used for differentiation of the two main components of cosmic radiation. Bhabha[1] has however pointed out how it is necessary to use 7·9 cm. of lead in order that all but 2% of the electronic component can be stopped. This naturally puts a limit to the minimum energy of the meson component that is measured. When therefore we try to measure the meson component by filtering out the soft electronic component with 7·9 cm. of lead, we measure in fact only mesons with energy greater than $1 \cdot 3 \times 10^8$ e.v. It is known however that there are mesons of less energy in the cosmic ray spectrum. According to Blackett,[2] all particles with energy less than 2×10^8 e.v. behave like electrons in their energy loss, but Anderson and Neddermeyer[3] find penetrating particles with less energy and have pointed out that Blackett's figure should be actually only $1 \cdot 1 \times 10^8$ e.v. Williams[4] has investigated the low energy spectrum, but has not made observations on the energy loss, and takes Blackett's observations to conclude that all the particles that he investigated in the low energy region were of electronic mass. More recently Bostick[5] has found evidence for slow mesons in a Wilson Chamber at 14,000 ft., and it is becoming increasingly clear that slow mesons are present in the cosmic ray spectrum. Rossi and Griesen[6] estimate that the slow mesons which get absorbed by 15 cm. of lead form 7% of the total meson intensity at an altitude of 850 ft., but may be as high as 27% at 14,100 ft. The results of Schein *et al.*[7] also point to the fact that the intensity of slow mesons increases rapidly with altitude.

Of late, the problem of knowing the correct proportion of electrons and mesons in the atmosphere at various altitudes has attracted a great deal of attention. Auger[8] and Griesen[9] have utilised accurate absorption experiments with lead and iron absorbers in order to get an estimate of not only the electron (soft) component, but also the meson (hard) component. In order to arrive at the slow meson component which he finds to be about 8%, Griesen has to make correction for what he calls the "Collision and Shower Effects". The estimation of the latter is perhaps the only weak link in an otherwise beautiful analysis. Stimulated by the idea of Bhabha to utilise the generation of secondaries of the soft component in order to exclude it, the author has tried out a new experimental arrangement for obtaining the intensity of slow mesons. The importance of this method lies not so much in reducing the weight of lead for measuring the meson intensity in balloon experiments, or in the exclusion of high energy electrons as in bringing for the first time the slow mesons in the field of direct experimental measurements.

2. *Method of Shower Anti-coincidences*

It has been found experimentally that a good proportion of the electrons measured by a cosmic ray telescope are already associated in the atmosphere with other ionising particles. The number so associated can be increased by placing in the apparatus a block of lead of thickness corresponding to the observed maximum of the Rossi curve. In order to exclude the



(*a*) (*b*)

FIG. 1. (*a*) Showing the arrangement of Jesse *et al.*
(*b*) Showing the experimental arrangement used for measuring shower anti-coincidences.

electrons, we can then devise an arrangement whereby the arrival of the associated particle can be cancelled by an anti-coincidence arrangement, and keep just so much additional lead underneath to absorb low energy electrons which might emerge from the top lead unaccompanied by other shower particles. In fact Schien, Jesse and Wollan[10] have utilised the phenomenon of shower production for making sure that the electron component was not greatly affecting the meson intensity that they measured in their balloon experiments with varying amounts of lead used to filter out the soft component. They measured events in which counters on the sides registered a particle associated with the penetrating particle in the main cone, as shown in Fig. 1 (*a*). Such an arrangement with the side counters working in anti-coincidence was initially suggested by Bhabha, but while on the basis of Auger's results, the atmospheric showers on account of their large spread will be probably quite well detected by this arrangement, the showers generated in the lead above may not be registered equally well on account of their small spread. In order to increase the efficiency of detection of both the atmospheric showers and those generated in the lead, it is desirable not to exclude the area of the main cone of measured radiation for the registering of the showers. This, however, cannot be accomplished by the use of the usual anti-coincidence arrangement, and a circuit is now devised whereby it is possible to tackle the main cone by placing two sets of counters in and adjoining the cone of the measured radiation (Fig. 1 *b*) and arranging matters so that only a coincidence between these two sets will cancel the event. This arrangement is simpler than the one now mentioned by Bhabha[1] and when used with quadruple coincidences would ensure that side showers do not vitiate the result. The circuit used for measuring the shower anti-coincidences is shown in Fig. 2. The two sets of anti-counters are connected in a Rossi coincidence arrangement with their mixer tube serving the dual role of a shower discriminator and a pulse reverser feeding the shower anti-pulse to the main coincidence circuit. Even though this means that the anti-pulse is fed through two stages as against the one stage for the main coincidence pulse, it is possible to attain an efficiency of 100% in the registration of shower anti-coincidences. The efficiency was measured in the following way:

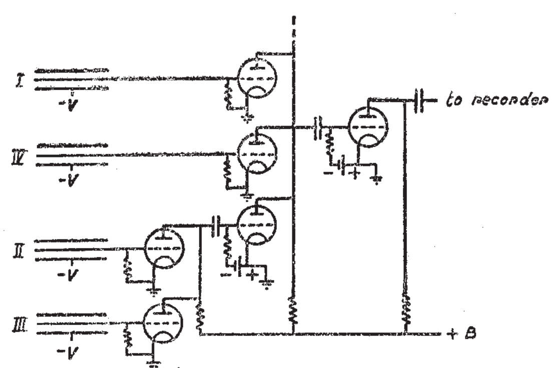


FIG. 2. Basic circuit used for measuring shower anti-coincidences. All tubes are Marconi Z21 and details are omitted.

An array of 4 counters A, B, C, D comprised a vertical telescope. The two end counters A, D were smaller both in length and diameter than the two middle counters B, C of the telescope. This ensures that every particle coming in the main cone determined by A, B will pass through the sensitive volumes of counters B, C. The double coincidences AD and the quadruple coincidences ABCD were measured. The difference in these two rates should be due to the effect of side showers and the inefficiency of counters B and C. This should equal the shower anti-coincidence rate AD -(BC) where the two centre counters are connected individually to the shower anti-coincidence tubes. The agreement of these counting rates was within a statistical accuracy of 1%. In order to see whether the feeding of one anti-pulse had any effect on the efficiency of registration of the main ~~anti~~ coincidence rate AD, it was compared with the counting rate AD-(C) and the rate AD-(B) wherein the anti-pulse was fed to only one of the shower coincidence tubes. No effect falling outside the statistical accuracy of the measurements was found.

The circuit for the measurement of shower anti-coincidences is now being utilised for an accurate study of the intensity of slow mesons, and the results will be communicated later. However, a preliminary test has been made at various altitudes in Kashmere during August and September 1943, and the results of this preliminary survey are presented below.

3. *Preliminary Survey of Meson Intensity at Various Altitudes in Kashmere*

In August 1943, an expedition was undertaken to Kashmere in order to find suitable locations where high altitude cosmic ray experiments could be performed. Though at that time the work on the experiment for measuring the slow meson intensity by the method of shower anti-coincidences had not progressed very far, it was decided to conduct that experiment at various altitudes in Kashmere to give a preliminary idea of both the working of the method of shower anti-coincidences and of the experimental technique involved in carrying out experiments on high peaks of the Himalayas. The most suitable period during which ascents can be undertaken to altitudes higher than 12,000 feet is from the middle of August to the middle of September. This consideration made it imperative to undertake the expedition in spite of the fact that the ideal experimental conditions for the method of shower anti-coincidences had not then been fully worked out.

A completely battery operated unit for registering fourfold coincidences along with shower anti-coincidences was set up. Marconi Z21 tubes were used for the amplifier on account of their low filament current drain, and the mechanical recorder was operated by a type 31 tube in the final stage. The B supply was furnished by a Stabilovolt regulator tube fed from a Vibrapack operated from one of two 6 volt accumulators taken with the expedition. The accumulators were charged at the location of the experiment by means of a petrol generator set which was carried to all altitudes except the highest. The high voltage for the counters was obtained from a small unit of dry cells made up of Eveready type 712 cells connected in series. The counters were operated 50 volts above threshold potential and were all well within the flat portion of their plateau. The counters were mounted on a portable wooden stand, and the exact geometrical arrangement is shown in Fig. 1 (*b*). It was found that within the main cone the efficiency of registering showers was greater with narrow counters than with counters of large diameter, but that outside the main cone the larger the sensitive volume used, the larger was the measured shower effect. The counters comprising the shower detecting tray were therefore of two diameters. The top counter I of the telescope measuring the vertical intensity was of smaller length than the others in order to ensure that the area of the block C included in the main cone was smaller than the area of the shower detecting tray. Electrons arriving along the boundary of the main cone will thus have a greater chance of being cut out by the showers they would generate in C.

The experiment was attempted at 5 different altitudes in Kashmere. It was first tried near Gangabal at Tronkhal (11,000 ft.) and then at Cosmic Ray point (13,900 ft.). Good consistent results were obtained at both these locations. It was then attempted at Srinagar (5,200 ft.) and, in order to obtain a check on the Gangabal results, at Gulmarg (8,900 ft.) and near Alpathar (12,800 ft.). Unfortunately, the Srinagar results were not satisfactory, and it was not possible to repeat them for want of time. At Alpathar, the shower anti-coincidence arrangement did not work on account of what was later detected to be the failure of one of the Z21 tubes. However, the total cosmic ray intensity was measured and has been used as a check on the other points. While all the experiments at Kashmere were carried out at geo-magnetic latitude 25° N., the experiment has been repeated at Bangalore (3,000 ft.) at geo-magnetic latitude 3° N. The latitude effect does not permit us to compare directly the results at Bangalore with those of Kashmere, but the Bangalore results serve to illustrate the working of the method of shower anti-coincidences.

At each location, the following counting rates were measured. Double coincidences I IV and shower anti-coincidences I IV–(II III) were measured with (1) no lead, (2) lead block C_x ($27 \cdot 7$ gm./cm.^{2}) placed above the shower detecting counters at X, (3) lead block C_x at X and lead block B_y (27·4 gm./cm.[2]) under the shower detecting counters at Y and (4) lead block C_x at X and lead blocks B_y and A_y (26·5 gm./cm.[2]) at Y. The double coincidence rate II III was also measured without any lead in the apparatus to register the intensity of atmospheric showers. The object of placing C at X was to increase the showers associated with the soft component, and varying amount of lead was placed at Y in order to investigate the absorption of the total intensity as measured by coincidences I IV and the meson intensity as measured by coincidences I IV–(II III). The experimental values of the intensity determined with the various arrangements at different altitudes are given in Table I.

TABLE I

Coincidence Counting Rates per minute	I IV	I IV –(II III)	I IV	I IV –(II III)	I IV	I IV –(II III)	I IV	I IV –(II III)	II III Atmospheric showers
Lead Blocks	..	..	C_x	C_x	C_x+B_y	C_x+B_y	$C_x+B_y+A_y$	$C_x+B_y+A_y$	..
Bangalore 3,000 ft.	2·876 ±·035	2·738 ±·037	2·526 ±·031	2·341 ±·029	2·282 ±·089	2·168 ±·043	2·129 ±·033	2·074 ±·035	29·05 ±·47
Gulmarg 8,900 ft.	4·61 ±·10	4·03 ±·17	3·65 ±·17	2·93 ±·16	3·01 ±·15	2·74 ±·11	2·66 ±·10	2·39 ±·06	52·40 ±1·54
Tronkhal 11,000 ft.	5·24 ±·14	.. ..	4·40 ±·15	4·00 ±·15	3·89 ±·18	3·66 ±·18	3·69 ±·10	3·28 ±·08	66·6 ±1·2
Alpathar 12,800 ft.	5·93 ±·16	.. ..	.. ..	.. ..	.. ..	.. ..	.. ..	.. ..	.. ..
Cosmic Ray Point 13,900 ft.	6·54 ±·20 ..	.. .. ..	5·82 ±·24 ..	4·58 ±·18 ..	5·03 ±·20 ..	4·41 ±·18 ..	4·10 ±·17 ..	4·02 ±·17 ..	78·4 ±2·7 ..

The absorption curves are shown in Fig. 3 for the different altitudes. These curves clearly exhibit that as the electron intensity gets absorbed with increasing lead, the difference between the rates I IV and I IV–(II III) steadily diminishes. The forms of the two curves are also different; for while the slope of the curve I IV appears to increase with diminishing thickness of lead, the slope of the curve I IV–(II III) seems to vary in the opposite direction. On theoretical grounds of decay the curve for the meson intensity should become horizontal for zero thickness of lead absorber, and we have here a striking demonstration of the fact that the intensity measured by shower anti-coincidences refers mainly to mesons only. While we are not justified in taking the value I IV–(II III) without lead as giving the meson intensity for no lead, because the efficiency of excluding electrons by their

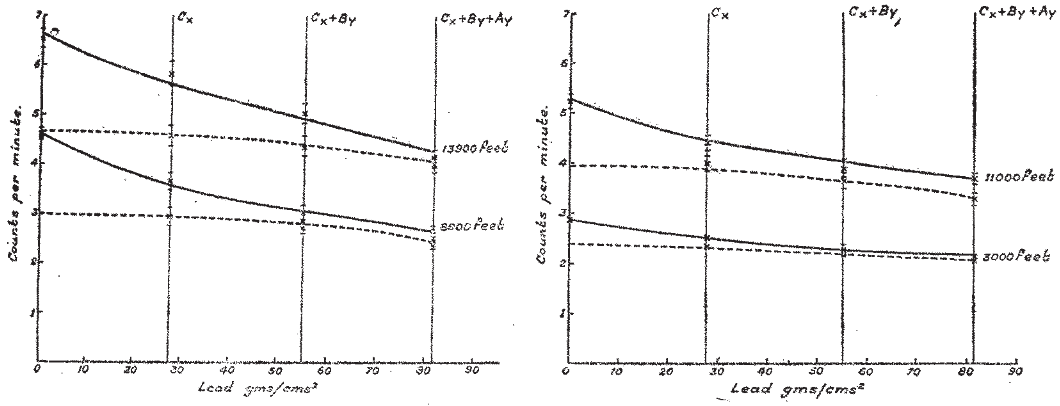


FIG. 3. Graphs showing for various altitudes the absorption by lead of the total intensity given by the counting rates I IV (continuous curves) and the meson intensity given by the counting rates I IV–(II III) (broken curves).

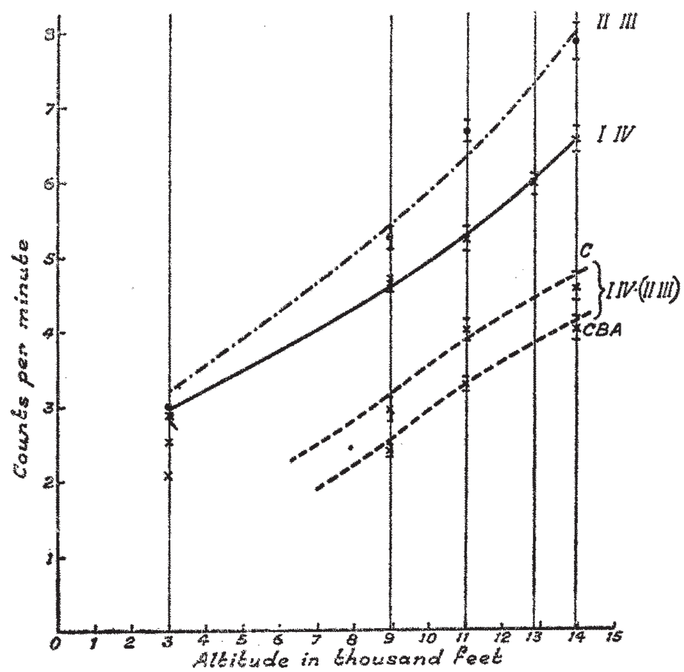


FIG. 4. Graphs showing intensity altitude curves for

(1) Atmospheric shower rate II III,

(2) Total intensity I IV, and

(3) Meson intensity as measured by I IV–(II III) with lead C_x and $C_x+B_y+A_y$. The Bangalore results have been plotted but are not directly comparable.

showers might be low without the lead block C, we can roughly extrapolate the shower anti-coincidence curve to zero thickness. It is then found that the percentage of mesons in the total cosmic ray intensity diminishes from

79% at 3,000 ft. to a value of 64% at 13,900 ft; but large error may be involved in both these estimates. At the same time however, the percentage of slow mesons in the total meson intensity appears to increase from 11% to about 18%.

The variation of the various counting rates with altitude is plotted in Fig. 4. The variation of the atmospheric shower rate is also given for comparison on the same graph. It is seen that while the total intensity I IV varies in a manner similar to the variation of the atmospheric shower intensity, the meson intensity as measured by the shower anti-coincidences has a flatter slope. The accuracy of the results is not such as to definitely conclude that the variation of the hard and soft components is very different in the region of the atmosphere investigated, but there seems to be little doubt that above 10,000 ft. the total intensity starts to rise more rapidly than the meson intensity. This is indeed in agreement with the results of Jesse *et al.*

4. *Discussion*

Judged by the preliminary results obtained at Kashmere, the method of shower anti-coincidences appears to be fairly satisfactory in giving the meson intensity. The Kashmere readings however suffered from one serious drawback in that only double coincidences were measured with and without shower anti-coincidences. The contribution of side showers to double coincidences can be quite appreciable, as demonstrated by Greisen and Nereson.[11] This contribution would depend among other things on the separation of the two counters measuring the double coincidence rate. In the experiment performed at Bangalore for determining the efficiency of registering shower anti-coincidences, the maximum contribution due to side showers came to 13% of the double coincidence rate assuming 100% efficiency for the two middle counters. The separation of the counters A and D was in that experiment only 14 cm., while the separation of counters I and IV in the Kashmere and Bangalore series was 43 cm. Another point which should be considered before judging the accuracy of the Kashmere results is that while the Kashmere results were obtained with the apparatus in a small tent, the Bangalore experiment was performed in a tiled roof building where the ceiling was about 30 ft. above the apparatus. Taking all these into account, it appears that the contribution of side showers could not be greater than 10% of the double coincidence rate I IV without lead absorbers. The effect of side showers would be independent of the amount of lead placed within the apparatus, and would therefore adversely affect the operation of the shower anti-coincidence arrangement in detecting mesons. This is because the percentage increase due to side showers in the meson intensity would be greater than in the total intensity and this would tend to increase the proportion of mesons.

The Kashmere results can be improved upon by placing a lesser thickness of lead at X than was actually used. The thickness of lead necessary for the maximum of the Rossi curve obtained from triple coincidences I II III would obviously be the ideal thickness to use. It comes to about 1·5 cm. Apart from being most effective in cutting out showers, it will also lower the low energy limit for the measurement of mesons. A further point that emerges is to test the absorption of the meson intensity as measured by shower anti-coincidences in the region of smaller thicknesses of lead absorber in the position Y. An accurate experiment is now in progress where quadruple coincidences are measured along with shower anti-coincidences and a much greater statistical accuracy is aimed at. The results will be shortly published in another communication.

The main defect of the method of shower anti-coincidences for measuring the meson intensity lies in the fact that multiple penetrating particles that are sometimes observed in a Wilson Chamber are also liable to be cut out. In addition, it is possible that knock-on electrons accompanying the mesons might prevent them from being measured. Both these effects would be more pronounced for high energy mesons and may not affect appreciably the intensity of slow mesons. The result of this might be to increase the measured proportion of slow mesons to the total number of mesons. The last and the most obvious possibility of error arises from electrons which may not produce large enough showers so as to be cut out by the shower anti-coincidence arrangement. With the help of a more accurate determination of the meson absorption curve, it is hoped that it would be possible to estimate the errors due to these causes.

One point that emerges from a comparison of the results at Bangalore and Kashmere is that at Bangalore there is a considerable hardening of the radiation. This is clearly seen in Fig. 4 showing the variation of the intensity with altitude, where the Bangalore values are also plotted. Probably the hardening is due to the latitude effect, but some of it might be attributed to causes connected with the different experimental environment at Bangalore. This hardening if confirmed by subsequent more accurate experiments would throw light on interesting questions regarding the origin of the meson component; but it would be too premature to draw any conclusions at present. Another point of interest in the altitude intensity curves is the tendency of the meson intensity curves to become flat with increasing altitude. Here too, little weight can be attached on account of the fact that there are only three points from which the shape of the curve can be judged. However, all these questions indicate the necessity of performing the experiment with greater accuracy and under more rigorous conditions at various altitudes and at different latitudes. This will be shortly undertaken.

It is a pleasure to acknowledge the support and assistance of Prof. Sir C. V. Raman and helpful discussions with Prof. Bhabha. The Kashmere expedition would not have been possible but for the willing help given by the State Officials and friends, and in particular the Prime Minister Sir Haksar, The Governor Pandit Dar, Col. Sir R. N. Chopra, and Maj. Haddow. I am grateful to Mrinalini Sarabhai, Gira Sarabhai, Gautam Sarabhai, Pandit Tikkalal, Dr. Dayal Singh and B. V. A. Iyer who helped during the expedition at Kashmere.

5. *Summary*

A new method of measuring the meson intensity by registering shower anti-coincidences is described. Its special merit lies in bringing for the first time under the field of direct experimental measurements, the slow mesons which are usually cut out in experiments where lead absorbers are used to filter out the soft electron component. The preliminary results obtained with this arrangement at altitudes up to 13,900 ft. in Kashmere are reported. Absorption curves for the meson and the total intensity at various altitudes as well as the altitude intensity curves for the total and the meson component have been given. Improvements in the technique by using fourfold instead of twofold coincidences for measuring the vertical intensity, and the use of optimum thickness of lead for generating the maximum number of showers are suggested.

Some special points of interest which emerge from the altitude intensity curves for mesons have been pointed out, and the need for more accurate measurement is indicated to decide the issues.

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THE SEMIDIURNAL VARIATION OF MESON INTENSITY

BY

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THE SEMIDIURNAL VARIATION OF MESON INTENSITY

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INTRODUCTION

FOR over a decade it has been known that the cosmic ray intensity at any particular place is not constant at all times. The small periodic and irregular variations in the intensity have been extensively studied at various stations; and the variations have been correlated with changes of the meteorological elements of pressure and temperature, and of the magnetic elements due to terrestrial and solar causes.

As shown recently by Duperier[1], the negative correlation between atmospheric pressure and cosmic ray intensity is due not only to an increase in the absorbing air mass with an increase of pressure, but also to the raising of the effective level at which mesons are formed, with a consequent increase in their probability of decay. The negative correlation with seasonal temperature of the atmosphere is also explained in terms of meson decay on lines originally suggested by Blackett[2]; but the experimental results are somewhat complicated by the fact that the temperature of the atmosphere near the earth's surface does not give a representative picture of the state of affairs at high altitudes. However, the work of Hess *et al.*[3] has indicated the methods by which the difficulties can be overcome by using radiosonde data. With respect to changes in intensity brought about by the variation of the magnetic field, Vallarta and Goddart[4] have shown how different factors depending on the latitude of the station are operative. The experiments indicate that the correlation between the intensity and the field at the place in question is negative for diurnal and seasonal changes but that it is positive during a magnetic storm.

While thus a good deal of theoretical and experimental study has been made of the variation of cosmic ray intensity; it is impossible to directly make use of this knowledge for correcting the results of accurate cosmic ray experiments because of the simple reason that normally one is not in possession of data of all the meteorological and magnetic factors responsible for the intensity variations. During the course of a recent investigation on the intensity of slow mesons by the method of shower anticoincidences[5], it was noticed in fact that large variations lying outside the statistical error were taking place in the measured intensity at different times of the day and from day to day. It was proposed to correct for this by means of another independent apparatus which had a counting rate large enough to make the statistical error negligible, and which followed the variations of the shower anticoincidence intensity. Thus a detailed study was begun of the variation of intensity as measured by different counter arrangements. As there are few puublished results of similar studies at stations near the geomagnetic equator, and the observations at Huancayo and Kodaikanal[6] were made with ionization chambers where intensities from all directions were measured, a correlation with atmospheric pressure was also attempted in the present work.

Experimental Results

To study the variation of intensity with local mean time, the hourly values of intensities were measured with counter arrangements giving the following:—

A. The total intensity as measured by two counters placed vertically on top of each other in double coincidence, giving a mean counting rate of 56·23 counts per minute. As the counters were touching each other, the solid angle was very wide, and there must also be a considerable side shower effect.

B. The shower rate measured under 1·5 cms. of lead by two parallel horizontal counters touching each other, and in double coincidence giving a mean counting rate of 21·605 counts per minute. Single particles incident at a zenith angle greater than 45° could also register a coincidence in this arrangement.

C. The shower anticoincidence rate measured with 1·5 cms. of lead at X (see earlier paper[5]) giving a mean counting rate of 1·5445 counts per minute. The vertical rate was in this case measured with quadruple coincidences in order to eliminate the side shower effect; and the vertically incident particles accompanied by showers either from the air above or the lead block at X were eliminated by the shower anticoincidence counters. It has been shown[5] that this counting rate is essentially due to the vertically incident mesons.

In addition to the above, the pressure was recorded continuously during the experiment with a microbarograph and hourly readings with a Fortin's barometer were taken as a check. Indian Standard Time is used throughout this paper and is one hour and twenty minutes in advance of the local mean time.

The result with the various arrangements is shown in Table I. It can be seen that A and B show the well-known diurnal variation of intensity with a maximum during the afternoon and a minimum during the night. Considering that in both these arrangements we are measuring an effect which is due to showers as well as single particles and that wide solid angles are subtended, it is not surprising that we obtain a variation which is similar in both cases and agrees with the results of the other workers who have studied this aspect with ionisation chambers. It should be noticed, however, that the percentage variation of B is much greater than of A. If this is due to the larger proportion of showers to single particles in B, we would be led to the conclusion that this phenomenon is mainly connected with the soft component.

TABLE I

Mean percentage variation of intensity and atmospheric pressure averaged for six hours in each column

Arrangement	Total counts	I.S.T. (1 hour and 20 minutes in advance of local mean time)			
		0300 to 0900	0900 to 1500	1500 to 2100	2100 to 0300
A from 8–9–1944 to 21–9–1944	872303	− ·037 ± ·147%	+ ·052 ± ·147%	+ ·244 ± ·147%	− ·260 ± ·147%
B from 10–9–1944 to 21–9–1944	342227	−1·127 ± ·229%	+ ·043 ± ·229%	+1·385 ±0·229%	− ·295 ± ·229%
C from 18–9–1944 to 24–9–1944	11120	−3·05 ±1·14%	+0·99 ±1·28%	−1·43 ±1·28%	+3·50 ±1·14%
Atmospheric pressure from 18–9–1944 to 24–9–1944		− ·0034%	+ ·0766%	− ·1117%	+ ·0418%

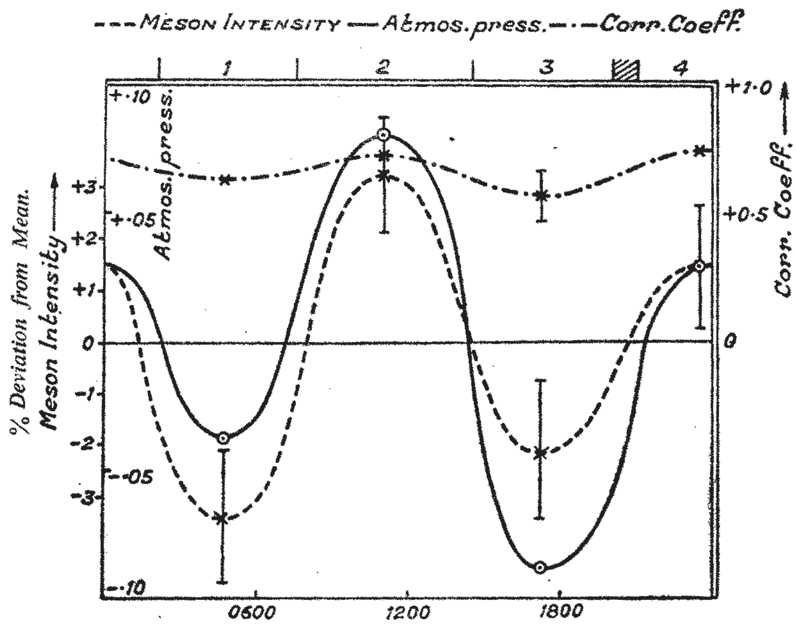
The course of variation of C is however totally different. We find, in the first place, that over 12 hour periods the intensity is slightly greater in the night than during the day. But in addition, we can clearly see a semidiurnal variation with a period of approximately 12 hours. What is more remarkable is that this variation is correlated with the semidiurnal variation of pressure and the total correlation coefficient comes out to be $+\cdot 46 \pm \cdot 11$. In order to quantitatively study this aspect, it was necessary to eliminate the secular changes of both the meson intensity and the atmospheric pressure. The importance of doing this is realised when we consider that the secular changes of pressure are negatively correlated with the intensity, as opposed to the positive correlation found in the semidiurnal variation. The elimination of these secular changes was carried out by taking the 24 hourly means and adjusting them to the total mean, making the assumption that the secular change is linear between any two 24 hourly means. The result of this correction is to reduce the mean of each day to the common mean, so that only the semidiurnal variation is left in the data. The figures given for C and the barometric pressure in Table I refer to the variation after correcting for the secular change.

TABLE II

Mean percentage variation of meson intensity and atmospheric pressure averaged over periods during which atmospheric pressure is either entirely above or below mean values in the semidiurnal variation

Arrangement	Total counts	Mean rate per minute	I. S. T.			
			0200 to 0730	0730 to 1430	1430 to 2000	2100 to 0200
C From 8–12–44 to 12–12–44	11113	1·8546 ±0·0118	−3·45 ±1·38	+3·26 ±1·12	−2·13 ±1·37	+1·41 ±1·28
Atmospheric pressure from 8–12–44 to 12–12–44			−0·0371	+0·0807	−0·0885	+0·2820
Correlation coefficient			+·62 ±·20	+·72 ±·14	+·56 ±·23	+·65 ±·17

Table II and Fig. 1 show the results of an independent experiment carried out from the 8th to the 12th of December at the Bangalore Meteorological Office to check the results of C obtained in the first experiment. In this case hourly values were not taken, but only at times corresponding to the epochs of the semidiurnal variation of pressure where the pressure is at its mean value. This is necessary for a proper correlation of the two variations because the semidiurnal pressure change does not have an exactly 12 hour period. Each of the four intervals now taken corresponds either to pressures entirely above mean or to those entirely below. The values between 2000 and 2100 hours were not considered as during this period the functioning of the apparatus was checked. The second experiment has shown a strong positive correlation of ·623 ± ·097. This represents the over all coefficient, but in Table II and the figure the correlation coefficient for each of the four periods is also shown. With the data so far available it is extremely probable that the positive correlation obtained in both cases is significant but quantitative



I. S. T. (*1hr.* 20 *mins. in advance of local mean time*)

FIG. 1. Graph showing the semidiurnal variation of meson intensity and the atmospheric pressure and the correlation coefficient connecting the two. Table II. Data obtained at the Bangalore Meteorological Office from 8-12-44 to 12-12-44.

treatment is not undertaken till the phenomenon has been completely confirmed by more extensive experiments now in progress.

DISCUSSION

A positive correlation between the semidiurnal variation of atmospheric pressure and the meson intensity has not so far been reported to the knowledge of this author. The semidiurnal variation itself seems to have been noticed independently by two German authors[7,8] as I have recently, after the completion of the above experiments, come across two abstracts of papers published since the outbreak of war. Ehmert[8] has suggested a connection with the oscillations of the atmosphere causing the semidiurnal variation of pressure; but details of his paper are not available. The somewhat puzzling positive correlation is explained very simply on the meson decay hypothesis if one considers the now accepted view about the nature of the atmospheric oscillations. The problem has been worked out in detail by Pekeris since the earliest work of Rayleigh. According to our present knowledge, the atmosphere has two free modes of vibration; one of these consists of a stationary wave of 12 hour period travelling along the parallels of latitude and having a node at about 30 km. The atmosphere vibrates horizontally in opposite phase above and below this level. It immediately follows therefore that a rise in pressure at the surface corresponds to a rarifaction in levels above 30 km., resulting in an effective lowering of the meson forming layer with an increase in the surface meson intensity. Apart from the theoretical justification for this view, it is found that the explanation of the semidiurnal variation of the magnetic field also requires a similar idea of phase inversion in the upper atmosphere.

A positive correlation between meson intensity and pressure does not necessarily imply that there is a causal relationship between the two. The above given reason can only be proved to be correct if it is known that the variation of meson intensity is not caused by the semidiurnal variation of the magnetic field with which it appears to be negatively correlated. Probably both the factors are operative; but as in magnetic storms there is a positive correlation with intensity this point requires further study before an answer can be given.

It is worthwhile considering the reason why this effect has not been noticed in the earlier investigations. It is clear, in the first place, that as at sea level the soft component is almost entirely secondary to the hard component, the study of the variation will be confused unless each component is studied by itself. Several of the ionisation chamber studies cannot be said to conform to this condition. Furthermore, the effect will be properly brought out only in instruments with narrowly restricted solid angles. A wide aperture will tend to blur the true variation and flatten the maximum. Lastly it must be remembered that the semidiurnal variation of pressure is strongest in the tropics and becomes quite negligible in temperate latitudes. As most of the other investigations have been done in higher latitudes, the effect might have escaped notice due to its small amplitude.

The picture presented here would, if confirmed, give a powerful tool for the study of the levels of meson formation. It is true that the heights of formation will have to be considerably higher than what was commonly supposed some years back. But after the experiments of Schein *et al.*[10] who found a continuously increasing meson intensity upto the stratosphere, the view that mesons are mainly created within the troposphere is being slowly given up. Further experiments are now being undertaken to clarify the issues and to determine the time variation of cosmic rays measured with other counter arrangements not using the method of shower anticoincidences.

I am deeply grateful to Prof. Sir C. V. Raman for his interest and helpful discussions. For help in taking round the dial readings, I am thankful to Messrs. B. V. A. Iyer, H. R. Sreenivasiengar and C. R. Ananda Rao; and later the staff of the Bangalore Meteorological Office. This work would not have been possible but for the whole-hearted co-operation of the Indian Meteorological Department and particularly Dr. K. R. Ramanadhan and Messrs. D. Basu and R. Pisharoty.

SUMMARY

An investigation of the diurnal variation of the cosmic ray intensity with different counter arrangements has been made. The results obtained are similar to those reported by previous investigators, except in the case of the meson intensity measured with the method of shower anticoincidences. Here a semidiurnal variation which is positively correlated with the semidiurnal variation of pressure has been found. An explanation in terms of the meson decay and the nature of the daily atmospheric oscillations has been suggested. The possibility of gaining knowledge about the altitude of the meson forming layer has been mentioned.

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THE SEMI-DIURNAL VARIATION IN MESON INTENSITY

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If the observed solar daily variation of cosmic-ray intensity is analysed into its Fourier components, it is usually found that the only important components are diurnal (24-hour period) and semi-diurnal (12-hour period). It is with the semi-diurnal component that we are chiefly concerned here.

Before comparing the experimental results of different workers, it is important to realise that the daily variation found may be expected to depend upon the precise constitution of the radiation observed. For instance, it is unlikely that the hard and soft components will be affected in the same way by meteorological changes, which changes certainly play an important part in determining the daily variation. Indeed, if there is any relation between the height of origin and the energy of the radiation measured at sea-level, we might expect to find different variations even for the more and the less energetic groups of the same component, since the meteorological changes vary with height.

In 1944 at Bangalore, near the geomagnetic equator, one of us (V. S.) began to study the daily variations observed with different Geiger-counter arrangements. It was soon evident that the variation of the total intensity was mainly diurnal, with an amplitude of about 0·2%, very like the variation already established for the total intensity. The atmospheric shower intensity had a similar variation but with an amplitude about five times greater. The meson intensity, on the other hand, showed hardly any diurnal variation, but a very pronounced semi-diurnal variation (amplitude between 1 and 2%), with maxima at 10.00 and 22.00 hours. A surprising feature of this was its fairly strong positive correlation with the semi-diurnal variation in atmospheric pressure.

With the end of the war and the reappearance of German periodicals there is striking confirmation of the positive correlation between the semi-diurnal variations of the intensity of energetic mesons and the atmospheric pressure. The most important results are those obtained by Regener and Rau (1939); they found conclusive evidence of this effect by means of two independent ionization chambers under 40 metres of water, at approximately latitude 50°. In this case the minimum energy of the rays measured was 10^4 Mev., and was, therefore, beyond the highest energy influenced by the earth's magnetic field at latitude 50° N. Other interesting results were obtained by Heorlin in Peru on the geomagnetic equator in 1932, and have been re-examined by Rau (1940). These results show a large semi-diurnal variation, positively correlated with pressure, when the chamber was shielded by 10 cm. Fe.

Without any shielding, Heorlin found the semi-diurnal variation was negatively correlated with pressure, which agrees with Duperier's results obtained at latitude 50° without shielding. At latitude 50°, with shielding of 10 cm. Pb, Forbush (1937) found that the negatively correlated semi-diurnal variation still persists; but with 36 cm. Pb. Barnothy and Forro (1937) found this variation to be positively correlated with pressure. It appears that the main experimental results can be summarized as follows:—

Pb thickness	0	10–15 cm.	$\geqslant$ 36 cm.
Latitude 0°	D, −S	+S	+S
Latitude 50°	D, −S	D, −S	+S

Here the letters D and S imply the occurrence of a significant diurnal and semi-diurnal component respectively. Positive or negative correlation with pressure in the semi-diurnal variation is indicated by a + or − sign. It should be noted that the experimental evidence, except for that furnished by Duperier with no absorber at latitude 50° and by Rau under 40 m. of water at approximately the same latitude, is not firmly established, and consequently this table may have to be modified as a result of future observations.

However, it seems to be established that if only fast mesons are observed the variation is mainly semi-diurnal and is positively correlated with atmospheric pressure. A predominant semi-diurnal variation is not likely to result either from temperature or from magnetic variations, as both would produce diurnal rather than semi-diurnal effects. Apart from this consideration, Rau's results show clearly that magnetic fluctuations are not responsible as the particles he observes all have energies too high to be affected by such fluctuations.

As has already been pointed out independently by Rau and Ehmert (1940) and Sarabhai (1945), a + S variation is just the type which would result from atmospheric oscillations of the kind predicted by Pekeris (1937). According to Pekeris' theory, the atmosphere has a natural mode of free oscillation of 12-hour period, and as a result the atmospheric oscillation of the same period, which is excited tidally and thermally by the sun, is magnified very greatly by resonance. The oscillation produced has a nodal surface at a height of 30 km., and the change of pressure and the horizontal velocity of winds due to the oscillation are reversed in phase in crossing this level; the vertical velocity of winds, however, is in phase at all levels. Provided that the bulk of the mesons observed arise above 30 km., such atmospheric oscillations will give rise to a semi-diurnal variation in meson intensity which is positively correlated with pressure. For imagine the pressure in the lower atmosphere to decrease, that in the upper atmosphere will increase and, on the whole, mesons will be formed higher; thus the probability of decay is enhanced and the sea-level meson intensity diminishes.

Strong support for this explanation of the + S variation is provided by the fact that the amplitude of the variation increases so markedly in going from latitude 50° to the equator (from about 0·2% to 1 or 2%), for on the Pekeris theory the amplitude of the pressure oscillation at the equator is about five times as large as at latitude 50°.

Let us assume for the moment that this explanation is valid and consider the consequences. As already mentioned, and as has been pointed out by Rau and Ehmert, the fast mesons must have originated above 30 km. in order to account for the phase of the observed variation. The height of origin can be fixed more definitely if the amplitude of the observed variation is also taken into consideration.

If it is assumed that the mesons all arise at a particular isobaric level, the amplitude of the variation in meson intensity at sea-level caused by a change δh

in height of this isobaric level may be easily calculated. Also, the Pekeris theory enables the amplitude δh of the oscillation about the mean height h of any isobar to be calculated. This latter calculation is extremely involved, but, fortunately for us, it has recently been carried out by Mr. K. Weekes and Dr. M. V. Wilkes with the aid of the Cambridge Differential Analyser, and these workers have very kindly provided us with their as yet unpublished results.

Using these results, we find that if the variation in meson intensity mesured by Rau is to be explained, the mesons must be created about 70 km. above sea-level. In deriving this result it was assumed that the mesons all arise at the same height, but in actual fact meson production will be spread over a considerable range in height. The effect of this spread will be to lower the height at which maximum production occurs, for the oscillation of the isobaric levels predicted by Pekeris increases rapidly with height above about 40 km., and mesons produced higher than the average have a much greater effect on the variation at sea-level than those produced lower. Taking into account the distribution of meson production with height we estimate that the height at which maximum production occurs is about 50 km. Now at 50 km. the pressure is only about 2 mm. Hg, which means that meson-producing primaries have only traversed about 1/400 of the total mass of the atmosphere before producing mesons. This corresponds to a much larger cross-section for meson production than seems possible if the primaries are protons, as is usually believed. On the other hand it is difficult to conceive of an alternative explanation of the + S variation found by Rau.

We will now pass on to mention very briefly the daily variation of the less penetrating component, consisting of low-energy mesons as well as the soft electronic component, and characterized by a diurnal variation and also a semi-diurnal variation which is negatively correlated with atmospheric pressure. The diurnal variation is probably a composite effect, resulting from a number of different causes such as diurnal meteorological changes and terrestrial magnetic fluctuations and, possibly, also a solar magnetic field; but as yet it is impossible to give any really satisfactory explanation of this effect. The − S variation is at least partly explicable as a mass absorption effect. It cannot be explained on the Pekeris theory as Duperier has suggested. To give a − S variation the mesons would have to be created below the node of the oscillation at 30 km., and anywhere below here the movement of the isobaric levels predicted by Pekeris is only about 2 to 3 metres, and is much too small to account for the effect observed.

A proper solution of these problems requires the study of groups of mesons covering different energy ranges in the spectrum. One of us (V. S.) hopes to make such a study shortly in India.

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In the Chair: Prof. L.Rosenfeld.

VARIATION OF COSMIC RAY INTENSITY AT LOW LATITUDES AND ITS RELATIONSHIP WITH METEOROLOGICAL FACTORS

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A small diurnal variation of cosmic ray intensity with an amplitude of 0.2 - 0.4% and with a maximum in the afternoon has been observed in the study of the variation of cosmic ray intensity conducted with ionization chambers. The ionization chamber technique, however, has the disadvantage that it has no directional effect.

RAU and REGENER in 1939, using ionization chambers under 40 meters of water, successfully measured essentially the vertical intensity. They obtained not a diurnal curve but a curve semi-diurnal in character, whose phase was positively correlated with the barometric pressure oscillations. This, as Ehmert has indicated, can be qualitatively explained using Pekeris' theory of atmospheric oscillations, which indicates a reversal of phase of pressure oscillation as one goes up above 30km.

Now, the amplitude of Rau's semi-diurnal curve is about 0.18%. To explain this effect in terms of Pekeris' theory and in view of the fact that he was measuring mesons of energy $\gtrsim 10^{10}$ev (since his measurements were made under 50 metres of water, including the atmosphere), the meson forming layer must be at a height of 60-70 km. (Nicholson and Sarabhai 1948). This, however, would imply that the cross section, even for the heaviest primary nuclei, would be ten times the geometrical cross section, presenting an insurmountable difficulty. No doubt, Nicholson and Sarabhai had considered a simplified process of meson formation without taking into account the possibility of plural and multiple production of mesons. At any rate the calculated height of 60-70 km appeared to be too high. Further experimental evidence was necessary therefore to resolve this difficulty. It was considered essential to measure intensities at low latitudes, where the amplitude of the atmospheric oscillation is large, being proportional to a factor of $\cos^3\lambda$. This experiment is being performed by Sarabhai, Desai and Kane at Ahmedabad. The experimental set up consists of five trays of five counters each. The angle of the telescope is 15° in the E-W and 35° in the N-S directions. A proper study of the diurnal component requires narrow angles of the telescope, but for statistical reasons, the counting rate cannot be brought down below a certain reasonable level. The hard and soft components were distinguished by coincidences in trays with thickness of 8 and 18 cms. of lead shielding between them. Two identical experimental set ups were kept in close proximity so that they could monitor each other. The experiment was conducted at a temperature of $105^{\circ} \pm 1^{\circ}$F.

The meteorological elements of pressure and temperature have been measured quite accurately at ground level, but radio sonde ascents, made to determine these elements at higher levels have not given all the information required. The instruments used are not calibrated for temperature above 250 millibars and in addition, there is a fading of radio signals between 500 and 300 millibars. During monsoon, the weather at Ahmedabad is disturbed. Moreover, we have observed that the seasonal variation of ground temperature and pressure is of totally different character as compared to a place such as Kew in England. In England there is no large systematic seasonal change of surface pressure and hence the seasonal change of temperature in the atmosphere causes a regular change of heights of isobaric levels. In Ahmedabad on the other hand the seasonal increase of surface temperature in the pre-monsoon hot season is accompanied by a marked decrease in surface pressure, and this compensates to some extent the changes in isobaric levels that would otherwise have resulted. In the absence of systematic radio sonde data going up to sufficiently high levels, it is difficult to make a detailed analysis of the day to day and seasonal changes and their dependence on upper air meteorological factors.

The preliminary results of the experiment outlined above in so far as the daily variation is concerned, are as follows: There is a high degree of correlation of both meson and electron components with ground pressure and temperature. From the results, we can get an equation connecting cosmic ray bihourly intensity variation with pressure and temperature.

The total intensity is found to fluctuate in the same general sort of way as Duperier found in London, and the meson component has the same general trend although with a smaller amplitude. Both exhibit a semi-diurnal variation in opposite phase to that of ground atmospheric pressure.

Now, Duperier's semi-diurnal curve has an amplitude of 0.18% and our curve has an amplitude of 0.5%. According to the Cos$^3\lambda$ law, our amplitude should be .61%. The agreement therefore, is fairly good and we can conclude that both the curves are the result of mass absorption due to increase of semi-diurnal pressure, and that they vary approximately in the same way as the amplitude of the pressure oscillation itself. From our data the pressure coefficient for the meson component works out to 2% per cm. of Hg compared to a value of 2.1% by Duperier and 1.7% by Malmfors from data on day to day variation. As the semi-diurnal variation of height of isobaric levels below 30 Km is negligible, it is not surprising that our value taken from the daily variation is so close to the value of pure mass absorption coefficient obtained by other workers. For the electron component our coefficient is about five times greater.

These results cannot be considered to be in contradiction with Rau's results, because Rau's results were for the hardest mesons with energy $\gtrsim 10^{10}$ ev, and these mesons may have a + S variation which can be proved only by repeating the above experiment under more lead.

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Daily Variation of Meson Intensity and its Possible Solar Origin

THE variation of meson intensity with solar time has been studied at Ahmedabad (mag. lat. 13° N., altitude 50 m.) and at Kodaikanal (mag. lat. 1° N., altitude 2,343 m.) with vertical triple-coincidence Geiger counter telescopes of narrow aperture with 11 cm. of lead. Observations at Ahmedabad with two similar independent telescopes extend over a period of two years, while at Kodaikanal with four independent telescopes they extend over a period of five months. Elaborate precautions were taken to keep experimental conditions very constant, and the results of independent but simultaneously operated telescopes at each place were similar. The intensity at each place was determined from hourly photographs of the mechanical recorders. For the purpose of the solar daily variation, the bi-hourly values of intensity were considered.

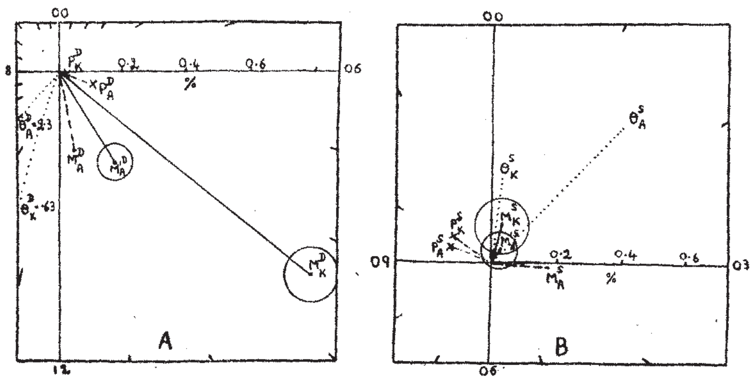
The solar daily variation of meson intensity is predominantly diurnal at Kodaikanal with an amplitude of 1·1 per cent. At Ahmedabad it has an amplitude of only 0·4 per cent with an important semidiurnal component as well. Figs. A and B show on 24-hr. and 12-hr. harmonic dials respectively the diurnal and semidiurnal harmonic components of the meson intensity M_A and M_K, the atmospheric pressure P_A and P_K and the ground temperature θ_A and θ_K at Ahmedabad and Kodaikanal. The diurnal and semidiurnal components are indicated by the additional suffixes D and S respectively.

At low latitudes the periodic daily variations of P and θ are larger and more pronounced than the irregular day-to-day variations which are so marked at places in high latitudes. Also, at low latitudes the daily variation of atmospheric pressure is mainly semidiurnal and that of temperature is diurnal. As a result, the semidiurnal components $P_A{}^S$ and $P_K{}^S$ are predominant, whereas $\theta_A{}^S$ and $\theta_K{}^S$ are negligible. This fortunately provides a means of studying the effect of pressure on meson intensity independently of other meteorological factors. At Ahmedabad, $M_A{}^S$ and $P_A{}^S$ have a very high correlation of $-$ 0·96, the pressure coefficient being $-$ 1·7 per cent per cm. mercury, in agreement with the mass absorption coefficient for mesons observed by other workers from day-to-day variations of intensity. At Kodaikanal, on the other hand, this correlation is only + 0·29. As, however, $M_K{}^S$ itself is only 0·12 per cent in amplitude and is not significant, this positive value might be fortuitous. The absence of the usual mass absorption coefficient indicates that during the atmospheric oscillations at Kodaikanal opposing factors act on M, and mask this absorption effect. These could be changes in heights of levels of meson formation or perhaps a density effect near these levels. An interesting feature of the present results is that, even near the equator for a high-level station, there is no marked semidiurnal variation of meson intensity positively correlated with pressure.

The atmospheric pressure plays an important part in the solar daily variation of mesons at the low-level station at Ahmedabad, but produces a negligible effect at Kodaikanal. The correlations of M_K with θ_K and of the pressure-corrected meson variation M'_A with θ_A are negligible. Ground temperature has therefore negligible effect at both places.

The curve of the residual meson variation corrected for pressure at Ahmedabad and the meson variation curve at Kodaikanal are both significant and strikingly similar. Both are diurnal with amplitude $M'_A = 0{\cdot}33 \pm 0{\cdot}06$ per cent and $M_K = 1{\cdot}1 \pm 0{\cdot}08$ per cent with maxima at 0950 and 0840 hr. local time respectively. It is unlikely that these variations are caused by a positive temperature effect such as is found by Duperier from day-to-day variations of mesons. Apart from the maxima being much earlier than the time at which a maximum of temperature in the upper atmosphere would be expected to occur, the amplitude of the diurnal temperature variation at the 200-mb. level is, on existing meteorological evidence, totally insufficient to account for a variation of meson intensity of 1·1 per cent as found at Kodaikanal. Variations of geomagnetic field are also not capable of explaining this variation.

There are thus grounds for believing that the observed diurnal variation of M is caused by an anisotropy of the primaries and is therefore extra-terrestrial in origin. The greatly reduced amplitude as well as a shift of maximum towards later hours at Ahmedabad when compared with Kodaikanal appears to be connected with the change of altitude between the stations. This is also seen in the ionization chamber results obtained at Huancayo as compared to the lower-level stations operated by the Carnegie Institution[1]. The amplitude of variation observed with our narrow-aperture Geiger counter-telescopes is larger than the omnidirectional ionization chamber results, as is to be expected. The increase of the percentage amplitude with elevation suggests the contribution of a larger number of low-energy particles which can make their effect felt at a high-level station but not at a sea-level station.



Amplitudes and hours of maxima in local time of harmonic components of meson intensity, atmospheric pressure and ground temperature variations. (*A*) 24-hr. harmonic dial; (*B*) 12-hr. harmonic dial

Since the variation is believed to be extra-terrestrial in origin, and the hour of maximum occurs at about the same local time during daylight hours throughout the year, a solar origin of this variation is suspected. The possibility of a part of the cosmic radiation originating from the sun, as deduced here from the nature of the residual diurnal variation of mesons, is supported by the occasional large increases in cosmic-ray intensity associated with solar flares, by recent observations associating variations of cosmic-ray neutrons with solar prominences, and by the large diurnal variation of the star intensity in the upper atmosphere reported by Lord and Schein[2]. Riddiford and Butler[3] have recently described processes by which particles from the sun can be accelerated to cosmic-ray energies. A close study of the occurrence of the hour of maximum under different conditions of observation of cosmic-ray intensity would throw a great deal of additional light on this subject. We hope to present shortly more data concerning this.

We are indebted to the Atomic Energy Commission of India for supporting this project. We are grateful to Prof. K. R. Ramanathan for many valuable discussions, particularly concerning the meteorological aspects of the problem.

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METEOROLOGICAL AND EXTRA-TERRESTRIAL CAUSES OF THE DAILY VARIATION OF COSMIC RAY INTENSITY

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1. INTRODUCTION

IT has long been realised that a study of the solar and sidereal time daily variations of the cosmic ray intensity could give some clue to the location of regions where cosmic rays originate. However, a successful attempt to follow up this line of thought has not so far been possible due to the uncertainty in separating the variations caused by terrestrial influences from those due to an anisotropy of the primary radiation.

In investigating the time variations of cosmic rays, the ionisation chamber offers the great advantage of constancy of operation, but being an omni-directional detector of radiation, it is hardly a satisfactory instrument for the study of an anisotropy of the primary radiation. Nevertheless, very valuable data have been collected with it. Apart from the Carnegie Institution studies made at widely separated places on the earth and reported by Lange and Forbush,[1] observations have been made, amongst others, by Hess and Grazeadei[2] at the Hafelekar, by Schonland, *et al.*,[3] at Capetown and by Hogg[4] at Canberra. Unidirectional measurements of the diurnal variation of the vertical meson intensity, performed with narrow angle geiger-counter telescopes could be more revealing than omni-directional measurements. But the only extensive data with vertically pointing telescopes comes from Duperier[5] in whose experiment the angles of the telescopes were fairly wide.

Interpretation of the ionisation chamber and Duperier's experiments has been much confused by various differing corrections for meteorological factors that have been applied, and it has not been possible finally to determine how much of the diurnal variation is due to an anisotropy of the primaries. To overcome this difficulty Alfven and Malmfors[6] and Elliot and Dolbear[7, 8] have studied the daily variation of cosmic ray intensity with telescopes pointing in the North and South directions. While the North-South daily variation difference curve is substantially independent of atmospheric effects and constitutes evidence for an anisotropy of the primary radiation, it is difficult to interpret it further. For, an anisotropy of primaries, such as may be caused by solar emission of cosmic rays, can produce a daily variation in both North and South pointing telescopes. The difference curve in consequence reflects an arithmetic difference between the daily variations in the two directions due to anisotropic cosmic ray primaries, but does not reveal the true nature of the daily variation due to primary anisotropy in either direction.

It is felt that a satisfactory solution to the problem must begin with an understanding of the nature of terrestrial effects on the solar daily variation of cosmic ray intensity. These have then to be corrected for, leaving a residual daily variation essentially of extra-terrestrial origin. The daily variation of meteorological elements is more pronounced and regular at places in low latitudes than at high latitudes. It is particularly appropriate therefore to study the daily variation near the equator. With this in view, apparatus has been designed to carry out comparable studies of the daily variation of the total intensity as well as the meson intensity at Ahmedabad (Mag. Lat. 13° N., Alt. 50 metres) and at Kodaikanal (Mag. Lat. 1° N., Alt. 2,340 metres). As it is important to study the intensity of particles incident in a narrow cone in a fixed direction, compromise has to be made in the design of the apparatus to make the angles of the telescope narrow and still to retain an adequate counting rate for good statistics. We shall describe in this paper details of the apparatus and the results obtained during the past two years at Ahmedabad. A summary of the results obtained at both stations has already been communicated elsewhere.[9] Details of the Kodaikanal results will be presented later as soon as more significant data are available. We discuss here reasons which lead us to believe that the solar time daily variation of meson intensity corrected for barometric pressure is caused by an anisotropy of the primary radiation, probably connected with the emission of charged particles from the sun.

2. The Apparatus

A schematic diagram of the apparatus is given in Fig. 1.

Five trays, each with four self-quenched geiger counters connected in parallel, form three triple coincidence vertically pointing telescopes of identical dimensions. The counters have copper cathodes 30 cm. long with diameter of 4 cm. The counters are placed in the N-S direction, and each telescope subtends a semi-angle of 22° in the E-W plane and a semi-angle of 37° in the N-S plane. Since the purpose of the experiment is to measure the daily variation of cosmic ray intensity connected with the rotation of the earth, the apparatus is oriented so that the telescopes present the smaller angle in the E-W plane.

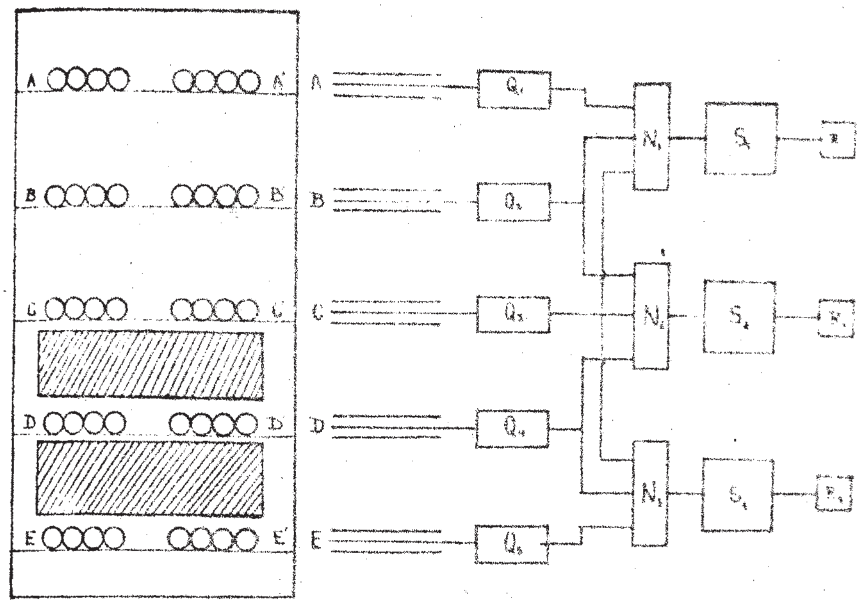

FIG. 1. Schematic diagram of apparatus showing counter trays A, B, C, D, E, A', B', C', D' and E', quenching units Q, triple coincidence units N and scale of four units S feeding the electro-mechanical recorders R.

Lead absorbers are placed between the 3rd and 4th trays and the 4th and 5th trays. While therefore, the uppermost telescope ABC measures the total cosmic ray intensity T, the lower two telescopes BCD and CDE measure intensity that can penetrate through 7 cm. and 17 cm. of lead respectively. The soft component E is almost completely eliminated by 7 cm. of lead and is given by the difference between counting rates of telescopes ABC and BCD. The penetrating component '*m*' consisting mostly of μ-mesons is measured by the telescope CDE. The small difference between the counting rates of telescopes BCD and CDE represents the intensity of an intermediate component 'I' consisting partly of the very energetic soft component and partly of the slow meson component. Since 'I' is negligible compared to '*m*', the counting rates of telescopes BCD and CDE may be considered together to represent the meson component M, when distinction is being made only with the electronic component E.

The complete apparatus has three duplicate telescopes A'B'C', B'C'D' and C'D'E' operating alongside the ones described above. These are also shown in Fig. 1. The object of providing these additional telescopes, measuring identical components of the cosmic ray intensity, is not only to improve the statistics but also to provide for continuance of data during periods when faults develop in counters or circuits connected with one or other of the telescopes.

All geiger counters are placed in a heat insulated box whose temperature is thermostatically regulated to 105° ± 2° F. Each counter tray is connected to an external electronic quenching unit which, for every discharge of one of the counters, feeds to their central wire a square negative voltage pulse of about 300 volts and 800 micro-seconds duration with a very sharp leading edge. These quenching units improve the flatness of plateau and prolong the life of self-quenched counters considerably by suppression of multiple discharges. This is important in time variation experiments where reliable operation over long periods of time is essential. The low impedence cathode-follower outputs of the quenching units are fed to fast triple coincidence units. Finally, the coincidences are scaled by a factor of 4 or 8 and recorded on telephone call registers which are automatically photographed hourly on standard 35 mm. film. All power supplies are electronically regulated to ensure stability of operation.

Hourly values of atmospheric pressure and temperature are obtained from daily charts of an accurate micro-barograph and a thermograph. Upper air meteorological data are obtained from radiosonde ascents, with I.M.D. F-type or the Vaisala type instruments, conducted by the atmospheric physics division of the laboratory under Prof. K. R. Ramanathan. Details of these experiments will be published elsewhere.

3. Analysis of Daily Variation Data

Even though the primary data for the intensity of cosmic ray components and the surface atmospheric pressure and temperature are available for hourly intervals, the analysis has been done for bihourly intervals commencing from midnight Indian Standard Time, which is 40 minutes in advance of the local time at Ahmedabad. The criterion used for elimination or inclusion of data for any particular day is the range of bihourly deviations. The data is discarded for days on which any individual bihourly value is more than 5% different from the mean for the particular day. This corresponds to a deviation exceeding three times the expected standard deviation for a bihourly value. Such cases are generally attributable to some faults either in the electronic circuits or in the counters. Cases of abnormally large daily variation in cosmic rays which may rarely occur are however also rejected on this criterion. The useful data, as presented here, extend from May 1950 to September 1952 and include about 600 days with a fairly even distribution over the four seasons.

The annual mean daily variation given by the bihourly percentage deviations from mean of the total intensity T, the meson intensity M and the electron intensity E are shown in Fig. 2. The bihourly deviations from

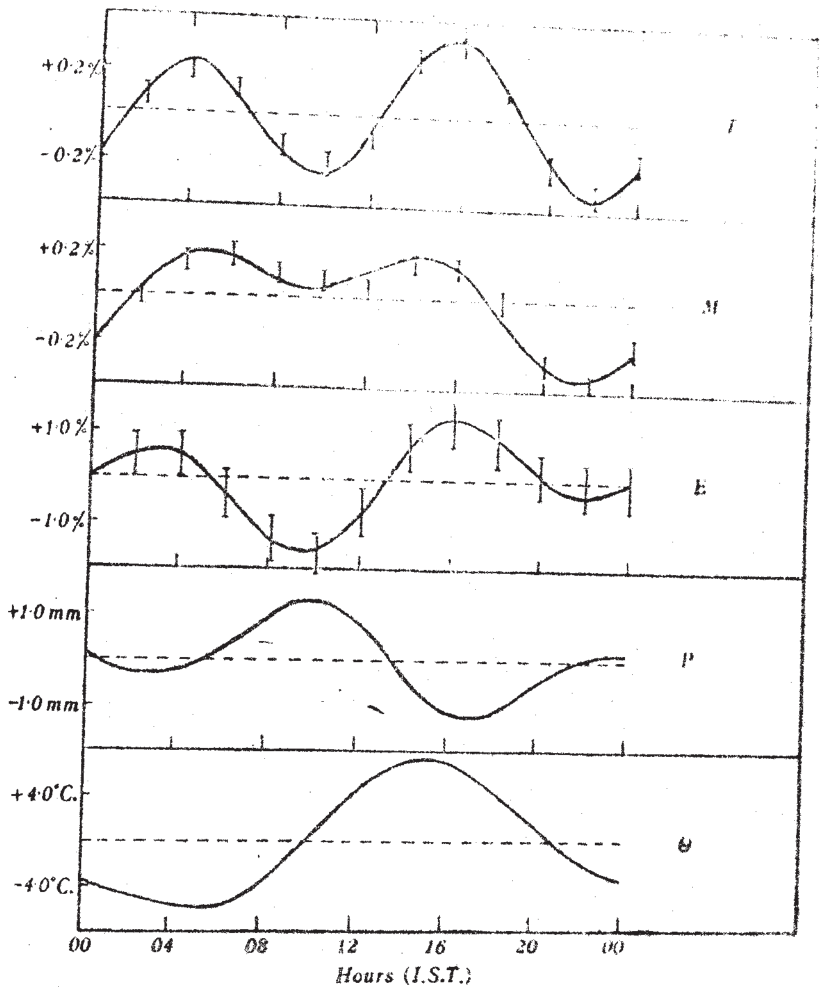

FIG. 2. The smoothened daily variation of total cosmic ray intensity T, mesons M, electrons E, barometric pressure P and surface atmospheric temperature θ. No correction has been applied to the cosmic ray values and the solid lines showing the daily variations are formed by the superposition of the diurnal and the semidiurnal components for each intensity.

mean of the atmospheric pressure P and the surface temperature θ are also shown. For the purpose of smoothening the data, moving averages over three consecutive bihourly intervals have been taken for all variates shown in the figure. The standard deviations for each bihourly value of cosmic ray intensity are also indicated.

The amplitudes and hours of maxima of the first four harmonic components of the unsmoothened daily variation of T, M, E as well as P and θ are indicated in Table I. The hour of maximum is expressed in terms of the angle in the harmonic dial representation between midnight and the vector for the particular harmonic component of the daily variation.

TABLE I

Amplitudes and hours of maxima of harmonic components of the daily variation of cosmic ray intensities and atmospheric pressure and temperature

Variate	1st Harmonic 24 hourly		2nd Harmonic 12 hourly		3rd Harmonic 8 hourly		4th Harmonic 6 hourly	
	Ampl.	Max.	Ampl.	Max.	Ampl.	Max.	Ampl.	Max.
T ..	·09 %	11°	·42 %	115°	·05 %	−2°	·02 %	29°
M ..	·22 %	144°	·23 %	119°	·09 %	38°	·03 %	108°
E ..	·80 %	−61°	1·40 %	112°	·30 %	81°	·30 %	78°
P mm of Hg	·86	115°	·95	131°	·04	135°	·00	..
θ° C. ..	6·60	54°	1·60	64°	·60	114°	·40	−62°

It will be observed that for all variates the predominant harmonic component is either the first or the second one. In mesons and in atmospheric pressure, the two components are about equally important. For total intensity and for electrons, the second harmonic is larger than the first; but for surface temperature, the converse is true. In all cases, the third and higher harmonics are small and may be neglected. In what follows therefore, only the 24 hourly diurnal and the 12 hourly semidiurnal components are taken into consideration. In discussing these components, it is convenient to adopt a notation explained in Table II.

4. INFLUENCE OF METEOROLOGICAL FACTORS ON THE DAILY VARIATION OF MESON AND ELECTRON INTENSITIES

Extensive studies have been made to relate the day-to-day variations of the cosmic ray intensity with meteorological changes in the atmosphere. Duperier[10] has shown that changes of meson intensity are connected with a mass absorption effect, an effect due to alteration of the probability of

TABLE II

Notation used for describing the amplitude and the hour of maximum of harmonic components

M_A^D = % amplitude of meson (M), diurnal variation (D) observed at Ahmedabad (A)

$M\phi_A^D$ = angle corresponding to hour of maximum of the meson (M) [illegible] variation [illegible] observed at Ahmedabad

M_A^S = % amplitude of meson (M) semi-diurnal variation (S) observed at Ahmedabad (A)

$M\phi_A^S$ = angle corresponding to hour of maximum of the meson (M) semidiurnal variation (S) observed at Ahmedabad

[illegible] T_A^D, E_A^D, P_A^D and θ_A^D represent the amplitudes of the diurnal [illegible] Ahmedabad of T, E, P and θ respectively

meson decay accompanying changes of heights of isobaric levels and an effect of the temperature or density of the atmosphere near the 100 mb. level. The physical processes responsible for the positive upper air temperature effect are not clearly understood but it should not be expected that in the daily variation the influence of these three factors on meson intensity would be identical to what is found for day-to-day variations. This is because in barometric pressure as well as in atmospheric temperature, the day-to-day changes are brought about under very different circumstances from those that produce the daily variations.

Processes responsible for day-to-day changes of barometric pressure are entirely different from those causing the dynamical periodic oscillations of the barometric pressure. The use of a barometric coefficient obtained from studies of day-to-day variations for correcting cosmic ray daily variation data in respect of the daily variation of pressure is therefore questionable. But this is exactly what has been done by most authors in the past. A better method appears to be to derive a barometric coefficient from daily variation studies for subsequent application to the same data. In doing this, we have to keep in [illegible] available knowledge on the physical processes responsible fo[illegible] the meteorological elements and the special features of the atmospheric oscillation.

It is difficult to draw conclusions about the effect of meteorological factors on cosmic ray intensities by a comparison of the daily variation curves of Fig. 2. Solar radiation and gravitational forces are the most important causes of the daily variations observed in geophysical elements. These variations, as well as one that could be caused in meson intensity by an anisotropy of the primaries due to solar emission of cosmic rays, would have a predominant 24 hourly diurnal component. Therefore, it is not clear how much of the M^D variation is connected with P^D and θ^D or a hypothetical upper air diurnal temperature variation, and how much is due to a solar cosmic component.

In the 12 hourly semidiurnal components however, the position is different. The atmospheric pressure, unlike temperature, has a very appreciable P^S component. At Ahmedabad, P^S_A is as important as P^D_A. At Kodaikanal, nearer the equator and at a higher level, P^S_K is 6 times P^D_K. As was originally pointed out by Kelvin,[28] the semidiurnal variation of pressure is due to resonance in the atmosphere which has a free period of oscillation of nearly 12 hours. Thus, even though the exciting solar force is diurnal, the semidiurnal component in pressure becomes important and is predominant at low latitudes. If attention is therefore confined only to the semidiurnal components, we have a means of studying the influence of pressure, uncontaminated with effects due to temperature variations in the atmosphere or due to an anisotropy of cosmic ray primaries.

The first two harmonic components of T, M and E along with those of P and θ are shown in Fig. 3 on 24 and 12 hourly harmonic dials. It will

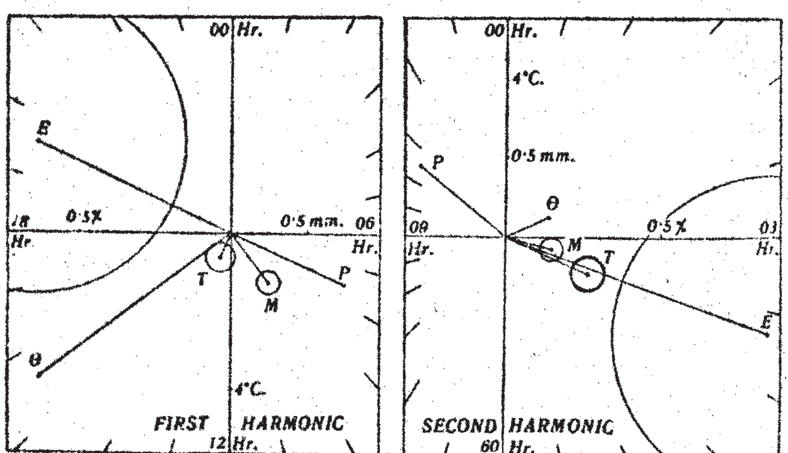

FIG. 3. Diurnal and semidiurnal harmonic dials showing amplitudes and hours of maxima of uncorrected variations.

be observed that while on the 24 hour dial, the vectors lie all around the clock, there is on the 12 hour dial a very striking grouping of the cosmic ray vectors almost completely opposite in phase with the pressure vector.

Correlation analysis of the semidiurnal vectors of cosmic ray components with atmospheric pressure give correlation coefficients and barometric coefficients as shown in Table III.

TABLE III

Correlations with barometric pressure and the barometric coefficients of the semidiurnal components of cosmic ray intensity

Cosmic ray component	Correlation coefficient with P_A^S	Barometric coefficient
T_A^S	$r_{TP}^{SS} = -\cdot 96$	$\beta_T = -4\cdot 2\%$ per cm. Hg
M_A^S	$r_{MP}^{SS} = -\cdot 98$	$\beta_M = -2\cdot 4\%$ per cm. Hg
E_A^S	$r_{EP}^{SS} = -\cdot 95$	$\beta_E = -14\cdot 0\%$ per cm. Hg

The barometric coefficient $\beta_M = -2\cdot 4\%$ per cm. Hg for mesons may be compared with the value found by other workers from day-to-day variations of cosmic ray meson intensity. Coefficients of $-3\cdot 0\%$ per cm. Hg for Huancayo and $-1\cdot 8\%$ per cm. Hg for Cheltenham, Christchurch and Godhavn have been determined and used for barometric pressure correction by Lange and Forbush[3] for the Carnegie Institution ionisation chamber data. It is not clear why at Huancayo the coefficient should be so much larger than at the other stations in spite of the shielding being the same for all instruments. Duperier's[10] barometric coefficient is $-1\cdot 50\%$ per cm. Hg and Dolbear and Elliot[11] have reported a value of $-1\cdot 88\%$ per cm. Hg obtained from the seasonal variation of intensity. These authors, by partial correlation analysis, give estimates for the three meteorological coefficients which affect meson intensity. These are shown in Table IV. Our value of the barometric coefficient for mesons is larger than the true mass absorption coefficient of Duperier but agrees well with the coefficient of Dolbear and Elliot.

It is important to examine if there is a substantial decay contribution to the semidiurnal variation. Pekeris,[12] and more lately Wilkes and Weekes[13] have examined the details of the modes of oscillation of the atmosphere. Nicholson and Sarabhai[14] have estimated the effect on meson intensity of

TABLE IV

Estimates of barometric coefficient β, true absorption coefficient μ, true decay coefficient μ′ and positive temperature coefficient α for mesons

Coefficient	Duperier[10]	Dolbear and Elliot[11]
β	− 1·50 % /cm. Hg*	− 1·88 % /cm. Hg
μ	− 1·05 % /cm. Hg	− 2·07 % /cm. Hg
μ′	− 3·90 % /km.	− 4·22 % /km.
α	+ 0·12 % /°C.	+ 0·14 % /°C.

* Weighted mean for 5 periods of observations.

the semidiurnal change of height of isobaric levels due to atmospheric oscillations. For meson production near 16 km., there should be a semidiurnal oscillation of the isobaric level which would not exceed 4 metres and thus would not change significantly the contribution of the pure mass absorption effect to the barometric coefficient. There is reason to believe therefore that the barometric coefficient derived by us from the semidiurnal variation corresponds mainly to the true absorption coefficient for the meson component.

The appropriate barometric coefficients experimentally determined from semidiurnal components can be used to correct the unresolved daily variations of T, M and E for the barometric daily variation. Smoothened bihourly values of the barometric pressure corrected variations designated as T′, M′ and E′ are shown in Fig. 4. The harmonic components of these are indicated in Fig. 5.

It will be noticed that T′ and M′ are left with a residual diurnal variation of amplitude ·33 ± ·05% and ·35 ± ·04% respectively and hour of maximum near 0900 hours I.S.T. E′ on the other hand has no significant variation exceeding the standard deviation of the individual bihourly points. This indicates that the daily variation of the electron component at sea level can be explained almost completely by a mass absorption effect connected with the barometric variation.

Duperier[15] has corrected the daily variation of mesons for a decay effect due to an estimated diurnal change of height of about 50 metres in the isobaric levels near 16 km. in consequence of a diurnal heating of the atmosphere. The process has been considered to be analogous to the seasonal variation of meson intensity where, during summer, the general expansion

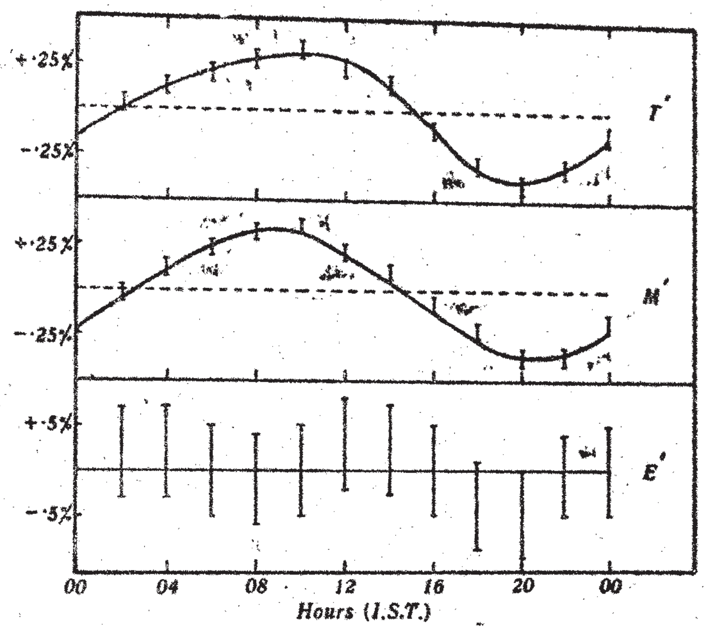

FIG. 4. The daily variation of total cosmic ray intensity, mesons and electrons, each corrected for barometric pressure.

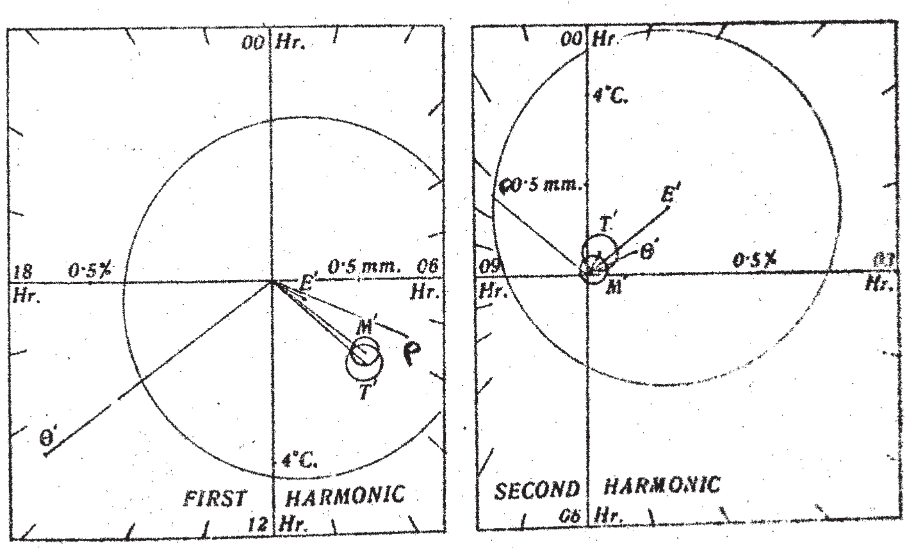

FIG. 5. Diurnal and semidiurnal harmonic dials showing amplitudes and hours of maxima of cosmic ray daily variations corrected for barometric pressure.

of the atmosphere produces a decrease of meson intensity. Dolbear and Elliot[11] have suggested a further correction for a diurnal positive temperature effect similar to the one demonstrated by Duperier[11] for day-to-day changes. The contribution of both these factors to the daily variation of mesons would depend on the magnitude of the diurnal temperature change at different levels in the atmosphere and particularly near the tropopause.

All available meteorological evidence goes to show that the daily variation of air temperature gets rapidly attenuated going upwards from ground, and becomes negligible beyond 2 km. above the surface of the earth. It may again become important in the ozone ultraviolet absorption region, well above the tropical tropopause. Duperier,[10] and Elliot and Dolbear[8] have based their arguments on radiosonde data obtained by the Meteorological Office, London, at Larkhill (100 km. S-W of London) and Downham Market (75 km. N-E of London). The interpretation of the data is however very suspect and Kay[16] has critically examined it to come to the conclusion that much of the apparent diurnal variation of temperature in the lower atmosphere is spurious and caused by inadequate radiation shielding of the thermal element. Flights have been made in India to test whether there is a diurnal variation in low latitudes. It has been tentatively found in ascents made with Vaisala instruments at Ahmedabad that there is no significant diurnal increase of temperature near the tropopause. There is ozone above 100 mb. but the heating effect due to absorption of solar radiation is considered to be of significance only at much higher levels.

An examination of Fig. 5 reveals that the barometric pressure corrected vectors for total intensity and mesons on the 24 hourly dial are both significant and are negligibly correlated with the surface atmospheric temperature. If the heating in the upper atmosphere were to take place from lower levels, the maximum temperature would occur at a later hour than the surface temperature and the correlation with T′ and M′ would be almost zero. For heating of the layers of air near 16 km. from above, the maximum temperature may occur nearer noon, but even so the correlation between the diurnal vectors for T′ and M′ and a temperature vector at noon would be quite low.

One is finally led to conclude that the atmospheric temperature has little or no part to play in producing the daily variation of meson intensity corrected suitably for barometric pressure.

5. THE BAROMETRIC PRESSURE CORRECTED MESON DIURNAL VARIATION

Having eliminated meteorological effects, it is necessary to consider possible geomagnetic and helio-magnetic influences on the residual daily variation of mesons. Janossy[17] has suggested the possibility of a diurnal variation of cosmic rays at latitudes beyond 40° due to the helio-magnetic field. Dwight[18] has worked out detailed implications, but this theory can be safely excluded in view, amongst other things, of the evidence from several quarters concerning the non-existence of an appreciable general helio-magnetic field at the present time. Vallarta and Godart[19] have discussed the influence in low latitudes of ionospheric current systems responsible for the geomagnetic diurnal variation. While the latter alters fundamentally in character with latitude, Thompson[20] has shown that the meson variation has similar features over a wide range of latitudes. It appears therefore that the barometric pressure corrected variation of mesons is of extra-terrestrial origin and is connected with an anisotropy of the primary radiation. Taking into consideration the occurrence of the maximum of the diurnal variation at about the same period of the day according to local time at widely separated places on the earth, it is reasonable to conclude that the anisotropy is caused by the solar emission of cosmic rays.

Duperier[15] has indeed made a similar suggestion by a consideration of the seasonal change of amplitude of the meson diurnal variation corrected for barometric pressure and decay coefficient. As however, the application of the decay effect is questionable for reasons mentioned earlier, the close agreement between the ratio of summer and winter diurnal amplitudes with what would be expected due to change of the solar zenith distance at the two periods may be fortuitous.

6. The Effects of Cosmic Rays from the Sun

The sun is known to emit corpuscular streams which take about 23 hours to travel to the earth and produce geomagnetic and auroral activity. It is also known to emit during some intense solar flares, moderate and low energy cosmic ray particles which travel with a velocity not very different from that of light and produce measurable effects at sea level on the cosmic ray neutron and charged particle intensity. The magnitude of the effect has a marked longitude dependence, and no effects have been observed at equatorial stations. Increases in neutron intensity reported by Simpson, *et al.*,[21] and charged particle intensity reported by Neher and Forbush[22] have been associated with the central meridian passage of active regions on the solar disc. These demonstrate the emission of more energetic particles from the sun which make their effects felt even at Huancayo on the geomagnetic equator. The present association of the meson diurnal variation with an anisotropy due to solar cosmic rays shows that the sun is a continuous emitter of cosmic radiation. Unlike the bursts of radiation following the observation of flares, this continuous emission is energetic enough to cause measurable effects in the charged particle intensity at sea level at all latitudes.

There is some evidence to show that the energy distribution of cosmic ray particles from the sun is displaced towards low energies as compared to the general energy distribution of cosmic rays from all other sources. For, the percentage amplitude of the diurnal variation increases with elevation as revealed by our comparative studies at Ahmedabad and Kodaikanal, by the Carnegie studies at Huancayo compared to the low level stations, and the studies made at the Hafelekar. Neher and Forbush have reached a similar view from the increase of the worldwide fluctuations of ionisation with altitude, and the fluctuations being less pronounced at the equator.

An important question arises about the observed hour of maximum $M\phi^{D}$ of the meson diurnal variation. For high energy particles from the sun which are not appreciably deflected by the geomagnetic field, one should expect the maximum to occur at noon local time. For less energetic positive primaries the maximum will be shifted to earlier hours, and for less energetic negative primaries to later hours. There is a divergence amongst the reported results of various workers concerning the precise hour of maximum. It varies in extreme cases from 0800 hours to 1600 hours. A great deal of this divergence is perhaps due to differences in methods of correcting for meteorological effects.

Hogg[23] has compared on a harmonic dial the diurnal vectors for meson dialy variation observed by various workers at different places. For Canberra data, a vector has been given for barometric pressure corrected meson variation as well as for one which has, in addition, been corrected for a temperature effect. There is a considerable difference between the amplitude and the hour of maximum of the resultant variation in the two cases. Forbush,[24] for Cheltenham data, has shown how the uncorrected meson diurnal vector at 1400 hours shifts to 1100 or 1000 hours according to the magnitude of the barometric coefficient which is applied for correction.

Some of the differences in the hours of maxima and amplitudes observed by various workers are probably connected with the nature of the measuring apparatus and the angle within which it allows incident radiation. Generally an omni-directional instrument would reveal a smaller amplitude of variation than a unidirectional one. In latitudes where there is an E-W asymmetry of the cosmic ray intensity, an ionisation chamber would effectively function like a West pointing telescope having a later maximum than a vertical telescope. In view of all these factors, comparisons between the diurnal variation at different latitudes and elevations can only be made where similar experimental technique is followed at the various stations, and appropriate similar corrections are applied to the basic experimental data. Carnegie Institution studies are therefore very valuable for this purpose, and when further significant data is available from our unidirectional studies at Kodaikanal and Trivandrum (Mag. Lat. 1° N., Alt. 0 metres) it might be possible to get a better insight in this subject. From our own studies, there is every indication that the maximum occurs before noon, and the hour becomes earlier when the diurnal amplitude increases in going from Ahmedabad to Kodaikanal. Though all sea-level stations run by the Carnegie Institution have maxima in the early afternoon, the mountain station of Huancayo has an earlier maximum before noon and of increased amplitude.

An important point that arises now concerns the relationship that can exist between the amplitude and the hour of maximum of the diurnal variation. The amplitude should be controlled, among other things, by the cut off in the solar cosmic ray energy spectrum either by geomagnetic blocking or atmospheric absorption. The mean energy of the allowed radiation determines the bending in the geomagnetic field and hence the hour of maximum of the diurnal amplitude. When changes in amplitude of the diurnal variation are due to alteration of the cut off energy, a change in the hour of maximum may also be expected. This consideration requires a revision of the past analysis made for detecting a sidereal time variation in cosmic rays from the seasonal change of the diurnal variation on lines suggested by Thompson.[25]

Due to bending of the trajectories of cosmic rays from the sun, there is every reason to expect a diurnal variation of intensity in both the North and the South pointing telescopes of Alfven and Malmfors,[6] and Elliot and Dolbear.[6] On account of the asymmetry of the geomagnetic field with respect to the earth's axis of rotation, the two telescopes may exhibit with respect to each other, a small shift of phase of the measured diurnal variation. Just as an East-pointing telescope would have an earlier maximum than a West-pointing telescope, a North pointing telescope in England should have an earlier maximum than one pointing to the South. This is what Dolbear and Elliot have found. While qualitatively the explanation is attractive, it remains to be seen whether it would hold quantitatively.

Elliot and Dolbear[8] have made the very significant observation that during days of increased geomagnetic activity, the diurnal variations in both N and S directions are enhanced, and the N-S difference changes from being a semidiurnal to a diurnal curve. Since it is known that geomagnetic disturbances are associated with solar corpuscular streams, it would appear that when there is increased activity of the solar M-regions, there is also increased cosmic ray emission from the sun. The radical change in the nature of the difference curve during magnetically disturbed days supports the view that it has no special physical significance apart from being the arithmetic difference of the diurnal variations in the two directions.

Recently, two of us (V. Sarabhai and R. P. Kane) have demonstrated large and long-term world-wide changes in the amplitude and the hour of maximum of the meson diurnal variation. These changes, at least during years of low solar activity, are well correlated with relative sunspot number and the American magnetic character figure. There is therefore good reason to believe that continuous emission of cosmic rays from the sun is an important cause for the diurnal variation of meson intensity. However, there are a number of points about the diurnal variation which are still to be cleared up. Perhaps the most important, concern the dependence of amplitude and hour of maximum of the diurnal variation on latitude, elevation and seasons. Our understanding of the problem is very much confused by the complex trajectories of charged particles from the sun. The very considerable deflection of cosmic rays from the sun is demonstrated by the occurrence both on the sunlit and the dark hemispheres of the abnormal increases of cosmic ray intensity associated with flares. It would be very valuable if the rather complicated problem of the effect of the geomagnetic field on non-isotropic cosmic ray primaries from the sun is tackled not only for a static case, but when the field wobbles with respect to the sun on account of the rotation of the earth.

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SUMMARY

The daily variations of total cosmic ray intensity and the intensities of meson and electron components have been studied at Ahmedabad with vertical geiger counter telescopes. The influence of meteorological factors on these variations has been examined, and it has been found that appropriate barometric coefficients for correcting the cosmic ray intensities can be obtained from a consideration of the semidiurnal components of the variations. The barometric coefficients for the three intensities are

$\beta_T = -4\cdot2\%$ per cm. Hg, $\beta_M = -2\cdot4\%$ per cm. Hg,

$\beta_E = -14\cdot0\%$ per cm. Hg.

The cosmic ray intensity variations are corrected with the appropriate coefficients for the daily variation of barometric pressure. No significant variation is then left in the electron intensity, implying that variations of this component are mostly caused by the mass absorption effect with a variation of barometric pressure. In total intensity and in meson intensity, on the other hand, there is a significant residual variation of about ·3% in amplitude. This is mainly diurnal in character with a maximum at 0900 hours I.S.T.

Reasons are given for concluding that the meson residual variation is not primarily caused by either the diurnal variation of temperature in the atmosphere or of geomagnetic elements. It is finally concluded that the bulk of the meson residual diurnal variation is extra-terrestrial in origin and is caused by continuous solar emission of cosmic ray particles. This conclusion is discussed in terms of the interpretation of omnidirectional and unidirectional measurements of the diurnal variation by other workers. A connection between changes in the amplitude and the hour of maximum of the diurnal variation has been suggested.

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World-Wide Effects of Continuous Emission of Cosmic Rays from the Sun

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The Carnegie Institution barometric pressure-corrected, cosmic-ray, meson intensity data for solar time daily variation at Huancayo, Cheltenham, and Christchurch have been harmonically analyzed. Time-series covering the period 1937 to 1946 have been derived for variations of the amplitude and hour of maximum of the meson diurnal variation. These reveal that the amplitude and hour of maximum undergo large long-term world-wide changes. The time-series for mean of the diurnal amplitude observed at the three stations has high positive partial correlations with relative sunspot number and American magnetic character figure. The correlations are higher during years of low sunspot activity.

The new evidence confirms earlier experimental findings of the authors indicating that the barometric pressure-corrected, meson intensity, diurnal variation is caused by an anisotropy of the primary cosmic rays connected with the emission of high energy charged particles from the sun. In addition, it reveals that the sun is a continuous source of cosmic radiation, the activity of emission varying broadly in step with the solar cycle.

I. INTRODUCTION

SEVERAL attempts have been made in the past to establish a connection between solar phenomena and cosmic-ray intensity. Few instances of world-wide cosmic-ray effects of a transient nature associated with intense solar flares have been reported. Simpson *et al.*[1] have suggested a connection between active solar regions and 19 maxima of neutron intensity distributed over a period of 3 months and observed simultaneously at three widely separated stations. Very recently, Neher and Forbush[2] have pointed out that correlations exist between cosmic-ray intensity at both high and low altitudes and the above neutron measurements. However, it has not been possible so far to establish any significant direct effect of a continuous nature. Hogg,[3] who has examined this point with ionization chamber data, has concluded that "there is a possible but not very likely connection" between monthly averages of sunspot numbers and the cosmic-ray intensity corrected for pressure and temperature. He has further stated that what relationship does exist between cosmic rays and solar phenomena could be attributed to changes in the earth's magnetic field brought about by solar effects.

The mean daily or monthly cosmic-ray intensity which has generally been considered for the study of solar relationships is known to be affected by complex meteorological and geomagnetic factors. There is particularly great difficulty in the elimination of terrestrial influences, owing to incomplete meteorological data available for the higher levels of the atmosphere and to our imperfect understanding of the magnetic storm-time variation of cosmic-ray intensity. It is not surprising, therefore, that a relationship between mean daily or monthly cosmic-ray intensity and solar activity has proved elusive.

Sarabhai *et al.*[4] have earlier communicated experimental results obtained in Ahmedabad and at the mountain station of Kodaikanal, concerning the solar-time daily variation of meson intensity. They have examined the contribution of terrestrial influences to this variation and have been led to the view that, after correcting it for barometric pressure, the residual variation is mainly due to an anisotropy of the primaries. Since the diurnal variation at different parts of the earth has approximately similar phase, with a maximum occurring near noon local time, they have concluded that the anisotropy is caused by the emission of cosmic-ray particles from the sun. The pressure-corrected diurnal variation of mesons is, therefore, a sensitive index of continuous solar activity for the emission of cosmic rays, and we should expect changes in it of a world-wide character associated with the sun, just as in ionospheric and geomagnetic phenomena. We shall deal here with new evidence which demonstrates world-wide changes of amplitude and the hour of maximum of the diurnal variation. The relationship of these changes with solar phenomena is also discussed.

II. WORLD-WIDE CHANGES IN THE DAILY VARIATION OF MESON INTENSITY

We have examined the Carnegie Institution cosmic-ray data for meson intensity at Huancayo (H), Cheltenham (C) and Christchurch (C') for the years 1937 to 1946, as furnished by Lange and Forbush.[5] Bi-monthly mean bi-hourly values of percentage deviations from mean of pressure-corrected, cosmic-ray intensity at each station were harmonically analyzed for the diurnal variation. Adopting the notation used in harmonic dial representation, the diurnal harmonic component can be specified in terms of the percentage amplitude M^D and the hour of maximum ϕ^D expressed as an angle measured in the clockwise direction from midnight local time. Thus, for Huancayo, we had sixty values each for the amplitude $M_H{}^D$ and the hour of maximum

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$\phi_H{}^D$. Similar sets of values were obtained from the other stations. In order to eliminate the seasonal effect, moving averages of six consecutive bi-monthly values of M^D and ϕ^D were taken. We thus obtained values of M^D and ϕ^D for annual mean diurnal variation centered at 55 successive bimonthly epochs. Further moving averages over three successive annual mean values were taken to smooth the data.

The time-series for each station for M^D and ϕ^D are plotted with coinciding mean values in Figs. 1 (a) and 1 (b) respectively. Figure 1 (c) shows the series for Zürich sunspot number R and Fig. 1 (d) for the American magnetic character figure C_A. Both these time-series were derived from the original bimonthly values in the same manner as described above for M^D and ϕ^D.

The most remarkable feature shown by Figs. 1 (a) and 1 (b) is that the amplitude and the hour of maximum of the diurnal variation do not remain constant through the years but undergo long-term changes of 30 to 40 percent which are world-wide in character. With the time-series for the mean amplitude $M_T{}^D=(M_H{}^D+M_C{}^D+M_{C'}{}^D)/3$, which has been drawn in the figure as a continuous line, the variations of amplitude at the individual stations have high positive correlations exceeding $+0.85$. Similarly, the mean hour of maximum $\phi_T{}^D$ is highly correlated with the values at the individual stations. The time-series for $M_T{}^D$ and $\phi_T{}^D$ represent therefore, world-wide variations of amplitude and hour of maximum of the diurnal variation.

An examination of Fig. 1 (a) reveals that during the period 1937 to 1940 (designated as Group I) which corresponds to the years when the sunspot number R is above its mean value for the 10 years, the variation of the meson diurnal amplitude at Huancayo differs substantially from the variation of the diurnal amplitude at Cheltenham or at Christchurch. It appears, therefore, that during the period of high sunspot activity, the mountain station of Huancayo is affected by anisotropic low energy, cosmic-ray particles which cannot make their effect felt at sea level. For the years 1941 to 1946 in Group II corresponding to low sunspot activity, there is no significant difference between the variations of the diurnal amplitude observed at different stations.

III. THE AMPLITUDE AND THE HOUR OF MAXIMUM OF THE DIURNAL VARIATION

The hour of maximum of the meson diurnal variation would depend on the deflection of the charged primaries from the sun in the geomagnetic field. Hence, the long-term, world-wide variations of ϕ^D may be attributed to changes in the energy spectrum or in the ratio of positive to negative particles of the radiation which causes the anisotropy.

An interesting relationship exists between the world-wide changes of amplitude and the hour of maximum of the meson diurnal variation. For Group II, corresponding to low sunspot activity, the correlation between the two is $+0.87$. This means that an increase of amplitude is associated with a shifting of the maximum to later hours. This can arise for positive primary particles if an increase of amplitude is accompanied by a shift of the energy spectrum towards higher energies. For negative primary particles, it may arise from an increase of amplitude being due to the addition of low energy particles which would shift the energy spectrum towards lower energies. Both effects may be operating simultaneously at some periods, but the effect of low energy negative particles would presumably be more evident at a high level station such as Huancayo. Further analysis of data, which is in progress now, is expected to throw some additional light on the sign and energies of the solar primaries causing the anisotropy of cosmic radiation at different times of the solar cycle. Group I, corresponding to years of high solar activity, is particularly interesting for this purpose.

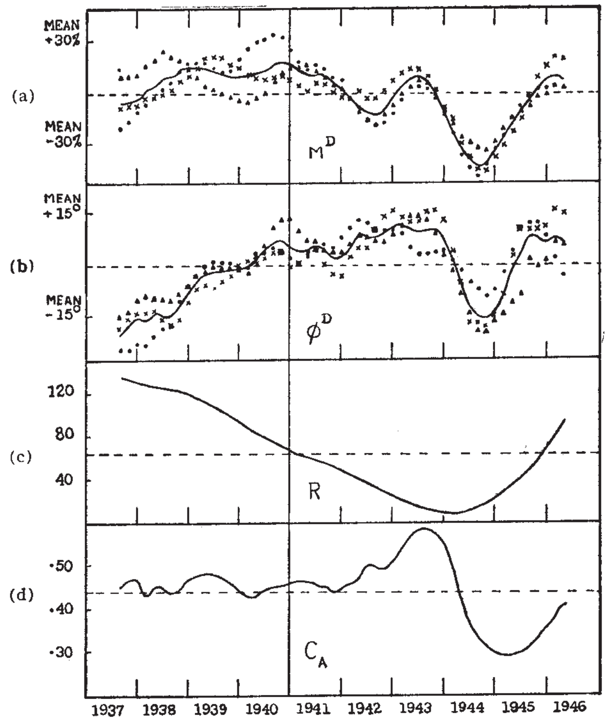

FIG. 1. Time-series for annual mean values during period 1937–1946 of (a) M^D meson diurnal amplitude; (b) ϕ^D meson diurnal hour of maximum; (c) R Zürich sunspot number; (d) C_A American magnetic character figure. The results from individual stations are indicated by ▲ for Huancayo, × for Cheltenham, and ● for Christchurch.

IV. SOLAR RELATIONSHIP OF MESON DIURNAL AMPLITUDE

The total and partial correlation coefficients of the meson diurnal amplitude $M_T{}^D$ with relative sunspot number R and the American magnetic character figure C_A are indicated in Table I for all years, and for years in Group II corresponding to low solar activity.

The high and significant values of the partial corre-

TABLE I. The total and partial correlation coefficients of the amplitude of the meson diurnal variation with relative sunspot number and American magnetic character figure. Group II years refer to a period of low solar activity.

Correlation	All years	Group II years
${r_T}^M{}_R$ between ${M_T}^D$ and R	+0.58	+0.57
${r_T}^M{}_{CA}$ between ${M_T}^D$ and C_A	+0.48	+0.56
${r_T}^M{}_{R.CA}$	+0.65	+0.88
${r_T}^M{}_{CA.R}$	+0.57	+0.86

lations of ${M_T}^D$ with R and C_A in Group II indicate that during years of low sunspot activity, regions responsible for cosmic-ray emission from the sun undergo a change in activity similar to that of the sunspots. It appears, therefore, that the active regions of the sun emitting high energy primaries whose effects are detectable at sea level have to be near the heliographic equator, as at periods of low sunspot activity, to be effective in producing an anisotropy of the cosmic radiation near the earth. This is analogous to what holds good for the corpuscular solar radiation responsible for magnetic storms and auroral activity. In view of this, it is not surprising that during the early part of the solar cycle, there is a lag of the cosmic-ray time-series with respect to the sunspot series. An examination of the time-series for solar activity confined to low heliographic latitudes is now in progress. The time-series for amplitude ${M_H}^D$ at Huancayo has better partial correlations than the mean amplitude ${M_T}^D$ with R and C_A for all the years. This is suggestive of the possibility that for emission of low energy cosmic-ray primaries from the sun whose effects are detectable only at mountain stations, the active regions can be further away from the solar equator than for high energy primaries.

While in years of low sunspot activity, there is a low and nonsignificant negative correlation between sunspots and the magnetic character figure C_A, the high positive partial correlation of C_A with cosmic-ray diurnal amplitude is very significant. It appears that this connection between cosmic rays and the magnetic activity is not a direct one. On the other hand, it probably implies that the M regions on the sun, believed to be responsible for the solar corpuscular emission causing magnetic disturbances, can themselves emit particles of cosmic-ray energy or are associated with regions which can do so. Hogg's assertion that solar effects on cosmic rays are only observed when they are simultaneously accompanied by geomagnetic disturbances is not tenable on account of the high partial correlation of diurnal amplitude with sunspot numbers.

A nonpersistent 27-day recurrence tendency in cosmic-ray intensity has been reported by several workers. In spite of differences in detail of the cosmic-ray pulses and magnetic pulses in the Chree diagrams, it has been believed by some authors that the cosmic-ray pulses are caused by geomagnetic disturbances. In view now of the other solar relationships of cosmic-ray intensity, a 27-day recurrence tendency in cosmic rays not necessarily directly connected with geomagnetic effects is understandable.

V. CONCLUSIONS

The facts presented here have far-reaching implications. They confirm our earlier view that the pressure-corrected diurnal variation of mesons is mainly due to an anisotropy of the primary radiation and is not caused by a positive upper air temperature effect. An explanation of the diurnal variation of mesons in terms of direct geomagnetic or heliomagnetic effects cannot be seriously considered in view of the marked latitude dependence which would be expected. We shall discuss separately, along with full details of the present work, the implications of our findings on current theories and past experimental results concerning the diurnal variation, with particular reference to the measurements from definite directions by Alfvén and Malmfors[6] and Elliot and Dolbear.[7]

Earlier work has shown that the sun can give rare bursts of high energy particles during some flares. There is also an association between some peaks observed in day-to-day changes of neutron and charged particle cosmic-ray intensity and the central meridian passage of active regions. The new evidence presented here demonstrates that the sun is a continuous source of cosmic radiation giving rise to a diurnal variation of the meson intensity on the earth. The level of activity for continuous solar cosmic-ray emission is not constant but varies substantially with the years broadly in step with the general solar cycle.

We are grateful to Professor K. R. Ramanathan for very valuable discussions and to Mr. K. A. Gidwani for assistance in computation of data. We owe our thanks to the Atomic Energy Commission of India for support given.

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Effects at Godhavn and Lower Latitudes of Changes in Energy and Composition of Solar Cosmic Rays

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Time series have been derived for changes of the amplitude and the hour of maximum of the diurnal component of the daily variation of the pressure-corrected meson intensity at Godhavn from Carnegie Institution data. While these series show some features which are strikingly similar to those observed at other stations, the variability at Godhavn is much greater than elsewhere. Comparison of the series at Godhavn with the corresponding series for the mean changes observed at Cheltenham and Christchurch permits information to be derived concerning changes in the mean energy of cosmic-ray primaries responsible for the daily variation, and their "stiffness" in the geomagnetic field. On the basis of an interpretation in terms of continuous emission of cosmic rays from the sun, there is evidence for an increase in the mean energy of solar cosmic rays from 1940 to 1944. Reasons are given for believing that during 1944, the solar cosmic rays became richer in alpha particles as compared to protons.

WE have earlier presented[1] evidence demonstrating world-wide changes in the daily variation of cosmic-ray meson intensity. Time series for the period 1937 to 1946 have been derived for changes in the amplitude M^D and the hour of maximum ϕ^D of the diurnal harmonic component of the daily variation of mesons observed at Huancayo (H), Cheltenham (C), and Christchurch (C'). Similar analysis has now been conducted for the daily variation of meson intensity at Godhavn (G) from data furnished by Lange and Forbush.[2]

Figure 1 shows the time series for changes in absolute magnitude of M_G^D and ϕ_G^D during the years 1939 to 1946. These series at Godhavn (mag. lat. 79.9° N) may be compared with the time series $M_{\langle C\rangle}^D$ and $\phi_{\langle C\rangle}^D$, which represent the mean of the time series for Cheltenham (mag. lat. 50.1° N) and Christchurch (mag. lat. 48.6° S). Huancayo has not been included in the mean time series because it is a high level station on the magnatic equator and during years of high solar activity, M_H^D exhibits a different course of changes compared to M_C^D or $M_{C'}^D$. Though the changes in the daily variation at G and $\langle C\rangle$ have broad similarities, there are certain important differences.

1. The variability of M_G^D and ϕ_G^D at Godhavn is much greater than the variability of $M_{\langle C\rangle}^D$ and $\phi_{\langle C\rangle}^D$.

2. For the period 1943 to 1946, the time series for M_G^D and ϕ_G^D are remarkably similar to those for $M_{\langle C\rangle}^D$ and $\phi_{\langle C\rangle}^D$, respectively. For 1939 to 1942 however, M_G^D has a low and almost constant value nearly equal to the minimum reached in 1944, while $M_{\langle C\rangle}^D$ steadily decreases from a high to an intermediate value in its total range. During the same period, ϕ_G^D has a peak at 1940 while $\phi_{\langle C\rangle}^D$ has a slowly increasing value.

G and $\langle C\rangle$ refer to sea level stations which lie outside the region where the geomagnetic latitude effect is observed at this depth of the atmosphere. However, if the daily variation is considered to be produced by

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cosmic rays from the sun, there can still be differences in its form at the two places because, with change of latitude, the sun's mean zenith distance and consequently the mean atmospheric path length for solar rays would alter. The atmospheric path length for the radiation would be greater at Godhavn on account of its higher latitude. This has the following consequences.

1. The $M_G{}^D$ series shows the changes of intensity of the high energy radiation which makes its effect felt at both G and $\langle C\rangle$.

2. The difference curve $M_{\langle C\rangle}{}^D - M_G{}^D$ shown in Fig. 1, reflects the changes of intensity of the low energy solar cosmic radiation which reaches $\langle C\rangle$ but not G.

3. The changes in $M_G{}^D$ and $M_{\langle C\rangle}{}^D - M_G{}^D$ thus give information of the changes of the high and the low energy radiations reaching $\langle C\rangle$. The two taken together indicate changes in the mean energy of the radiation responsible for $M_{\langle C\rangle}{}^D$.

When it is realized that the trajectories of positive particles from the sun would be bent in the geomagnetic field so that they would appear to come from the west and would register a maximum which would be earlier for the more deflected trajectories, we can look upon the $\phi_{\langle C\rangle}{}^D$ and $\phi_G{}^D$ series as indicative of the mean deflections suffered by the solar particles approaching $\langle C\rangle$ and G, respectively. The radius of curvature of a trajectory is proportional to $(mv)/Z$, so that for either protons or alpha particles or a combination of both in a constant proportion, the energy hardening of the radiation would be accompanied by an increase of the radius of curvature and an increase of ϕ^D corresponding to a later hour of maximum. ϕ^D however, should tend to approach a maximum value since for large energies the deflection of the trajectories is negligible.

In terms of the interpretation given above, we can draw certain broad conclusions regarding the changes in intensity and composition of the solar cosmic-ray emission. The increased emission in 1943 appears to be confined to high-energy primaries which make their effect felt at G as well as $\langle C\rangle$. From 1940 to 1944, the $M_{\langle C\rangle}{}^D - M_G{}^D$ series decreases steadily, while $M_G{}^D$ does not decrease likewise. Hence at $\langle C\rangle$, the mean energy of the solar radiation increases from 1940 to the year 1944. Up to 1943, $\phi_{\langle C\rangle}{}^D$ also increases and appears to approach saturation. In 1944 however, there is a rapid and large decrease of $\phi_{\langle C\rangle}{}^D$ although the mean energy of the radiation continues to increase. In early 1945, the radiation at $\langle C\rangle$ again becomes energetically softer, but this is accompanied by a rapid increase of $\phi_{\langle C\rangle}{}^D$. It is possible to reconcile the changes of mean energy of incoming radiation and of ϕ^D during 1944 and 1945 if we postulate an alteration in the proportion of protons and alpha particles in the solar cosmic-ray emission. The present interpretation requires that during 1944, the solar cosmic-ray emission became richer in alpha particles as compared to protons.

The form of the mean daily variation curve for mesons for the period 1939–1946 at G is strikingly dif-

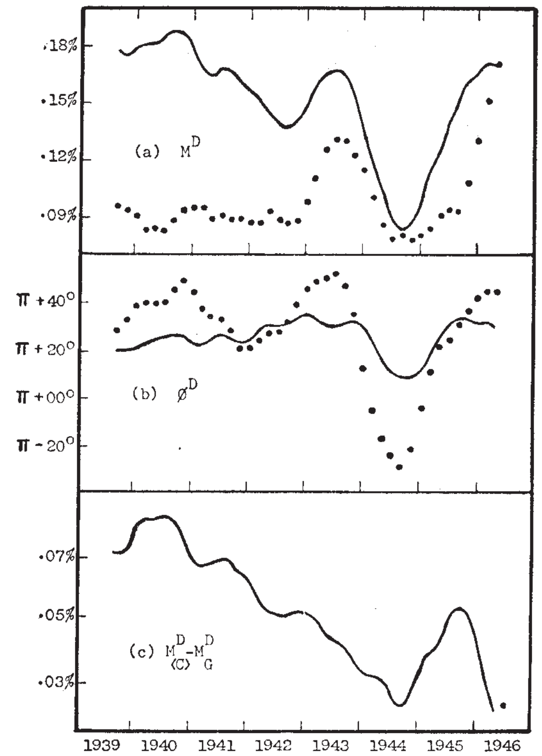

FIG. 1. Time series for annual mean values during period 1939 to 1946 of (a) M^D, meson diurnal amplitude; (b) ϕ^D, meson diurnal hour of maximum expressed in degrees; π corresponds to mid-day and 15° to one solar hour. (c) $M_{\langle C\rangle}{}^D - M_G{}^D$, difference between diurnal amplitudes at $\langle C\rangle$ and G. In (a) and (b), the continuous lines indicate the values for $\langle C\rangle$, and . . the values for G.

ferent[3] from the corresponding curve at $\langle C\rangle$. At G the amplitude $M_G{}^D = 0.10$ percent is much less than at $\langle C\rangle$ where the amplitude $M_{\langle C\rangle}{}^D = 0.16$ percent. Also, the maximum at G is much flatter than that at $\langle C\rangle$. This is qualitatively in agreement with the view that the difference at the two places is due to differences in the mean value, as well as in relative changes, during the day, of the atmospheric path length for solar cosmic rays. A quantitative analysis is rendered difficult in the absence of knowledge of the true trajectories of solar cosmic rays. Considerable deflection of the trajectories in the geomagnetic field would alter substantially an oversimplified view based on optical paths for particles from the sun.

While only a very tentative interpretation is possible with the relatively scanty data that are available, the present analysis is indicative of the type of information about the primary radiation which could be obtained from a close study of the changes of meson daily variation at a number of stations on the earth. We are grateful to Professor K. R. Ramanathan and Professor B. Peters for helpful discussions, and to Mr. K. A. Gidwani for computational assistance. Our thanks are due the Indian Atomic Energy Commission for financial assistance.

[3] J. G. Wilson, *Progress in Cosmic Ray Physics* (North-Holland Publishing Company, Amsterdam, 1952), p. 468.

cesses which can be considered to have been established and are generally accepted. If, in the future, there are important aspects which cannot be explained on a simple hypothesis of solar origin, we shall of course have to look elsewhere for an explanation. For the time being, it is fruitful to pursue the subject vigorously from the experimental side and devise a telescope and a technique which would be most suitable for studying the anisotropy of the primary radiation.

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Report of the Committee on Standardisation of Cosmic Rays continuous reccrding equipment

by

Pr SARABHAI

Present. Daudin, Ehmert, Elliot, Nagata, Sändstrom, Sarabhai, Simpson

Meetings. The Committee met in the afternoons on 7. 7. 53 and 8. 7. 53.

Decisions.

1. A reference has been made by the Special Committee for the 3rd International Geophysical Year (1957–58) to standardise equipment for the organisation of worldwide studies of geophysical interest in cosmic rays.

There was agreement that it would be appropriate to standardise a neutron monitor and a wide angle counter telescope equipment for study of the solar and terrestrial relationship and the irregular variations of cosmic ray intensity. This would also furnish, incidentally, information concerning the daily variation of cosmic ray intensity. A large number of workers in different countries (App. I) are already interested in time variations of cosmic rays. Some would gladly set up units of standard design whose results would be comparable.

By means of recommandations to the National Committees on this subject by the Special Committee for the I.G.Y., and by the international body to be specially charged with responsabilities for the coordination of cosmic ray research the workers in individual countries could be provided the support of their own Government in order to organise a wide network of cosmic rays stations.

2. At least five countries, namely, Australia, Germany, India, Japan and Sweden have expressed an interest in standardisation of narrow angle telescopes which would furnish comparable information particularly useful for understanding the anisotropy of primary radiation. However the experimental situation at the present moment is not clear enough for standardisation of an apparatus of optimum design.

It was therefore decided that interested workers in this field should privately communicate with one another their experience with the variety of experimental set ups that are at present being tried out. If the positions clarifies during the positions clarifies during the next two years, as may well be, a standardised apparatus could later be decided on for the I.G.Y. programme.

3. For the continued coordination of a worldwide programm of Cosmic Ray time variation studies it is necessary to establish an organisation similar to that set up for worldwide geomagnetic studies. Since it would be appropriate that physicists are mainly connected with it, the I.U.P.A.P. may take it up. Alternatively I.A.T.M.E. of I.U.G.G. may be charged with the responsibility as suggested by the special Committee of the I.G.Y. Dr Sarabhai* was authorized to communicate with Prof. Chapman, the President of the Special Committee for the I.G.Y., with the President of the Cosmic Ray Commission of the I.U.P.A.P. and with the President of the I.A.T.M.E. of I.U.G.G. Till an international body can take over the coordination of Cosmic Ray Work, Dr. Sarabhai will transmit information to the various groups mentioned in Appendix 1, so that

Details of Apparatus

a) For time changes of the low energy primary component, duplicate neutron monitors would be used.

These would be designed to have minimum of 200 counts per minute per monitor at sea level for latitudes in excess of 48°. Dr. Simpson will furnish details of the apparatus including geometry, counters, electronic equipment, technique of calibration, pressure indicators and barometric correction. The design will be for counters with enriched and ordinary BF_3. Dr. Elliot will advise on modifications required for substituting components available in England. Dr. Simpson will send 18 copies of reports by Oct. 30 or Nov. 15, 1953 to Dr. Sarabhai for further distribution.

b) For time changes of the meson intensity in the lower atmosphere duplicate triple coincidence telescopes of cubical geometry are decided upon. They would individually have a counting rate of not less than 50000 counts per hour. There should be an absorber between the extreme trays of 10 cm of Pb or its equivalent in gms/cm2 of Fe.

The resolution time of the coincidence units

* Lire après that : " standardisation of equipment

should be between 3 and 5 micro-secs. Dr. Ehmert and Dr. Elliot will furnish recommandations for electronic units, particularly for quenching and for scaling. Dr. Sandstrom will recommand details of a suitable test equipment. Photographic or teleprinting methods may be chosen for recording the counts. Dr. Ehmert will furnish details of cost and reliability of a German teleprinter. 15 minute records will be available, but only bihourly records of intensity of each telescope and of the barometric pressure, along with the barometric correction will be separately tabulated.

A microbarograph of good make with daily chart would be used. The barometric readings may be photographed if found convenient.

The counter telescopes and associated apparatus would be checked regularly at weekly intervals.

:ation of apparatus.

It is desirable to have the widest possible network of Cosmic rays stations operating one or both types of standardised equipment. It is preferable to locate the apparatus at stations where radiosonde data is regularly available and where a ionospheric station is also operating.

The apparatus should be located in a place having no more than 20 gm/cm2 in the roof between the top counters and the free atmosphere. The apparatus may be operated at an ambient temperature (or temperatures depending on seasons) which is most suitable for local conditions. However the diurnal range of temperature to which the apparatus is subject should not exceed 10°C.

Data will be submitted monthly by each participating station before the end of the following month. Wen an international central coordinating body is created, only duplicate copies need be sent to it. However in the meantime, as soon as some stations participate in an informal ways, 12 copies should be sent to Dr. Sarabhai for immediate retransmitted to participating groups.

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AHMEDABAD TEXTILE INDUSTRY'S RESEARCH ASSOCIATION

By Dr. VIKRAM A. SARABHAI

Director

ON April 10, Mr. Jawaharlal Nehru, Prime Minister of India, opened the new laboratory building at Navrangpura, Ahmedabad 9, of the Ahmedabad Textile Industry's Research Association, the foundation stone of which was laid in November 1950 by the late Sardar Vallabhbhai Patel, Deputy Prime Minister of India. The Association is modelled on the same lines as the research associations in Great Britain, and this constitutes the first enterprise of its kind in which industry and the Government of India have co-operated in the field of research. The past five years have witnessed the growth in India of a chain of national laboratories inspired by Sir Shanti Bhatnagar, director of the Council of Scientific and Industrial Research, and Sir Shanti has also been actively associated with the growth and development of the new Association at Ahmedabad, which is the second largest centre of the textile industry in India.

The idea of establishing a textile research laboratory maintained by the joint effort of industry and the Government of India was first conceived by the Ahmedabad Millowners' Association in 1944, and the Ahmedabad Textile Industry's Research Association was registered in December 1947. Its seventy-one founder-members made an initial contribution of approximately £370,000 towards the initial expenses, and the Government of India gave approximately £145,000. The recurring expenses are shared equally by industry and the Government. Recently, membership of the Association was thrown open to mills all over India, and co-operative research is now increasingly made use of by the premier industry of the country.

The laboratories are on the Gujarat University campus and consist of a multi-story central block, covering an area of 100,000 sq. ft., which accommodates the library, offices and laboratories of the various research divisions, the administrative offices, the stores and precision workshop, and the services in a basement. The block is connected at one end to a single-story building which houses the pilot mill. At the other end are situated a cafeteria and an auditorium. The pilot mill is equipped with complete machinery for spinning, weaving and chemical processing, with facilities for experimenting under a variety of conditions. The physical testing laboratory has a comprehensive range of modern testing instruments for fibres, yarns and fabrics. The unit plant laboratory has a number of laboratory models of standard dyeing and printing machines and will also be equipped in the near future for some of the unit processes of chemical engineering. The entire building is air-conditioned for comfort, except for the physical testing room and the pilot mill, which have separate air-conditioning to maintain required constant temperatures and humidities.

Even though the laboratory building has only now been completed, the work of the Association commenced about five years ago in the Science College at Ahmedabad with the recruitment of staff for statistics, chemistry, physics and psychology. Recognizing the increasing importance of industrial psychology and the science of management, the Association decided from the outset to include these in its organization. It was also felt that during its early years the Association should commence its work with the utilization of existing scientific knowledge and apply this for the immediate benefit of the industry. Emphasis was deliberately placed on operational research aimed at standardization and rationalization of existing processes and work methods, and on applied research designed to introduce developments of practical use to the industry. This was done with the view of fostering scientific consciousness among those who work in the industry and creating confidence in the practical utility of applying the scientific method to the problems of industry.

Operational and applied research is generally carried out in the mills in collaboration with the technical staff of the mills. At all stages of the experiment, critical evaluation is continuously done in frequent conferences among the staff of the Association and in discussions with mill management and technicians. After the successful completion of experimental studies in two or three mills, the results are published in the form of research notes. This, however, constitutes only half the work. Successful implementation and translation of the benefits to industry are equally important tasks on which the Association has placed great emphasis. It believes it to be its duty to demonstrate without cost to its members, in their own mills, the full utility of implementation of its research work. However, every effort is made to ensure that its resources are not diverted to routine operations which legitimately fall within the domain of individual mill management. When circumstances require that the Association should be engaged in routine services, separate units are created for this purpose. In this way the Association operates routine physical and chemical testing laboratories and provides servicing and supervision of quality control, training-within-industry programmes and other management techniques to industry. The cost of these units is defrayed by the mills which participate in these benefits.

To-day the Association has eight Divisions dealing with Physics, Chemistry, Statistics, Psychology, Liaison, Technology, Library and Documentation and Administration.

Pending the establishment of the Textile Technology Division, the Physics Division mainly concentrated during the initial years on problems of spinning. It modified the micro-sample spinning technique developed in other laboratories so that a sample of one pound of cotton may be spun in a short time on the usual mill spinning plant under mill conditions of speeds, settings, etc. The yarns produced by this small-sample spinning method check well in lea strength with the yarns produced by the normal large-scale mill processes. This technique has also been used for investigating the application of various spinning aids and in the investigation of blending of cottons. A study has been undertaken of the fibre length distribution and the evenness of the material under process at various stages in spinning. This Division has a well-equipped optics laboratory in which work is being done at present on a study of the adsorption of dyes and other chemicals on the surface of textile materials. Attempts are also being made to correlate the degree of orientation of mercerized fibres with lustre and to use the X-ray technique for determining the degree of mercerization. A modest beginning in instrumentation and electronic developments has been made by creating a separate section for these in the Physics Division.

The Chemistry Division started initially with a survey of the various textile chemical processes in the member mills of the Association and the determination of optimum conditions for these processes. A detailed study of sizing practice was made, and simple experimental methods for the evaluation of sizing materials and methods were demonstrated to mills. Extensive studies were also made to assess the value of tamarind kernel-powder, an indigenous material, as a sizing material for cotton warps for both bleached and grey sorts. Suitable modifications were worked out to overcome the objectionable reddish colour of this material. A long-term fundamental study of sizing has been planned, and work on this programme has been started very recently. Attempts are also being made to produce improved finishes, using so far as possible indigenous materials. Three such processes have been worked out on a laboratory scale and will shortly be tried in mills on a pilot-plant scale. In order to explore the possibilities of mercerizing textiles made from Indian cottons, an extensive study has been undertaken on a comparison of the mercerization of different cottons (Indian, African, American and Egyptian) in fibre, yarn and cloth stages. The Chemistry Division also maintains a technical service which undertakes investigation of a number of production problems from the chemical processing departments of member mills.

The Textile Technology Division has been created this year with the arrival of machinery for the pilot mill. Among the problems that are being taken up for investigation are (1) the relationship between individual fibre characteristics of a blend and the properties of the yarn and its weavability, and (2) the effect of yarn conditioning, atmospheric conditions and loom tensions on weavability.

The main effort of the Statistics Division has been directed to the development and application of quality control methods to the textile industry. With the Association's collaboration, quality control sections have been established in about twenty-four mills, and statistical methods have been applied by these sections to improve operational characteristics such as breakages, uniformity, waste, damages and efficiency. The Statistics Division has also carried out a number of short-term experiments in spinning, including studies on the effect of mixing soft waste with cotton, the effect of vibrating bobbins, the effect of different speeds and settings in processing, a comparison of two and three passages of drawing, and an improved method of ribbon lap preparation. Theoretical studies of machine interference have also been made and are being checked with the results of actual mill working. At present the quality control technique is being extended to chemical processing. The possibility of introducing acceptance sampling is also being explored. The Division maintains a computing section to analyse the data coming from various Divisions as well as from the quality-control sections of mills; it publishes a quality-control bulletin incorporating the data collected by the various quality-control sections in mills and the results of experiments carried out by them, and conducts classes for training technicians in statistical methods.

The Psychology Division has been concerned mainly with problems of attitudes, labour management relations, supervisory training, incentives, time-and-motion studies, the effect of physical working conditions on the health of workers and their efficiency, etc. A number of interesting results have been obtained in these various fields, some of which have found practical application on a large scale in mills. A project was conducted during 1950–51 in collaboration with Prof. Gardner Murphy, Unesco consultant to the Government of India, in order to study labour-management tension within the textile industry. As a result of this study, the need for supervisory training was emphasized and training-within-industry programmes were started in 1953 to fulfil this need with the technical assistance of the International Labour Organization. Thirty-one mills are participating at present, and in the short period of one year 2,884 supervisors have been trained. The three training-within-industry programmes have been translated into the Gujerati language so that a greater number of supervisors can participate in them. At the joint request of organized industry and labour, the Psychology Division has worked extensively on assessment of work loads in the various occupations of the industry and on applying the job evaluation methods for recommending a scientific wage structure.

Recently the newly established Liaison Division has taken over, from the research divisions, primary responsibility of maintaining close contacts with member mills and the quick translation of the Association's research into routine industrial practice.

With the completion of the first five years of the Association, the need for a properly balanced research programme covering both fundamental and applied problems has been increasingly felt. Such a programme, where fundamental and applied research would complement one another and constantly provide new ideas, has now been initiated. With technical assistance from Unesco, a project for the study of the nature of macromolecules has been started. An equilibrium centrifuge and gas adsorption apparatus have been set up. Some of the other fundamental problems in this programme are the preparation and properties of colloid solutions with special reference to spinning aids ; the spectrophotometric, colorimetric and chemical study of adsorption of substances on textiles ; changes in the surface and mechanical properties and in the fine structure of textiles, caused by processes such as sizing, dyeing, mercerizing and finishing ; the theory of tensile strength of yarns ; the relation between structural geometry and mechanical properties of fabrics ; and morale and attitude surveys. Along with the national laboratories of India, the Ahmedabad Textile Industry's Research Association is playing a significant part in tackling the great and important problems which face India to-day.

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Cycle of World-Wide Changes in the Daily Variation of Meson Intensity

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Physical Research Laboratory, Ahmedabad, India
(Received May 13, 1954)

The study by Sarabhai and Kane of the world-wide changes in the daily variation of meson intensity has been extended by an analysis of unpublished Carnegie Institution data, kindly supplied by Dr. Forbush. Comparison of Carnegie Institution measurements at Huancayo and Cheltenham for the period 1937 to 1952 reveals high correlation between changes of the times of maxima at the two stations. The changes of amplitudes of the daily variations are not equally consistently related. The change of intensity of the coronal 5303A emission line exhibits the major features seen in the change of the daily variation of meson intensity. Both follow the usual 11-year solar cycle of activity.

SARABHAI and Kane,[1] in a paper later referred to in this article as I, have shown, by an examination of the Carnegie Institution data[2] for the period 1937 to 1946, large world-wide changes in the amplitude and the time of maximum of the daily variation of meson intensity, corrected for barometric pressure. These changes were found to follow the broad pattern of the eleven-year solar cycle. In a later communication, Thambyahpillai and Elliot[3] have drawn attention to the progressive change, from 1940 to 1952, of the time of maximum of the daily variation to earlier hours. They have compared data from different types of instruments at different periods and have suggested a twenty-two-year cycle of change.

Directional studies made at Stockholm and Manchester and recent work at Ahmedabad clearly reveal the dependence of the time of maximum $M\phi^D$ and the amplitude M^D of the diurnal component of the daily variation of mesons on the sensitive cone of the measuring instrument and its orientation. The treatment of results from ionization chambers and counter telescopes on a directly comparable basis therefore appears questionable. A test of this, and further extension of our earlier studies have now been made possible by the supply of unpublished data covering 1946 to 1953 from the Carnegie Institution stations, through the kind generosity of Dr. Forbush.

Figures 1 (a) and (b) show the changes of M^D and $M\phi^D$ computed from the annual mean daily variation centered at successive bimonthly epochs. Unlike the treatment in I the present authors have not smoothed out their results by taking moving averages over three successive bimonthly values. Uninterrupted data are available for Huancayo and Cheltenham from 1936 to 1953, while for Christchurch there is a large gap from 1st July 1942 to 30th April 1946 due to irregular stoppages.

An examination of Fig. 1 reveals that:

(1) The changes in the amplitude M^D at the different stations do not appear to be well correlated except during the period 1940–1946. For Christchurch and Cheltenham which are sea-level stations at comparable latitudes south and north of the equator, respectively, the changes in amplitude are better related than between either station and Huancayo. The prominent disturbance in 1943 followed by a quiet period in 1944 is strikingly revealed in all curves.

(2) The changes in time of maximum $M\phi^D$ at all stations are highly correlated. For the entire fifteen-year period, the correlation between Huancayo and Cheltenham is 0.93.

The change in the annual mean relative sunspot number R, centered at successive bimonthly epochs, is shown in Fig. 1 (c). Alongside are also given corresponding values of the total solar emission of the coronal line 5303 A. These have been computed, after interpolating at bimonthly intervals, from the observations of Waldmeier[4] at different epochs. It is clearly seen that changes of $M\phi^D$ follow the normal solar cycle, there

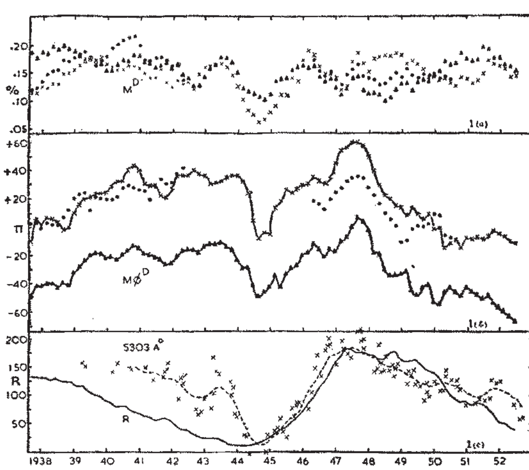

FIG. 1. Time series for annual mean values during 1937–1953 of (a) M^D, meson diurnal amplitude; (b) $M\phi^D$, meson diurnal time of maximum; (c) R, Zurich relative sunspot number and total emission of 5303-A coronal line. In (a) and (b) the results from individual stations are indicated by ▲ for Huancayo, ✕ for Cheltenham, and ● for Christchurch. In (c), ✕ indicate the values of coronal emission reported by Waldmeier. In (b), π in the ordinate relates to 1300 hours instead of noon.

[1] V. Sarabhai and R. P. Kane, Phys. Rev. **90**, 204 (1953).
[2] I. Lange and S. E. Forbush, Carnegie Institution of Washington Publications, No. 175, 1948.
[3] T. Thambyahpillai and H. Elliot, Nature **171**, 918 (1953).
[4] M. Waldmeier, Z. Astrophys. **26**, 264 (1949).

being no evidence for a twenty-two year period. While the mechanism of solar control is still obscure, we have earlier interpreted the new results as indicative of continuous solar emission of cosmic rays and changes of $M\phi^D$ as caused by magnetic bending of the trajectories of charged solar particles. The consistent world-wide character of changes of $M\phi^D$ is then not surprising.

Coronal emission in 5303 A is the most satisfactory index we know for activity in solar cosmic-ray emission. This is demonstrated strikingly in 1943, and in the pronounced shift of $M\phi^D$ in 1947 to later hours. Therefore, Simpson's observations with neutrons relating to low-energy primaries and the daily variation of mesons related to a more energetic primary component both lead to the same conclusion. They must focus our attention on the solar corona for an understanding of the processes of continuous cosmic-ray emission from the sun.

We are deeply indebted to Dr. S. E. Forbush and to Professor Waldmeier for furnishing the unpublished data, which have made the present study possible. It is a pleasure to acknowledge assistance from Mr. K. A. Gidwani, Mr. Duggal, and Mr. Bhatt, and support from the Atomic Energy Commission of India.

ORGANISATION OF RESEARCH FOR THE TEXTILE INDUSTRY:

Dr. Vikram Sarabhai, Director, Ahmedabad Textile Industry's Research Association, Ahmedabad.

I want to examine a particular problem which faces us today in organising research for industry.

Co-operative Research Associations originated in England and they admirably fulfill the needs of industries which are diversified and which contain small independent units. In the United States, the pattern of research is very different. There are large corporations which either sponsor private research in institutions or have extensive Research and Development sections within their own organisations. We are all aware how successful this has been in placing the U.S.A. in the forefront of industrialised countries.

In the Textile Industry in India, as in England, there are a large number of small units who by themselves, because of their size, cannot afford to have extensive organisations of their own. In India, I believe the pioneer experiment in co-operative research is the Indian Jute Mills Association's Research Institutes in Calcutta. Anyone who has visited its laboratory would be struck, as I was, by the splendid support which it has received from industry. In a certain sense, the achievements of IJMARI are unique, because IJMARI is a one hundred percent industry supported organisation — an organisation in which, apart from providing the capital fund, I believe the industry spends Rs. 8 lakhs every year. This laboratory, which is so far tackling problems in fundamental physical sciences and technology sciences, has got no section dealing with human relations. It has a Liaison Section, with an extensive staff which is maintaining day-to-day contacts with mills.

In ATIRA, we have got not only the co-operative effort of industry, but Government also contributes fifty percent to the incoming capital and recurring expenditure.

In what follows I should like to consider the responsibilities and functions of a co-operative research association and how they are related to the functions of the mill unit itself.

If we analyze the nature of research that can be done we can broadly classify it into three aspects, even though, as Dr. Krishnan pointed out before, there is no hard and fast distinction between these aspects. In the first, the emphasis is on what is now spoken of as "Operational Research."

This received widespread publicity during the last war because of the striking results that were achieved from it. It was customary for the science of warfare to be regarded as an exclusive prerogative of the professional soldier, but it was soon realised that problems of total warfare go much beyond the competence of regular army men, and require the services of mathematicians and scientists. In England, for instance, pure scientists were drafted into the Admiralty, into the Air Force and into other branches of the armed forces in order to formulate solutions to specific problems on a rational scientific basis. One had, for instance, to determine the optimum size of a convoy which with a given number of escorting naval vessels could be most effectively protected from enemy submarines. Operational research involved people who had knowledge of Physics, Chemistry, Mathematics and other subjects and who applied their fundamental knowledge to problems to produce effective solutions.

One of the troubles in many of the applied sciences is that we are used to applying empirical methods for the solution of our problems. In operational research, we have to ask ourselves the question whether we are dealing with a particular problem in the best and the most effective way, what are the alternative ways, and if there are a number of alternatives, which is the best suited to us under our particular circumstances? So it can be seen that in industry there is a tremendous scope for ope-

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This received widespread publicity during the last war because of the striking results that were achieved from it. It was customary for the science of warfare to be regarded as an exclusive prerogative of the professional soldier, but it was soon realised that problems of total warfare go much beyond the competence of regular army men, and require the services of mathematicians and scientists. In England, for instance, pure scientists were drafted into the Admiralty, into the Air Force and into other branches of the armed forces in order to formulate solutions to specific problems on a rational scientific basis. One had, for instance, to determine the optimum size of a convoy which with a given number of escorting naval vessels could be most effectively protected from enemy submarines. Operational research involved people who had knowledge of Physics, Chemistry, Mathematics and other subjects and who applied their fundamental knowledge to problems to produce effective solutions.

One of the troubles in many of the applied sciences is that we are used to applying empirical methods for the solution of our problems. In operational research, we have to ask ourselves the question whether we are dealing with a particular problem in the best and the most effective way, what are the alternative ways, and if there are a number of alternatives, which is the best suited to us under our particular circumstances? So it can be seen that in industry there is a tremendous scope for ope-

ORGANISATION OF RESEARCH FOR THE TEXTILE INDUSTRY:

Dr. Vikram Sarabhai, Director, Ahmedabad Textile Industry's Research Association, Ahmedabad.

I want to examine a particular problem which faces us today in organising research for industry.

Co-operative Research Associations originated in England and they admirably fulfill the needs of industries which are diversified and which contain small independent units. In the United States, the pattern of research is very different. There are large corporations which either sponsor private research in institutions or have extensive Research and Development sections within their own organisations. We are all aware how successful this has been in placing the U.S.A. in the forefront of industrialised countries.

In the Textile Industry in India, as in England, there are a large number of small units who by themselves, because of their size, cannot afford to have extensive organisations of their own. In India, I believe the pioneer experiment in co-operative research is the Indian Jute Mills Association's Research Institutes in Calcutta. Anyone who has visited its laboratory would be struck, as I was, by the splendid support which it has received from industry. In a certain sense, the achievements of IJMARI are unique, because IJMARI is a one hundred percent industry supported organisation — an organisation in which, apart from providing the capital fund, I believe the industry spends Rs. 8 lakhs every year. This laboratory, which is so far tackling problems in fundamental physical sciences and technology sciences, has got no section dealing with human relations. It has a Liaison Section, with an extensive staff which is maintaining day-to-day contacts with mills.

In ATIRA, we have got not only the co-operative effort of industry, but Government also contributes fifty percent to the incoming capital and recurring expenditure.

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rational research. We have plants, which might be 10 years, 20 years, 30 years, and even 100 years old. We have got mills with various types of machinery, we have the men, we have the technicians, and the management — this is a known situation which we cannot radically alter. How to deploy the machinery and the men most effectively to get the optimum result is really the basic question of Operational Research.

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I would like to mention that in some of these things nomenclature is important. When we talk of Research and Development Section, we must really emphasise research and development as a particular task to be done, in which specialists are co-operating with the production people. So much about the organisational structure and the relationship of the line and the staff. I would however like to emphasise one more thing. It is very necessary that there should be one person sufficiently senior in a mill organisation who is charged with the responsibility of this research and development section. Unless there is a very senior top man who is himself interested in making progress in the operational research, and who can convey to the line staff that operational research is something to be valued, I do not believe that the specialist by himself, can produce any results in a mill. I would therefore like to suggest that if mills do realise that operational research is an important thing for their working, it is absolutely essential that one senior man of management be made responsible for this very special activity.

When we start thinking in terms of research and development of a mill, the question arises as to the expenditure a mill should incur. In this connection I might be permitted to take a few minutes and find out where we stand in relation to our competitors. Often, when we talk of labour, we compare our labour standards with America or England, and feel dejected when we know the number of machines attended by an operative there. We also get awfully dejected about the quality of Indian cloth. But I believe it is worthwhile to see what has really contributed to the present position of America and England in the industrial field. (I am going to show you one of the slides that will make this point clear). In 1952, a detailed survey was made in England of 18 companies engaged in textiles that were sponsoring research and development within their own organisation. These companies put together spent approximately Rs. 50 lakhs annually, which amounted to 0.5% of their turn over. In addition, they were supporting co-operative research at the Shirley Institute. In 1950, this institute had a budget of Rs. 30 lakhs. In comparison, the budget of ATIRA in 1954 was about Rs. 10 lakhs, and the entire contribution from industry to ATIRA at present amounts to no more than 0.03% of its sales. Our effort therefore is insignificant, and I would like to put forward a plea to industry to ear-mark at least 0.3% of sales for research and development. Of this, approximately a fifth could be spent for co-operative research and the remaining for operational research within the mill organisation.

Let me illustrate with one concrete example. An average mill which is a member of ATIRA contributes Rs. 4,000 per year to ATIRA. This comes to .03% of the sales. If this was increased to 0.3% the mill would have a budget for research and development of Rs. 40,000 a year. It should contribute about Rs. 8,000 per annum to a co-operative research organisation, and the rest, that is, Rs. 32,000/- for Operational Research. A mill could therefore engage in its Research and Development Section a staff of a chemist, a person for physical testing, a statistician, a psychologist, and five investigators.

For larger units, it would certainly be worthwhile to have a more ambitious scale involving a greater number of specialists. I would, therefore, in concluding, say that we must sooner or later do something radical in our way of thinking of economics and realise that contribution to research and development is necessary if for no other reason than to stand in competition with others.

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STUDY OF THE ANISOTROPY OF COSMIC RAYS WITH NARROW ANGLE TELESCOPES

By V. Sarabhai, F.A.Sc., N. W. Nerurkar and P. D. Bhavsar
(Physical Research Laboratory, Ahmedabad-9, India)

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When appropriate corrections to remove terrestrial influences are applied to the daily variation of meson intensity, it shows up the anisotropy of the primary cosmic radiations as viewed by an apparatus fixed to the spinning earth. Early data relate almost exclusively to measurements made with ionisation chambers for study of the various types of time variations of cosmic ray intensity. In these, the instruments measure radiation from all directions and are therefore not particularly appropriate for study of the daily variation of intensity. Several later studies have been made with counter telescopes having directional characteristics. However in an effort to secure a high counting rate and good statistical reliability of the results, the telescopes generally subtend large angles and hence most of them ignore the requirements for a specialised study of the daily variation. From available determinations it has been in consequence erroneously assumed by several workers that the meson intensity at sea level does not exhibit a daily variation with an amplitude in excess of 0·2 to 0·4%. The notable exceptions to this way of thinking have been the Japanese group of workers and the group at Physical Research Laboratory, Ahmedabad.

Sekido and his co-workers have drawn attention in a series of papers[1,2,3] to the remarkable differences observed in the nature of the daily variation and its changes during periods of magnetic disturbance when measurements are made with vertical telescopes having semi-angles of 12°, 40° and 85°. Having concluded that the daily variation is better observed with narrow angle telescopes they[4] have conducted an experiment with a telescope having a semi-angle of 5° to determine sources of cosmic rays in the galaxy.

About three years ago experiments were commenced at Ahmedabad to determine the result of pushing the technique of narrow angle telescopes to what was considered a practical lower limit. Observations have been made by one of the authors (P. D. B.) with a triple coincidence telescope having a semi-angle of 1·8° in the E-W. plane and a semi-angle of 6·7° in the N-S. plane. The intensity relates to the component of cosmic radiation which can penetrate a minimum thickness of about 27 cm. of iron at sea level. The experiment was conducted from November 1952 to August 1953 and the mean bi-hourly rate was about 35 counts. The percentage mean daily variation is shown in Fig. 1. In view of the large probable error of each bi-hourly deviation, moving averages over three consecutive bi-hourly values

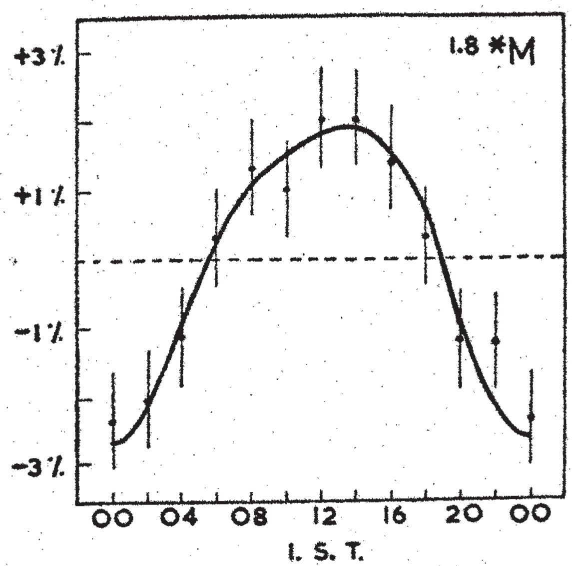

FIG. 1. Daily variation measured with $^{1\cdot8}$T.

have been taken. Harmonic analysis of the daily variation given by the bi-hourly percentage deviations from mean, before taking moving averages, shows that the diurnal amplitude M^D is $2\cdot2 \pm 0\cdot5\%$ and occurs at noon. The semidiurnal component with an amplitude of $0\cdot4 \pm 0\cdot5\%$ is not significant but has a negative correlation of $-0\cdot81$ with the semi-diurnal component of the daily variation of barometric pressure.

The large amplitude of the daily variation found in this experiment with a narrow angle telescope has prompted us to make a more elaborate study involving simultaneous measurements with telescopes of different angles. It was hoped thereby to determine with some precision the profile of the anisotropy of primary cosmic radiation and also to establish an optimum experimental technique for study of the daily variation of meson intensity.

In Fig. 2 we show the arrangement of counters in an experiment set up by one of the authors (N. W. N.). The apparatus furnishes triple coincidences from three independent telescopes $^{2\cdot5}$T having semi-angles of $2\cdot5°$, from tw

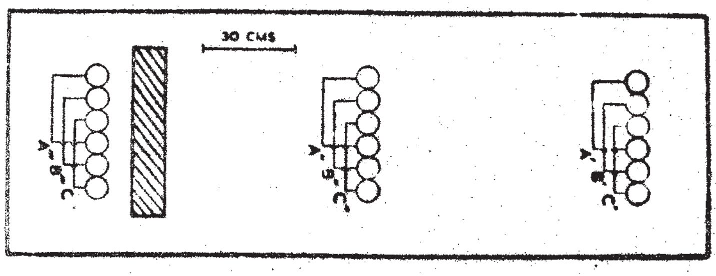

FIG. 2. Experimental Arrangement.

$^{2.5}$T —A′ A″ A‴, B′ B″ B‴, C′ C″ C‴.
^{5}T —(A′B′) (A″B″) (A‴ B‴), (B′C′) (B″C″) (B‴C‴).
^{15}T —(A′B′C‴) (A″B″C″) (A‴B‴C‴).
^{90}T —(A‴B‴C‴).

telescopes ^{5}T with semi-angles of 5° and from one telescope ^{15}T with a semi-angle of 15° in the E-W. plane. All telescopes have semi-angles of 19° in the N.-S. plane. In addition, the total rate ^{90}T from a battery of counters has been taken to give the omni-directional intensity. 12 cm. of lead has been used as shielding in every case. To increase the counting rate of telescopes without change of semi-angle, duplicate sets of counters are placed horizontally displaced from the first set, but connected with them in parallel. This introduces no error except for a negligible contribution from penetrating air showers.

In Table I are given details of the telescopes, their characteristics and period of operation. Since it is known that the daily variation of meson

TABLE I

Details of Telescopes

Telescope	$^{2.5}$T	^{5}T	^{15}T	^{90}T
Daily Variation	$^{2.5}$M	^{5}M	^{15}M	^{90}M
Semi-angle of Telescopes ..	2·5°	5°	15°	90°
No. of Telescopes ..	6	4	1	1
Period for which data available	1954 Jan.-May, Sep.-Dec. 1955 Jan.-March	1954 Jan.-May Sep.-Dec. 1955 Jan.-March	1954 Sep-Dec. 1955 Jan.-March	1954 Jan.-May Sep.-Dec. 1955 Jan.-March
Mean bi-hourly counting rate per Telescope	199	251 × 4	448 × 16	499 × 1024

intensity can alter with the passage of time, it is obviously necessary to compare the performance of the different telescopes over a period when all instruments have simultaneously been working. For such a period we show in Fig. 3 the mean percentage daily variations $^{2\cdot5}M$, ^{5}M, ^{15}M and ^{90}M, superposing the data of as many similar telescopes as have been simultaneously in operation. Figures 3 *a* and 3 *b* relate respectively to the daily variations before and after application of a barometric pressure coefficient $\beta' = -2\cdot2\%$ per cm. of Hg. The amplitudes and the times of maxima of the diurnal and the semi-diurnal harmonic components of the daily variations measured with different arrangements are given in Table II. The diurnal components are also shown on harmonic dials in Fig. 4. The values before and after correction for the daily variation of barometric pressure are shown alongside of each other, the former being indicated by asterisks.

The following features emerge from a comparison of the daily variations of meson intensity observed with the different types of instruments.

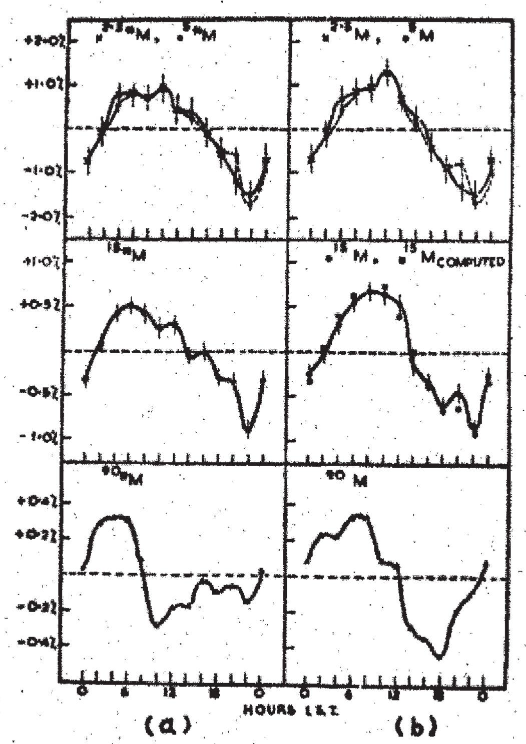

FIG. 3. Daily variations measured with $^{2\cdot5}T$, ^{5}T, ^{15}T and ^{90}T. Figures (*a*) and (*b*) relate respectively to values before and after applying correction for daily variation of pressure.

TABLE II

Percentage amplitudes and the times of maxima of the 1st and the 2nd harmonics of the daily variation measured with different telescopes

Daily Variation	${}^{2.5°}M$	${}^{2.5}M$	${}^{5°}M$	${}^{5}M$	${}^{15°}M$	${}^{15}M$	${}^{90°}M$	${}^{90}M$
Standard Error	±0·15%	±0·15%	±0·08%	±0·08%	±0·05%	±0·05%	±0·007%	±0·007%
M^D	1·05%	1·21%	0·96%	1·15%	0·44%	0·68%	0·21%	0·31%
$M\phi^D$	134°	133°	135°	134°	122°	121°	50°	80°
M^S	0·32%	0·13%	0·28%	0·06%	0·20%	0·02%	0·16%	0·06%
$M\phi^S$	114°	84°	133°	154°	133°	−82°	135°	−53°
γ	−0·950	..	−0·992	..	−0·999	..	−0·998	..
β	−0·30	..	−0·20	..	−0·20	..	−0·16	..

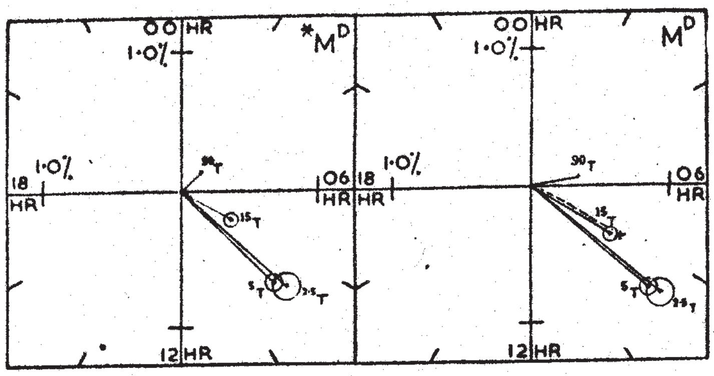

FIG. 4. Harmonic dials showing diurnal components of $^{2.5}M$, ^{5}M, ^{15}M and ^{90}M before (L.H.S.) and after (R.H.S.) applying correction for daily variation of pressure.

1. $^{2.5}M$ and ^{5}M are almost identical. They differ markedly from ^{15}M and again from ^{90}M.

2. The percentage amplitude of the diurnal component $^{2.5}M^D$ is slightly greater than $^{5}M^D$, but not significantly so. However the amplitude which is about 1·2% for the narrow angle telescopes, decreases rapidly for wider semi-angles beyond 5°, and is only about 0·25% for the omnidirectional intensity.

3. The time of maximum $M\phi^D$ of the diurnal component corresponds to about 0900 hours for $^{2.5}M$ and ^{5}M but becomes progressively earlier with wider semi-angles. $^{90}M\phi^D$ corresponds to about 0500 hours.

4. The semi-diurnal component of the daily variation does not alter as much as the diurnal component when measurements are made with the different instruments. There is an indication that the amplitude M^S decreases with increasing angle of telescope, but not to the same extent as M^D. The time of maximum is fairly constant.

5. There is high negative correlation between the semi-diurnal variations of meson intensity and of barometric pressure, the omnidirectional intensity having the highest correlation. The application of a uniform correction for the daily variation of barometric pressure using a coefficient $\beta = -2{\cdot}2\%$ per cm. of Hg, results in a virtual elimination of the semi-diurnal components in $^{2.5}M$, ^{5}M and ^{15}M. However ^{90}M is still left with a significant semi-diurnal component.

The choice of $\beta = -2{\cdot}2\%$ per cm. of Hg is dependent on considerations described elsewhere,[5] but it is not clear whether the application of the same coefficient to ^{90}T as well as to the narrower telescopes is fully justified.

It will be observed that in ${}^{2.5}$T and ^{5}T, the barometric correction with a co-efficient of this magnitude makes relatively little difference to the daily variation of meson intensity. Hence, there is likely to be no great ambiguity in interpretation on account of the operation of uncertain meteorological influences.

Computation shows that meson intensity incident on ^{90}T from directions inclined less than 5° from the vertical, makes a contribution of less than 1·0% to the total omnidirectional counting rate. Thus ^{90}M with a diurnal amplitude of 0·24% represents the integrated daily variation of intensity incident from all directions, and is little affected by the special features of the daily variation characteristic of intensity in directions close to the vertical. On the other hand ${}^{2.5}$M and ^{5}M indicate that the intensity which exhibits a large daily variation of diurnal amplitude 1·2% is confined almost exclusively to a narrow vertical cone of incidence with a semi-angle of about 5°.

If we assume that intrinsically there are two types of daily variations, the V-type characteristic of the vertical intensity and the O-type characteristic of the omnidirectional intensity, then we have V $\approx {}^{5}$M $-$ ^{90}M and O $\approx {}^{90}$M. These are shown in Fig. 5. ^{15}M is compatible with a superposition of the two types with appropriate weightage factors. This is clear from Figs. 3

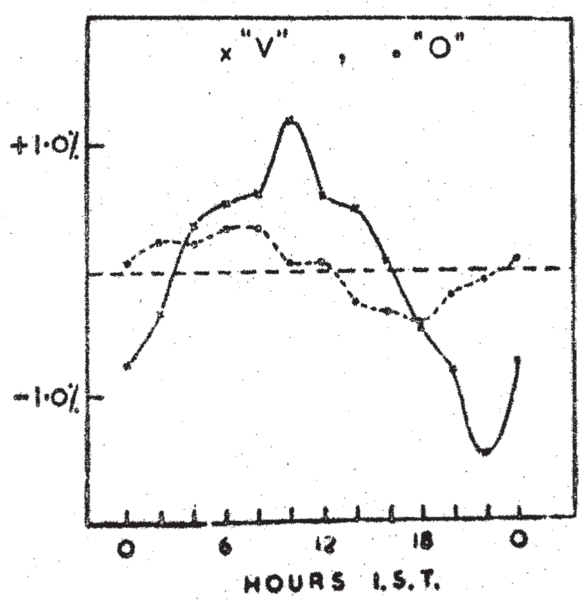

Fig. 5. The V and the O types of daily variations of meson intensity.

and 4 where we show the experimental and computed values of ^{15}M and its diurnal component respectively. The weightage factors have been evaluated from considerations of the geometry and dimensions of ^{5}T, ^{15}T and ^{90}T.

It is remarkable that there is sharp attenuation of intensity showing V-type of daily variation for incidence at angles exceeding 5° with the vertical. Simpson *et al.* have reported for local production of neutrons a daily variation comparable in amplitude to V. Since the nucleonic component of cosmic radiation, which is responsible for the local production of neutrons, gets rapidly attenuated with increasing zenith angle, the neutron monitor essentially measured vertical intensity. Thus a large amplitude of the daily variation appears to be a characteristic of a radiation, which can only penetrate to low levels of the atmosphere at small zenith angles. The main difference in amplitudes of the daily variations[6] observed with Simpson's neutron monitor and the Sitkus ionisation chamber could possibly arise from considerations of directional sensitivity of the measuring instruments rather than from difference in mean energies of primaries to which they respond.

It is important to understand the O variation and its origin. This is dependent on study with narrow angle telescopes pointing towards directions making different angles with zenith in the E.-W. plane. If, as appears likely, the O variation does not arise due to an integration of daily variations vastly different in character for different zenith angles towards east and west, we might be here dealing with a general modulation of the cosmic ray intensity. This would presumably occur near the top of the atmosphere but be under solar control.

Narrow angle telescopes open up a wide new field for experimental investigation of the anisotropy of primary cosmic rays. With low counting rates, data have to be averaged over an extended period to get significant results. Since the nature of the anisotropy changes, often radically, with passage of time, the averaging of the daily variations for several days is rather unsatisfactory. We can however, get around this difficulty by having simultaneous measurements with an array of several independent narrow angle telescopes. Work is now in progress along these lines and a report will be published separately.

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Solar Influence on the Anisotropy of Primary Cosmic Radiation. I. Studies at Low Latitudes*

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A study of the daily variation of meson intensity at low latitudes has been conducted with counter telescopes of identical design at Ahmedabad and at the mountain station of Kodaikanal. The analysis of the data shows that the semidiurnal component of variation, like the diurnal component, undergoes significant long-term changes. The appropriateness of a barometric coefficient applicable to the daily variation of meson intensity is discussed. Long-term changes of the daily variation reveal that these are due to the addition or attenuation of a day and a night contribution, both of which are principally diurnal in character and at Ahmedabad have maxima at about 1300 and 0300 hours, respectively.

For corroboration of these findings, data from 1937 to 1952, from the Carnegie Institution stations of Huancayo and Cheltenham have been analyzed. While at the equatorial station of Huancayo, the mechanism of change of daily variation is similar to what is observed at Ahmedabad and Kodaikanal, there are some differences in detail at Cheltenham, which lies in middle latitudes. There is evidence that some characteristics of the daily variation, notably the hour of maximum of the diurnal component and the amplitude of the semidiurnal component, follow the eleven-year solar cycle of activity. However, there is an indication that the nature of the composite daily variation, the hour of maximum of the semidiurnal component, and the pattern of addition and attenuation of the day and night contributions follow a 22-year cycle of change. The activity of the day and night contributions in relation to solar activity is discussed.

I. INTRODUCTION

THE current status of our experimental knowledge concerning the daily variation of meson intensity may be summarized as follows.

(1) It is now fairly clear that the daily variation of barometric pressure is the only terrestrial influence of importance which affects the daily variation of meson intensity. The mean daily variations of atmospheric temperature and of the heights of isobaric levels near the 100-millibar level are both of small magnitude.[1] On account of this, the atmospheric mass absorption effect appears as the principal factor in the total barometric coefficient applicable to the daily variation of meson intensity.[2]

(2) Barring rare exceptions[2–5] which are not yet reconciled, there is high negative correlation between the semidiurnal variations of meson intensity and of barometric pressure. It has been suggested by Sarabhai *et al.*[2,5] that the barometric coefficient derived from the relationship of the semidiurnal components of the daily variations can be applied to correct the daily variation of meson intensity.

The barometric coefficient so derived by them and applied to the daily variation of meson intensity at Ahmedabad is $\beta = -2.4\%$ per cm of Hg. Other workers have used a coefficient derived from day-to-day variations of meson intensity and of barometric pressure, and this coefficient, in general, has a value ranging from -1.5 to -3.0% per cm of Hg.

(3) The solar daily variation of meson intensity, corrected for barometric pressure, may be designated by M. It has, in general, only two principal harmonic components. The diurnal component may be specified by its percentage amplitude M^D and the local time of its maximum $M\phi^D$ expressed as an angle from midnight in a clockwise direction on a 24-hourly harmonic dial. Similarly the semidiurnal component may be specified by M^S and $M\phi^S$ respectively, in terms of a representation on a 12-hourly harmonic dial.

(4) The nature of M depends on the cone of incidence of the measured radiation and the orientation of the axis of the cone with respect to azimuth and zenith. It also depends on the mean energy of the measured radiation, the latitude, and the elevation of the place of observation.

* We are indebted to the Atomic Energy Commission of India for generous support.

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The amplitude M^D of the variation increases as the cone is made narrow.[5–7] M^D is larger at an equatorial mountain station than at stations at low elevation in high latitudes.[7,8] $M\phi^D$ is earlier at low latitudes than at high.[5,7,8] It becomes earlier still at low latitudes and at mountain elevations.[5,7] Directional studies[9–12] reveal that $M\phi^D$ at intermediate latitudes north of the equator is earlier for north azimuth than for south and for east than for west. M^S is present[12] for south azimuth but not for north to the same degree.

(5) M is known to change with magnetic disturbance. M^D increases and $M\phi^D$ is displaced to earlier hours on days that are magnetically disturbed.[13–16] In contrast to this, M^S decreases markedly.[17] The effect is more pronounced in narrow-angle telescopes than in instruments admitting radiation over a wide cone.

(6) M is known to undergo an annual change.[11,12,18–21] Several attempts have been made to identify in this a true seasonal variation and a distinct contribution of a sidereal time daily variation. However, the two effects are small and the facts have not been clearly established.

(7) M undergoes worldwide changes broadly in step with the eleven-year solar cycle of activity.[22,23] Changes of the time of maximum $M\phi^D$ are highly correlated at widely separated places on the earth.[24] Changes in M^D are not equally consistently correlated. The change of activity of solar coronal emission 5303 A is best related to changes observed in M.

(8) Changes in M have been shown to be related to changes in the nature of the daily variation of cosmic-ray neutron intensity.[25,26]

There is, therefore, weighty evidence to indicate the existence of an anisotropy of the primary cosmic radiation which is under solar control. Of the suggestions put forward to explain this, perhaps two have to be seriously considered. There is the possibility of continuous solar emission of particles of cosmic-ray energies.[22] Then there are processes[27] such as those suggested by Alfvén, by which emission of particles of inferior energy from the sun can disturb the isotropy of primary cosmic radiation, itself originating outside the solar system. Under certain circumstances, both processes may be operative. Further progress in our understanding of this important problem is now dependent on a closer examination of the finer features of changes in M occurring with time, and of the nature of M observed at different stations and under differing experimental conditions.

The influence of the anisotropy of the primary cosmic radiation on an apparatus fixed to the spinning earth is best observed with directional telescopes. A project was therefore commenced some years ago at the Physical Research Laboratory, Ahmedabad, for continuous measurement of the meson intensity with counter telescopes of standardized geometry at stations in low latitudes. One station has been in operation at Ahmedabad (latitude 23° 02′ N, longitude 72° 38′ E, geomagnetic latitude 13° N, altitude 180 ft above sea level) since September, 1950. Another was started in June, 1951 at the mountain station of Kodaikanal (latitude 10° 14′ N, longitude 77° 28′ E, geomagnetic latitude 1° N, altitude 7688 ft above sea level). A third has recently been started at Trivandrum (latitude 8° 30′ N, longitude 76° 55′ E, geomagnetic latitude 1° N, altitude sea level). Details of the apparatus and early results from the first two stations have been previously reported.[5] We are now able to present a more comprehensive picture of the daily variation of meson intensity at low latitudes. Changes in M observed during the past four years reveal new and interesting features and we have attempted to find corroboration for our findings in the Carnegie Institution data extending over a much longer period of time.

II. EXPERIMENTAL METHOD AND NOMENCLATURE

The standardized instrument, consisting of duplicate independent sets of two triple-coincidence counter telescopes in each set, has been described elsewhere.[2] The telescopes subtend a semiangle of 22° in the E-W plane and a semiangle of 37° in the N-S plane. Each counter tray has a sensitive area of about 600 sq cm and the mean bihourly rate of a telescope is about 3400 counts at Ahmedabad and about 4000 counts at Kodaikanal. The monthly mean solar daily variation of meson intensity is denoted by $*M$. It relates to the percentage bihourly deviations from the monthly mean cosmic-ray intensity measured with an absorber equivalent in thickness of lead from 7 to 15 cm. For

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TABLE I. Meaning of symbols.

M	The monthly mean daily variation of meson intensity, corrected for barometric pressure, and expressed as bihourly percentage deviations from monthly mean intensity.
P	The monthly mean daily variation of barometric pressure expressed as bihourly deviations in mm of mercury from monthly mean barometric pressure.
M^D	The percentage amplitude of the diurnal component of M.
$M\phi^D$	The time of maximum of M^D given by the angle in a clockwise direction between the direction of midnight and of the vector for M^D on a 24-hourly harmonic dial.
M^S	The percentage amplitude of the semidiurnal component of M.
$M\phi^S$	The time of maximum of M^S given by the angle in a clockwise direction between the direction of midnight and of the vector for M^S on a 12-hourly harmonic dial.
M_X	The determination of M made at station X. For the stations we use the following symbols: A—Ahmedabad, K—Kodaikanal, H—Huancayo, C—Cheltenham, C'—Christchurch, G—Godhavn.
$^*M$	The daily variation M before applying correction for barometric pressure.
$_{x.y}M$	Value of M for year x and month y.
$_{x.y}\bar{M}$	12-monthly mean value of M centered at year x and month y.
$^\circ M$	Smoothed M obtained by superposition of its first and second harmonic components.
$\Delta^\circ\bar{M}(x.y-x'.y')$	The difference between $_{x.y}{}^\circ\bar{M}$ and $_{x'.y'}{}^\circ\bar{M}$.

Ahmedabad and Kodaikanal, it is specified by $^*M_A$ and $^*M_K$, respectively.

Both at Ahmedabad and at Kodaikanal, one to four identical telescopes have been in operation at various times. $^*M_A$ and $^*M_K$ represent the mean daily variations of as many telescopes as were in operation on various days during each month. When a bihourly deviation from mean daily counting rate exceeds three times the standard error, the data for the particular telescope for the day are neglected.

$^*M^D$ and $^*M\phi^D$ signify the percentage amplitude and the angle corresponding to the time of maximum of the first harmonic or diurnal component of $^*M$. Similarly, $^*M^S$ and $^*M\phi^S$ relate to the second harmonic or semidiurnal component of $^*M$. β is the barometric coefficient that is applied to the data to correct for the influence of the daily variation of barometric pressure. The daily variation of meson intensity after applying this correction for barometric pressure is indicated by the corresponding symbols M, M^D, $M\phi^D$, etc. without asterisks.

The year and the month of the observation is indicated by small figures preceding the symbol. Thus $_{52.\mathrm{XI}}M_A{}^D$ indicates the percentage amplitude of the diurnal component of the mean daily variation of meson intensity at Ahmedabad during the eleventh month of 1952. The 12-monthly mean variation is denoted by $\bar{M}$. The year and month of the epoch at which this period is centered is indicated by small figures preceding the symbol. Thus $_{52.\mathrm{XI}}\bar{M}_A{}^D$ indicates the mean of 12 values commencing with $_{52.\mathrm{VI}}M_A{}^D$ and ending with $_{53.\mathrm{V}}M_A{}^D$.

Even though the number of telescope days differs from month to month, equal weight is given to the mean M for each month in calculating the 12-monthly mean $\bar{M}$. However, where there is complete absence of data in a particular month as at Ahmedabad in the month of August, 1952, the 12-monthly means involving this month relate only to data for eleven months instead of the usual 12 months.

In discussing the characteristics of the daily variation of meson intensity, it is advantageous to smooth out random irregularities in M. Since the main contribution to M is known to be due to only the first two harmonic components, we frequently derive a smoothed $^\circ M$ by building up bihourly percentage deviations from mean by superposition of the first and the second harmonic components.

Changes of the daily variation may be considered by looking at either the composite variation $^\circ\bar{M}$ or the amplitudes and times of maximum of its first two harmonic components. We express by $\Delta^\circ\bar{M}$ (49.VI −48.VI) the difference between 12-monthly mean daily variations centered at June, 1949 and at June, 1948. This is obtained by subtracting respective bihourly percentage deviations from mean for $_{48.\mathrm{VI}}{}^\circ\bar{M}$ from those for $_{49.\mathrm{VI}}{}^\circ\bar{M}$.

For the daily variation of barometric pressure, we use the letter P in place of the letter M. The conventions adopted in this terminology are summarized in Table I.

III. BAROMETRIC PRESSURE CORRECTION FOR THE DAILY VARIATION OF MESON INTENSITY

Sarabhai *et al.* have earlier drawn attention to the high negative correlation between the semidiurnal components of $^*M_A$ and P_A. On the assumption that the principal effect of an anisotropy of the primary radiation would be to produce a diurnal variation of the meson intensity, they attributed the semidiurnal variation entirely to the semidiurnal oscillation of the atmosphere. A barometric coefficient was then derived by them from the semidiurnal components of $^*M_A$ and P_A.

In Fig. 1, we indicate the 12-monthly mean values $^*\bar{M}^S$, $^*\bar{M}\phi^S$, $\bar{P}^S$, and $\bar{P}\phi^S$ centered at successive months. Figure 1 refers to observations made at Ahmedabad during the period October, 1950 to June, 1953, and to observations made at Kodaikanal from May, 1952 to June, 1954. The correlation coefficient r between the semidiurnal components of $^*\bar{M}$ and $\bar{P}$, and the apparent barometric coefficient β calculated from them, are also shown in the figure.

Since we are now considering 12-monthly mean values centered at successive months, seasonal changes would not be revealed. As is to be expected according to the theory of atmospheric tides, there is great constancy of the semidiurnal oscillation of barometric pressure represented by $\bar{P}^S$ and $\bar{P}\phi^S$. However, $^*\bar{M}^S$ and $^*\bar{M}\phi^S$ show significant and large changes. In consequence, r as well as the apparent barometric coefficient β undergo long term changes. At Ahmedabad, the correlation coefficient r ranges from -1.00 to -0.79 and β has values ranging from −4.6% to −2.1% per cm of mercury. At Kodaikanal similarly, values of r range from −1.00 to −0.93 and of β from −6.4 to −3.5% per cm of mercury. Since on physical considerations, it is difficult to imagine long term changes of the 12-monthly mean barometric coefficient of meson intensity, it is clear that contrary to our original belief, the semidiurnal variation of $^*M$ cannot be completely ascribed to the semidiurnal oscillation of P. We must conclude that there is a significant semidiurnal contribution in $^*M$ which is not of meteorological origin and may be ascribed to the anisotropy of primary cosmic rays. This agrees with the observation of Elliot and Dolbear[12] from directional studies made at Manchester. We can further state that like the diurnal component of $\bar{M}$, the semidiurnal component also undergoes significant changes with time. The observation by Sekido and Yoshida[17] of the change in the semidiurnal component of the daily variation of meson intensity during magnetically disturbed days fits in with this view.

Sarabhai *et al.*[5] have reported a nonsignificant positive value $r=+0.29$ for Kodaikanal for the data of 4 months from July to October, 1951. In Table II, we give the values of the three-monthly mean r and β at Kodaikanal. These have been obtained after taking moving averages of three successive monthly values of the semidiurnal components of $^*M_K$ and P_K. Not only are these three-monthly mean values subject to larger random errors than the 12 monthly means, but they also include 12-monthly changes in addition to long-term changes. The table reveals the interesting fact that there are periods during which r has a low negative value.

TABLE II. Correlation coefficient r and barometric coefficient β calculated from three-monthly mean values of the semidiurnal components of $^*M_K$ and P_K.

Period centered at	r	β% per cm of Hg
52.VI	−0.52	−1.5
VII	−0.91	−4.3
VIII	−0.96	−6.4
IX	−0.97	−6.1
X	−0.85	−4.3
XI	−0.79	−3.7
XII	−0.87	−5.1
53.I	−0.96	−7.1
II	−1.00	−7.1
III	−0.99	−5.9
IV	−1.00	−5.5
V	−0.96	−6.3
VI	−0.98	−8.0
VII	−0.98	−6.9
VIII	−0.90	−6.6
IX	−0.97	−4.5
X	−0.87	−5.0
XI	−0.73	−2.2
XII	−0.99	−1.8

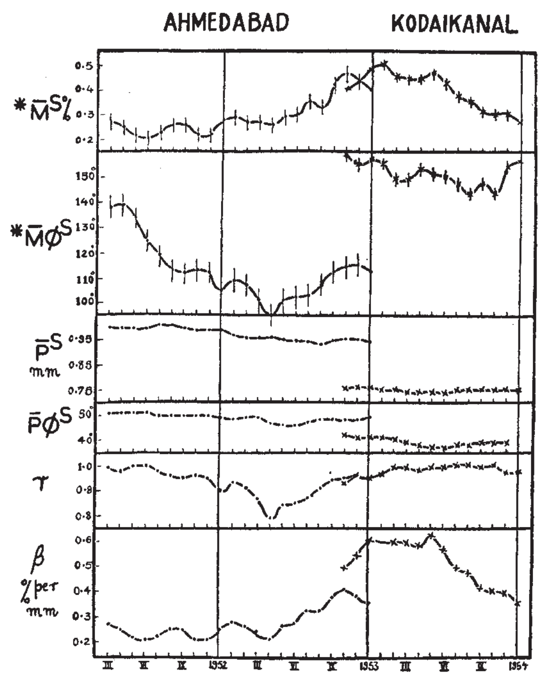

FIG. 1. Time series for 12-monthly means of (1) the amplitude $^*\bar{M}^S$ and the time of maximum $^*\bar{M}\phi^S$ of the semidiurnal component of meson intensity before applying correction for barometric pressure, (2) the amplitude $\bar{P}^S$ and time of maximum $\bar{P}\phi^S$ of the semidiurnal component of the barometric pressure, (3) the correlation coefficient r derived from the semidiurnal components of meson intensity and pressure, and (4) the barometric coefficient β derived from the same. The results at Ahmedabad are shown at the left side while those at Kodaikanal are shown on the right.

Our present work clearly demonstrates that the barometric coefficient β, derived from the semidiurnal components of $^*M$ and P, can be in error due to a semidiurnal contribution of the anisotropy of cosmic radiation. Experimental studies by Dolbear and Elliot,[28] Duperier,[29] and Trumpy and Trefall[30] and theoretical calculations by Olbert[31] reveal that β is related to a mass absorption coefficient μ, a decay coefficient μ', and a temperature coefficient α. Hence values of β alter as a result of variation in the pattern of changes in the vertical distribution of atmospheric temperature that accompany changes of barometric pressure.

While the daily variation of barometric pressure results from the diurnal heating of the layers near the ground and the excitation of resonant oscillations of the atmosphere, the nonperiodic changes of pressure are accompanied by quite different alterations of the temperature distribution of the atmosphere. On physical ground therefore, there is little justification to apply, to the daily variation, a β derived from day-to-day or nonperiodic changes of meson intensity and of barometric pressure.

In the absence of an experimental determination of a β appropriate for correcting the daily variation of meson intensity, we have to fall back on making an estimate of its value, partly on experimental and partly on theoretical considerations, from a knowledge of the

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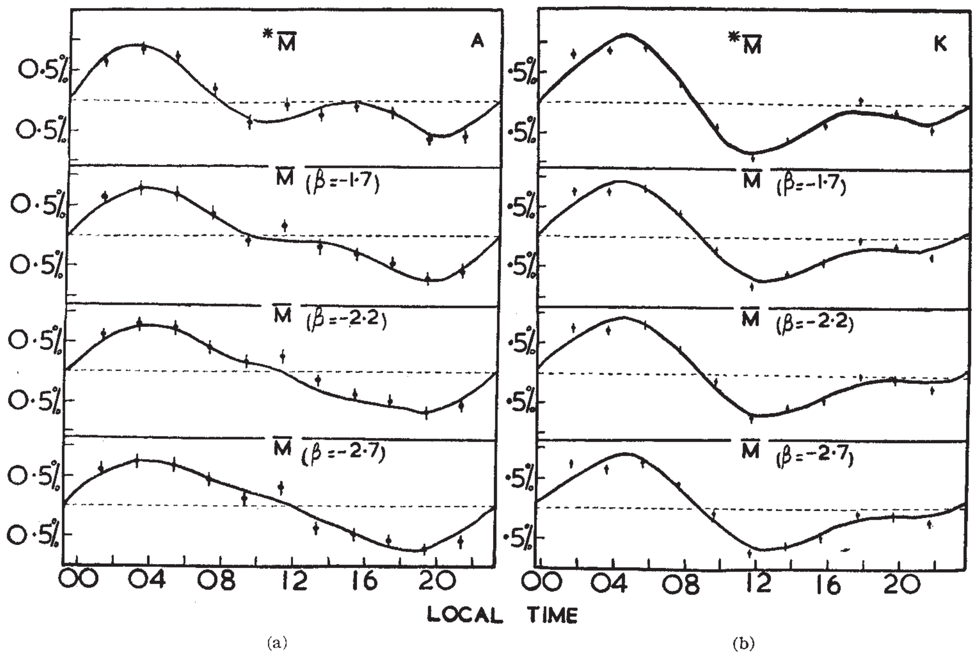

FIG. 2. The 12-monthly mean daily variation $*\bar{M}$ centered at December, 1952, before applying barometric correction and the same after applying barometric correction, using for β, the barometric coefficient, the values -1.7, -2.2, and -2.7% per cm of Hg. Figure 2(a) refers to Ahmedabad and Fig. 2(b) to Kodaikanal.

daily changes of temperature, barometric pressure, and heights of isobaric levels in the atmosphere. There is experimental evidence to indicate that the diurnal change of air temperature near the 100-millibar level is insignificant. Further, calculations by Nicolson and Sarabhai[32] show that due to atmospheric oscillation the amplitude of the vertical semidiurnal movement of isobaric levels near the 100-millibar level is no more than 12 meters at the equator.

There is therefore reason to adopt for the correction of $*M$ a β which has a negligible contribution of the temperature coefficient α, a small contribution of the decay coefficient μ', and a principal contribution from the mass absorption coefficient μ. Various determinations of these individual coefficients from studies of non-periodic changes of meson intensity and meteorological elements at different levels in the atmosphere have been made. These are shown in Table III.

Determinations of μ, μ', and α have not been possible either at Ahmedabad or at Kodaikanal on account of the absence of radiosonde data. We have however taken $\beta=-2.2\%$ per cm of Hg for the pressure correction of $*M$ at both places. The arbitrariness in making this choice is unsatisfactory. However, it is well to realize the implications of an error in making this estimate. In Fig. 2, we indicate for a 12-monthly period centered at December, 1952 the mean daily variation curves of $*\bar{M}$ as well as of $\bar{M}$ using barometric coefficients $\beta=-1.7$, $\beta=-2.2$, and $\beta=-2.7\%$ per cm of Hg. Figure 2(a) relates to Ahmedabad and Fig. 2(b) to Kodaikanal. Values of -1.7 and -2.7% per cm of

TABLE III. Absorption coefficient μ, decay coefficient μ', and positive temperature coefficient α.

Coefficient	Duperier[a]	Dolbear and Elliot[b]	Trumpy and Trefall[c] I[d]	Trumpy and Trefall[c] II[e]
μ% per cm Hg	−1.05	−2.07	−1.69 ±0.11	−1.49 ±0.14
μ'% per km	−3.90	−4.22	−4.45 ±0.53	−3.48 ±0.60
α% per °C	+0.12	+0.14	+0.036 ±0.021	+0.038 ±0.019

[a] See reference 29.
[b] See reference 28.
[c] See reference 30.
I[d] refers to hard componetn penetrating 10-cm lead absorber and II[e] to component penetrating 22-cm lead absorber.

[32] P. Nicolson and V. Sarabhai, Proc. Phys. Soc. (London) **60**, 509 (1948).

TABLE IV. First and second harmonics of 12-monthly mean daily variation of meson intensity at Ahmedabad, corrected for barometric pressure.

Year and month	$\bar{M}_A{}^D$ %	$\bar{M}\phi_A{}^D$	$\bar{M}_A{}^S$ %	$\bar{M}\phi_A{}^S$
51.III	0.22	174°	0.07	172°
IV	0.23	164°	0.05	$\pi+11°$
V	0.26	165°	0.02	$\pi+63°$
VI	0.27	153°	0.02	0°
VII	0.26	152°	0.04	44°
VIII	0.30	159°	0.08	60°
IX	0.28	164°	0.09	54°
X	0.24	157°	0.06	34°
XI	0.31	150°	0.08	45°
XII	0.38	141°	0.13	58°
52.I	0.40	130°	0.12	66°
II	0.47	130°	0.12	59°
III	0.46	121°	0.13	48°
IV	0.48	118°	0.16	40°
V	0.48	114°	0.16	55°
VI	0.53	116°	0.16	60°
VII	0.56	106°	0.11	56°
VIII	0.58	91°	0.16	76°
IX	0.72	91°	0.23	95°
X	0.74	89°	0.26	101°
XI	0.71	85°	0.23	100°
XII	0.66	88°	0.21	93°

Hg for β may be considered to be the reasonable limits within which the true coefficient applicable to the daily variation of meson intensity is expected to lie. This is because β is expected to be greater than μ, but less than the value of the barometric coefficient measured in day-to-day changes where all the three factors are operative. It is seen that at both places, the limiting values of β make little difference to the resulting $\bar{M}$. Without making a distinction between applicability to day-to-day changes and to daily changes, Forbush has justified the use of $\beta=-3.0\%$ per cm of Hg at Huancayo, and $\beta=-1.8\%$ per cm of Hg at Cheltenham, Christchurch, and Godhavn.

Until a better evaluation is possible, we consider it reasonable to apply $\beta=-2.2\%$ per cm of Hg to our data. In what follows, we have used this value for observations at Ahmedabad as well as at Kodaikanal.

TABLE V. First and second harmonics of 12-monthly mean daily variation of meson intensity at Kodaikanal, corrected for barometric pressure.

Year and month	$\bar{M}_K{}^D$ %	$\bar{M}\phi_K{}^D$	$\bar{M}_K{}^S$ %	$\bar{M}\phi_K{}^S$
52.X	0.60	52°	0.25	173°
XI	0.61	50°	0.27	165°
XII	0.64	57°	0.32	166°
53.I	0.76	56°	0.34	163°
II	0.78	46°	0.29	155°
III	0.82	41°	0.28	153°
IV	0.83	40°	0.28	159°
V	0.85	36°	0.30	156°
VI	0.84	36°	0.25	154°
VII	0.81	37°	0.21	151°
VIII	0.77	33°	0.19	144°
IX	0.78	28°	0.15	152°
X	0.79	29°	0.14	144°
XI	0.80	30°	0.14	168°
XII	0.82	29°	0.12	175°

IV. LONG-TERM CHANGES OF THE HARMONIC COMPONENTS OF THE DAILY VARIATION OF MESON INTENSITY, CORRECTED FOR BAROMETRIC PRESSURE

We have reported earlier[23] the characteristics of long-term changes in $\bar{M}^D$ and $\bar{M}\phi^D$ at the Carnegie Institution stations of Huancayo, Cheltenham, and Christchurch, and the relationship of these changes to the solar cycle of activity. Where M is measured with directional telescopes, the diurnal and semidiurnal components have greater amplitudes than are observed with ionization chambers and it is therefore of interest to look for similar changes in our data. In Tables IV and V we give values of $\bar{M}^D$, $\bar{M}\phi^D$, $\bar{M}^S$, and $\bar{M}\phi^S$ during the entire period of observation at Ahmedabad and at Kodaikanal. In Figs. 3(a) and 3(b), we show, with the aid of harmonic dial representation, the changes in the diurnal and semidiurnal components of $\bar{M}$ at the two stations. Because of shifting the laboratory at Ahmedabad towards the latter part of 1953, there is an unfortunate break of continuous data. 12-monthly mean values

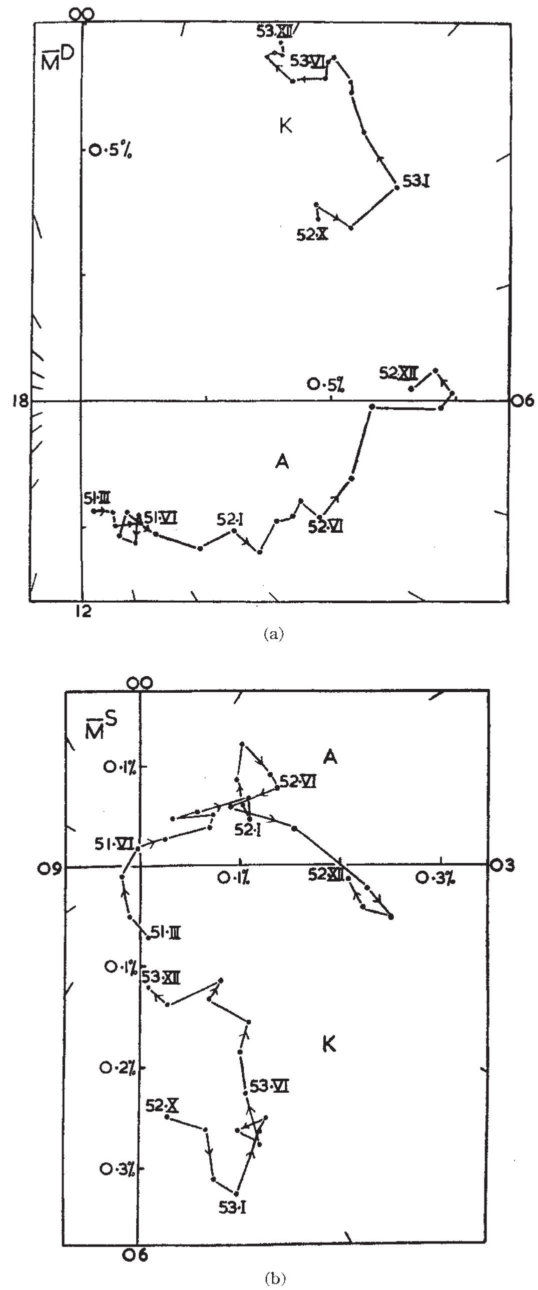

FIG. 3(a). Harmonic dial showing the movement of the first harmonic of the 12-monthly mean daily variation of meson intensity $\bar{M}_A{}^D$ at Ahmedabad and $\bar{M}_K{}^D$ at Kodaikanal. (b) Harmonic dial showing the movement of the second harmonic of the 12-monthly mean daily variation of meson intensity $\bar{M}_A{}^S$ at Ahmedabad and $\bar{M}_K{}^S$ at Kodaikanal.

at Ahmedabad are available for periods centered up to December, 1952, while at Kodaikanal they commence from October, 1952. Thus, even though the units at Ahmedabad and at Kodaikanal were simultaneously in operation for a period of 14 months, there is overlapping data for 12-monthly means for only 3 months. We are hence unable to compare the time series at the two places.

It is nevertheless interesting to observe in Figs. 3(a) and 3(b) that the amplitudes of the diurnal and semidiurnal daily variations at Ahmedabad and at Kodaikanal are comparable for the overlapping period centered at December, 1952. However, the diurnal time of maximum is about two hours later and the semidiurnal time of maximum about three hours earlier at Ahmedabad than at Kodaikanal. Comparison of some preliminary results[5] during 1951 had shown on the other hand that $M_K{}^D$ was significantly greater than $M_A{}^D$. $M\phi_A{}^D$ was then later by about one hour than $M\phi_K{}^D$, as it is during the present overlapping period of observation. The available evidence thus indicates that while the time of maximum of the diurnal component is earlier at the mountain station near the equator than it is at the sea level station at higher latitude, the amplitude is not always greater at the former location.

Carnegie Institution data[23] reveal that the changes of the diurnal time of maximum are worldwide in character. The correlation between time series for $\bar{M}\phi_H{}^D$ and $\bar{M}\phi_C{}^D$ from 1938 to 1952, is found to be +0.92. There is an overlapping period from March, 1951 to June, 1952 during which changes at Ahmedabad can be compared with changes at Huancayo and Cheltenham. In Fig. 4, the time series of $\bar{M}\phi_A{}^D$, $\bar{M}\phi_H{}^D$, and $\bar{M}\phi_C{}^D$ are shown for these 15 months. The scale for the time of maximum has been considerably expanded for the two Carnegie Institution stations. Curiously, during this period, Cheltenham does not exhibit the progressive decrease of $\bar{M}\phi^D$ that is so marked at the two stations in the tropics. Between the changes at Huancayo and at Ahmedabad there is indeed very close resemblance. The correlation between the two is +0.93. Changes in $\bar{M}\phi^D$ at the two stations can be related by means of the regression equation:

$$\delta(\bar{M}\phi_A{}^D)=2.8\delta(\bar{M}\phi_H{}^D).$$

This means that changes observed in the diurnal time of maximum are about three times as great at Ahmedabad, where a directional telescope is used, than at Huancayo where an omnidirectional ionization chamber records the meson intensity. The magnified changes observed with the counter telescope may well have been larger if the instrument was at a mountain station like Huancayo instead of being at sea level. It is clear from this evidence that changes of $\bar{M}\phi^D$ from different types of instruments cannot be directly compared. The putting together of data, on a common diagram without appropriate normalization, from counter telescopes and ionization chambers as has been done by Thambyahpillai and Elliot[24] is therefore not justified.

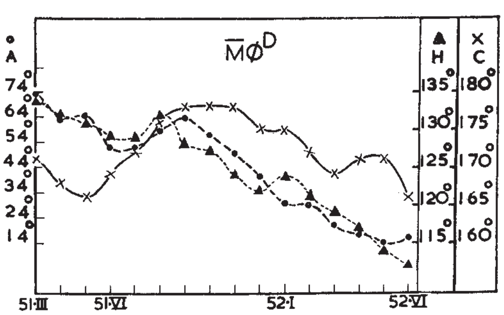

FIG. 4. Time series for $\bar{M}\phi^D$, the time of maximum of the first harmonic of the 12-monthly mean daily variation of meson intensity. The results from individual stations are indicated by ▲ for Huancayo, × for Cheltenham, and ● for Ahmedabad. The ordinate scale for the latter station has been compressed.

V. THE CHANGE OF 12-MONTHLY MEAN DAILY VARIATION OF MESON INTENSITY AT AHMEDABAD AND KODAIKANAL

The change taking place in $\bar{M}_A$ during the period March, 1951 to December, 1952 is quite remarkable. Reference to Table IV reveals that the notable increase of $\bar{M}_A{}^D$ from 0.24 to 0.70% is accompanied by an almost parallel increase of $\bar{M}_A{}^S$ from 0.07 to 0.21%. Simultaneously $\bar{M}\phi_A{}^D$ advances to an earlier time by as much

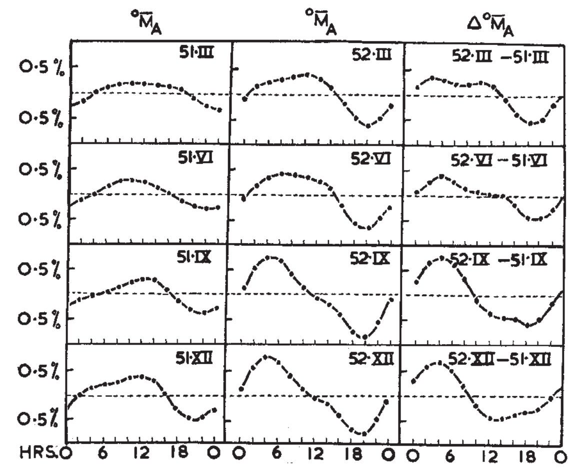

FIG. 5. The 12-monthly mean daily variation $°\bar{M}_A$ at Ahmedabad centered at successive epochs and the year-to-year differences $\Delta°\bar{M}_A$.

as six hours, and $\bar{M}\phi_A{}^S$ becomes later by nine hours. We can get a better insight into the phenomenon if instead of considering changes in the harmonic components of the daily variation, we look at changes in the nature of the unresolved daily variation after correcting for barometric pressure. We could for this purpose use $\bar{M}$, but in order to smooth out random fluctuations we use $\bar{M}°$ formed by the superposition of the first two harmonic components of $\bar{M}$. In Fig. 5, we show $°\bar{M}_A$ centered at successive epochs separated by 3 months. The 12-monthly changes $\Delta°\bar{M}_A$, also shown in the figure, relate to the difference between the 12-monthly mean curves $°\bar{M}$ at epochs separated by one year. Thus the 12-monthly change from ${}_{51.\mathrm{III}}°\bar{M}$ to ${}_{52.\mathrm{III}}°\bar{M}$ is expressed by $\Delta°\bar{M}(52.\mathrm{III}-51.\mathrm{III})$.

It is clearly seen that ${}_{51.\mathrm{VI}}°\bar{M}_A$ is mainly diurnal with a maximum at about 1100 hours. However, a new diurnal contribution is added to it with a maximum near 0300 hours, so that about 8 to 9 months later we have a double-humped curve. During the subsequent 6 months, the day time diurnal contribution gets attenuated and ${}_{52.\mathrm{XII}}{}^{\circ}\bar{M}_A$ has once again a mainly diurnal character but with a maximum in the early morning. From the curves for $\Delta^{\circ}\bar{M}_A$ shown alongside, it is seen that the radical changes taking place in $\Delta^{\circ}\bar{M}_A$ may be looked upon as caused by changes in the comparative magnitudes of two distinct contributions to the daily variation. These contributions are principally diurnal in character but each has a characteristic time of maximum which remains comparatively constant. The maximum of the first contribution occurs at about 0300 hours and of the second at about 1300 hours local time at Ahmedabad.

In Fig. 6 we show similarly the changes in ${}^{\circ}\bar{M}_K$ and $\Delta^{\circ}\bar{M}_K$ at Kodaikanal. During the period covered by Kodaikanal data, less violet changes have occurred than during the immediately preceding 18 months at Ahmedabad. In ${}^{\circ}\bar{M}_K$ for most of the period, only the maximum at about 0400 hours undergoes change of amplitude without an appreciable shift of the local time at which it occurs. In $\Delta^{\circ}\bar{M}_K$, we have evidence of an early morning diurnal contribution which has a maximum almost at midnight and a second much smaller diurnal contribution with a maximum near noon. Thus it appears that at Kodaikanal both contributions have maximum intensity at an earlier hour than at Ahmedabad.

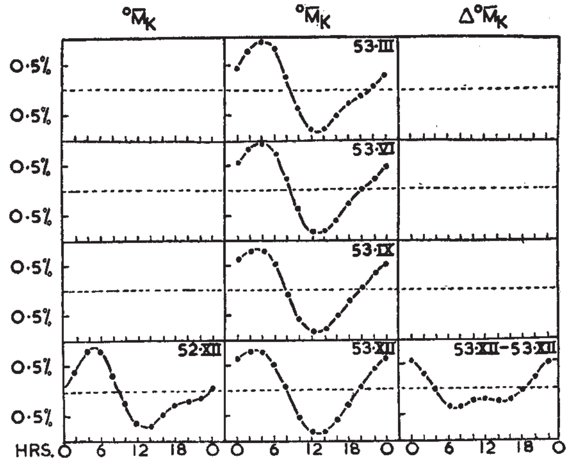

FIG. 6. The 12-monthly mean daily variation ${}^{\circ}\bar{M}_K$ at Kodaikanal centered at successive epochs and the year-to-year differences $\Delta^{\circ}\bar{M}_K$.

VI. CHANGE IN THE 12-MONTHLY MEAN DAILY VARIATION OF MESON INTENSITY AT HUANCAYO AND CHELTENHAM

In order to confirm the view we have reached about the manner in which ${}^{\circ}\bar{M}$ changes at Ahmedabad and Kodaikanal, we can examine Carnegie Institution data from 1937 to 1952. The long term changes in $\bar{M}^D$ and $\bar{M}\phi^D$ have been described by us elsewhere.[23] Figure 7 shows the time series for $\bar{M}^S$ and $\bar{M}\phi^S$ at Huancayo and Cheltenham. The change of 12-monthly mean relative sunspot number R is also shown therein.

With ionization chambers the semidiurnal component of the daily variation of meson intensity, corrected for barometric pressure, is small and in general not much significance can be attached to small changes in it. While this is consistently so at Cheltenham and Christchurch, which are in middle latitudes, substantial changes in the semidiurnal component occur at the equatorial station of Huancayo, where the figure clearly reveals a continuous trend over the years. $\bar{M}_H{}^S$ is generally greater during sunspot maxima than during years of low activity, and it follows approximately the variation of the relative sunspot number R. However, correspondence with the eleven-year solar cycle of activity which is so clearly discernible in the time series for $\bar{M}\phi^D$, is not visible in changes in the time of maximum of the semidiurnal component of the daily variation. On the other hand, $\bar{M}\phi_H{}^S$ shifts steadily to later hours by as much as 5 hours in the period 1938 to 1950.

In view of significant changes in the semidiurnal component at Huancayo, it is interesting to look at changes of the total daily variation ${}^{\circ}\bar{M}$. Figure 8 relating to the equatorial station of Huancayo reveals the most striking changes that take place from year to year in the 12-monthly mean daily variation of meson intensity ${}^{\circ}\bar{M}$. The variation which is predominantly diurnal in character with a maximum around noon in the period 1939–1941, has progressively a new component added to it in the following six to seven years. This component may be considered to have a predominant diurnal character but with a maximum around 0100 hours. During 1946–1948, as a result of the day and the night components being both present to an almost equal degree, the daily variation ${}^{\circ}\bar{M}$ appears as a double-humped curve. In the following years, the day component gets progressively attenuated with the result that in 1952 we are left once again with ${}^{\circ}\bar{M}$ which has mainly a diurnal character. However, the essential difference between this and the earlier curve of 1940 is that the maximum now occurs in the night instead of during the day. The period separating these two types of daily variation curves is about 11 years, but undoubtedly the cycle of change is not complete and at first sight it would appear that in this period we are only going through half the cycle. While there is in the time series for $\bar{M}\phi^D$ a period corresponding to the normal solar cycle of activity, the daily variation as a whole might still undergo a 22-year cycle of change.

Another interesting feature revealed in Fig. 8 is that while the time of maximum of the day component remains almost stationary near 1300 hours from 1937 to 1944, it shifts significantly to later hours during the period 1944 to 1948. The night component also follows a similar shift to later hours during 1944 to 1948.

The changes in ${}^{\circ}\bar{M}$ at Cheltenham, representative of a

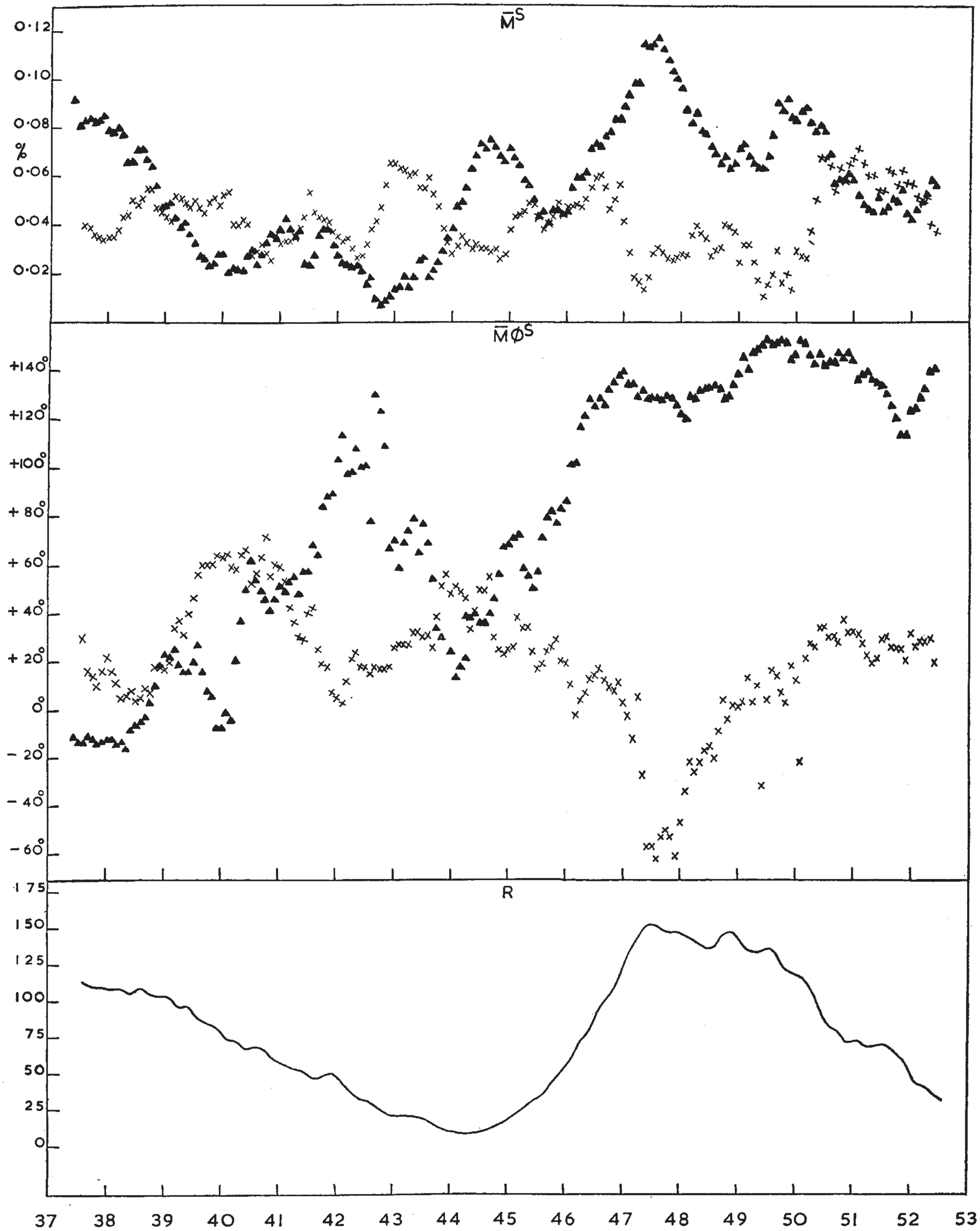

FIG. 7. Time series for the amplitude $\bar{M}^S$ and time of maximum $\bar{M}\phi^S$ of the semidiurnal component of 12-monthly mean daily variation $\bar{M}$, and of the Zurich relative sunspot number R. The results from Huancayo are indicated by ▲ and those from Cheltenham by ×.

station in middle latitudes are shown in Fig. 9. The changes are not as striking as at Huancayo. While $°\bar{M}_C$ never has a pronounced second maximum as is observed in $°\bar{M}_H$ during some years, noteworthy changes are seen to occur both in its magnitude and form. Since the semidiurnal component of the daily variation is small at

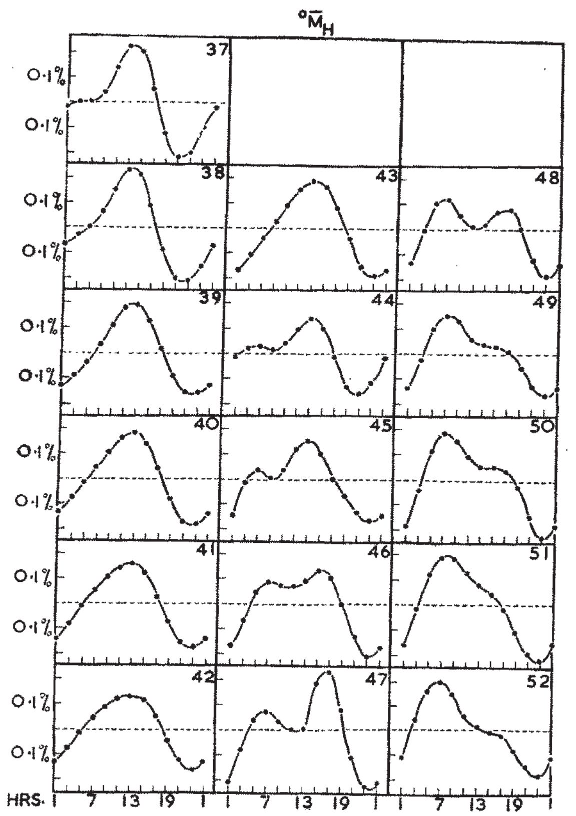

FIG. 8. The 12-monthly mean daily variations $°\bar{M}_H$ at Huancayo centered on June of each year, from 1937 to 1952.

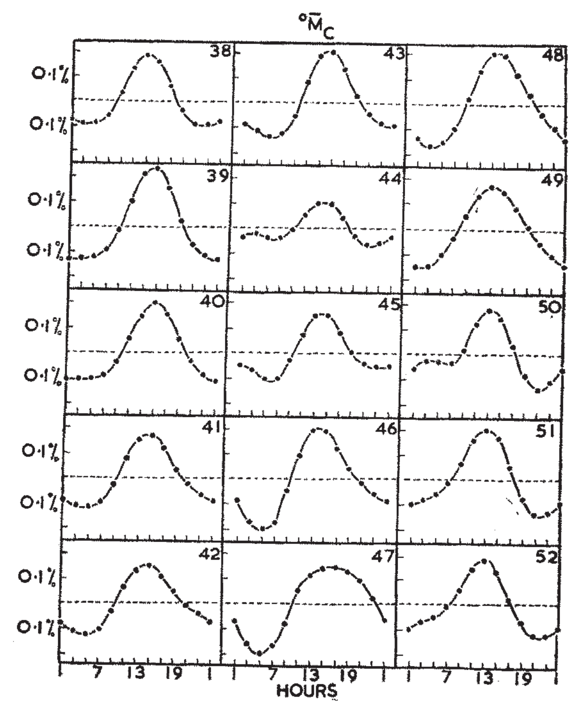

FIG. 9. The 12-monthly mean daily variations $°\bar{M}_C$ at Cheltenham centered on June of each year, from 1938 to 1952.

Cheltenham, it is of course to be expected that the observation of the changes in $°\bar{M}$ cannot be much more revealing than study of the changes of the amplitude and the time of maximum of only the first harmonic component of the variation.

We can now examine the year to year difference curves $\Delta°\bar{M}$ at Huancayo. These are shown in Fig. 10. We have seen earlier that there is reason to believe that the changes in $°\bar{M}$, at least at low latitudes, take place due to additions or subtractions of two mainly diurnal contributions, one having a maximum in the daytime and the other at night. To study the form of these contributions we take the year to year difference by subtracting $°\bar{M}$ for each year from the one for the preceding year. Normally therefore we have $\Delta°\bar{M}(\langle x+1\rangle.y-x.y)$. However, in periods where the contributions are getting attenuated, we get difference curves which are reversed in relation to the curves for the periods where the contributions are increasing from year to year. To facilitate visual comparison of the curves, we therefore take the differences $\Delta°\bar{M}(x.y-\langle x+1\rangle.y)$ wherever there is an indication that attenuation of the contributions is taking place. Such difference curves are drawn with dotted lines.

Figure 10 shows that at Huancayo, $\Delta°\bar{M}$ is composed of two contributions, one having a night and the other a daytime maximum, just as we have found at Ahmedabad and Kodaikanal. It may be argued that had we changed the sign of all our differences, we would conclude that the two contributions are at 0600 and at 1800 hours. Such a view can be legitimately taken if we look at only the difference curves $\Delta°\bar{M}$. However, if we wish to have a simple explanation of the $°\bar{M}$ curves also on the basis of similar contributions, we have clearly no choice but to reject this alternative manner of picturing the physical mechanism of the change of the daily variation of meson intensity.

VII. THE RELATIONSHIP OF CHANGE OF 12-MONTHLY MEAN DAILY VARIATION OF MESON INTENSITY WITH THE SOLAR CYCLE OF ACTIVITY

The year-to-year changes of $°\bar{M}_H$ are generally small and it is therefore advantageous to group together several years where there is indication of similar changes having occurred. By examination of Fig. 8 relating to Huancayo, it is clear that the entire period from 1937 to 1952 may be divided into six groups. The first group extends from 1937 to 1942 during diminishing solar activity. The second and third groups relate to the period 1942 to 1944 near sunspot minimum when violent changes have occurred in $°\bar{M}_H$. The fourth group extends from 1944 to 1947 during increasing solar activity and the fifth group to the period 1947 to 1951 when solar activity diminishes after reaching a maximum. The last group including the years 1951, 1952 represents the period just preceding sunspot minimum.

In Fig. 11(a) we show the difference curves representing the change of $°\bar{M}_H$ for the pairs of years at the beginning and end of each group. The mean relative sunspot number R for the years comprising each group is also indicated. As before, we have shown the difference curves with dotted lines whenever there is an indication that the day and night contributions are being attenuated.

It is seen from the figure that for the solar cycle extending from the maximum in 1937 to the maximum in 1947, with the exception of the period near the sunspot minimum from 1942 to 1944, there is in groups one and four a continued attenuation of the day and the night contributions. However, after the sunspot maximum in 1947, there is in group five an addition of the two contributions up to the year 1951 preceding the next sunspot minimum. With approaching sunspot minimum, there is first a period with only the day contribution. While this contribution is added in group two, it is attenuated in group six during the next cycle. Thus the pattern of change appears to be reversed on the completion of the first eleven-year period from sunspot maximum in 1937 to the following maximum in 1947. There may here be an indication that the addition and attenuation of contributions alternates in successive solar cycles of eleven years. Further data from Carnegie Institution stations would enable a confirmation of the important feature that the complete cycle of changes takes place in 22 years.

The changes described above may be compared with corresponding ones at Cheltenham by examination of Fig. 11(b) relating to $\Delta°\bar{M}_C$. There is same evidence of

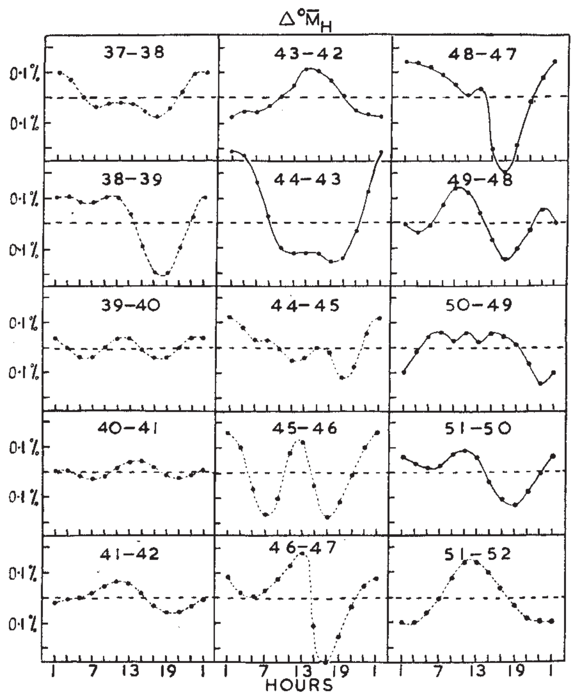

FIG. 10. The year to year difference curves $\Delta°\bar{M}_H$ representing the change in $°\bar{M}_H$ during successive years. Broken line curves indicate negative change with respect to those with full lines.

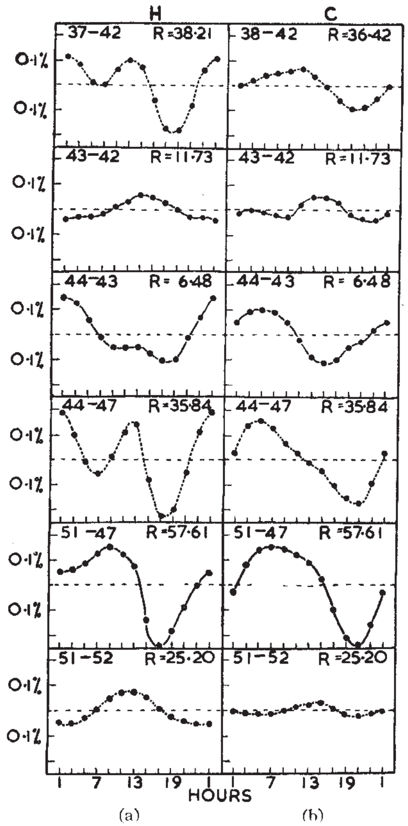

FIG. 11. The difference curves $\Delta°\bar{M}$ representing the change of $°\bar{M}$ for the pairs of years at the beginning and end of groups of years arranged according to solar activity. R gives the mean relative sunspot number for the years comprising each group. Figure 11(a) refers to Huancayo, and Fig. 11(b) to Cheltenham. Broken line curves indicate negative change with respect to those with full lines.

a night contribution at 0500 hours and a day contribution at 1500 hours. However, both contributions are more diffuse than at Huancayo and instead of characteristic double-humped curves, we observe distorted or broadened diurnal curves. The change of form of difference curves with solar cycle is broadly similar to what we observe at Huancayo.

We can see from the foregoing that there are three basic types of changes that take place in $°\bar{M}$. In the first type both contributions are active. In the second the day contribution is individually active, while in the third only the night contribution is active. The six groups discussed earlier can therefore be reduced to three by combining groups one, four and five; two and six; leaving three as before. Since we are interested in the form of contributions in each type, we neglect the question of their addition or attenuation and algebraically superimpose the curves as shown in Figs. 11(a) and 11(b). The values so obtained in each type are then divided by the number of year to year changes that are involved in the period covered by the type. Thus we finally obtain the form of the mean year-to-year change for each type. These are shown for Huancayo and for Cheltenham in Figs. 12(a) and 12(b).

It will be realized that the mean year-to-year difference curve of type 1 is an abstraction of what may be supposed to take place repeatedly over a period of years. In fact, there is not a uniform change every year by an amount corresponding to the curve shown. Reference to Fig. 10 reveals that the magnitude of the change is much greater in some years than in others.

The position of the maxima in the type 2 and type 3 curves correspond almost exactly with the two maxima of the type 1 curve. The concept of the day and the night contributions being responsible for the change of $°\bar{M}$ appears therefore to be well borne out. A further insight into the rapid and striking change from the activity of the day contribution to the activity of the night contribution approaching the year of minimum solar activity is obtained by following the changes in $°\bar{M}_H$ at epochs separated by three months. These are shown in Fig. 13, where we can clearly follow in $\Delta°\bar{M}_H$ the progressive attenuation of the day contribution and the addition of the night contribution over the period of 18 months. But this type of change occurs only near sunspot minimum, and for the rest of the solar cycle the two contributions are added or attenuated simultaneously. It is noteworthy that the amplitude of the mean year-to-year difference curve is greatest for type 3. There is great similarity of the difference curves at Huancayo and Cheltenham in types 2 and 3. However, the maxima in both types occur a little later by about 2 to 4 hours at Cheltenham than at Huancayo.

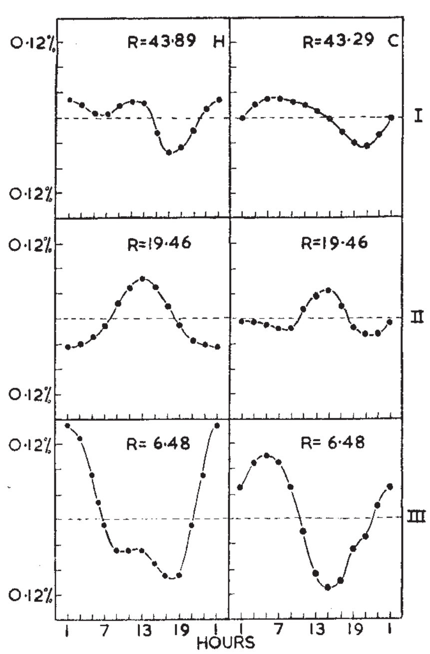

Fig. 12. Mean year-to-year difference curves representing three types of changes. Figure 12(a) refers to Huancayo and Fig. 12(b) to Cheltenham.

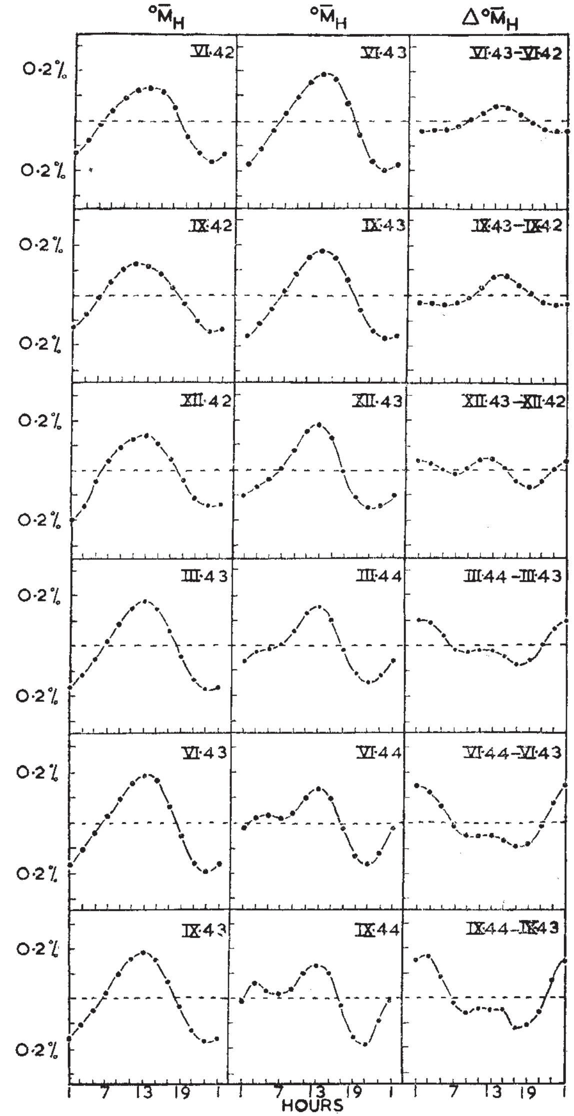

Fig. 13. Year-to-year difference curves $\Delta°\bar{M}_H$ at epochs separated by 3 months during a period of rapid change in $°\bar{M}_H$ at Huancayo.

VIII. CONCLUSIONS

The study of the daily variation of meson intensity with counter telescopes at low latitudes has revealed new and important features which have a bearing on its interpretation. These may be summarized as follows:

(1) The semidiurnal component of the daily variation of meson intensity is not only due to the semidiurnal variation of barometric pressure, but also arises from the anisotropy of the primary cosmic radiation. Instances[3,5] where the correlation between the semidiurnal components of $*M$ and P is positive may therefore arise when the semidiurnal effect of the anisotropy is in opposition to and larger than the semidiurnal effect of the change of the barometric pressure.

(2) There is no satisfactory experimental determination at the present moment of β, the barometric

coefficient that should be applied to the daily variation of meson intensity. However there is good reason to use a barometric coefficient of about -2.2% per cm of Hg in order to correct atmospheric influences. The daily variation so corrected can be ascribed to an anisotropy of the primary radiation.

(3) The semidiurnal component of $\bar{M}$, the 12-monthly mean daily variation of meson intensity after correcting for barometric pressure, undergoes significant long-term changes, particularly at low latitudes. It was shown earlier that the diurnal component of $\bar{M}$ also undergoes significant long-term changes.

(4) The examination of long-term changes of the amplitude and the time of maximum of only the first harmonic component does not reveal the true nature of the physical process which is operating. Similar is the handicap in looking separately at the changes of the amplitude and time of the maximum of the second harmonic component.

(5) It is important to consider changes of the daily variation $\bar{M}$ rather than of its harmonic components. However, in so far as $\bar{M}$ has generally only the first two harmonic components with significant amplitudes, it is convenient to deal with a smoothed $^{\circ}\bar{M}$ which is built by superposition of the first two components.

(6) Changes of $^{\circ}\bar{M}$ at Ahmedabad and Kodaikanal are suggestive of a mechanism which involves the addition or attenuation of two distinct daily contributions. Each is principally diurnal in character and while one of them has a maximum near midnight, the other has a maximum near noon.

(7) Changes of $^{\circ}\bar{M}_H$ at Huancayo, calculated from Carnegie Institution data from 1937 to 1952, reveal similarly the operation of day and night contributions. At Cheltenham also, there is some evidence of the two contributions, although the simultaneous action of both contributions is not as clearly seen as at stations in low latitudes.

(8) The activity of the two contributions is closely related to the solar cycle of activity. In general, the day and the night contributions are simultaneously added or attenuated. However, just preceding sunspot minimum there is a brief period when only the day contribution is active. This is immediately followed by a short period when only the night contribution is active. The pattern of addition and attenuation of the contributions appears to get reversed after 11 years.

(9) The amplitude of the semidiurnal component of $^{\circ}\bar{M}_H$ changes in a general way like the changes in the relative sunspot number R. Thus at low latitudes $^{\circ}\bar{M}^S$ and $^{\circ}\bar{M}\phi^D$ exhibit an eleven year cycle of change.

(10) The changes of $^{\circ}\bar{M}\phi^S$ and of $^{\circ}\bar{M}$ indicate that in eleven years perhaps only half the cycle of change is completed and the complete period may extend to 22 years.

(11) The changes of $\bar{M}\phi^D$ recorded by a counter telescope of moderate aperture are much greater than what are revealed by an omnidirectional instrument such as an ionization chamber. Thus in regard to both the magnitude of the daily variation as well as to its changes, an instrument with directional sensitivity offers advantages over one with omnidirectional characteristics.

The phenomological study of long-term changes of the daily variation of meson intensity has prompted a quantitative evaluation of changes of the day and the night contributions and their relationship with solar activity. The results of this analysis will be presented in a later communication.

Our grateful thanks are due to P. D. Bhavsar, N. W. Nerurkar, E. V. Chitnis, T. S. G. Shastry, and to the other research workers of the Physical Research Laboratory whose efforts have contributed to continuous cosmic ray recordings at Ahmedabad and Kodaikanal. K. A. Gidwani and S. R. Thakore have given valuable computational assistance. Comparison with unpublished data for the years after 1946 from Carnegie Institution stations would not have been possible but for the generosity of Dr. S. E. Forbush. We have used some early analysis in which Dr. R. P. Kane was associated.

Changes in the Daily Variation of Meson Intensity

By

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When Sarabhai and Kane[1] first reported long term changes in the daily variation of meson intensity measured by the Carnegie Institution recorders from 1937 to 1946, they drew attention to the worldwide nature of the changes and to their relationship with the solar cycle of activity. However, later extension of the analysis by Sarabhai et al[2] for data from 1946 to 1952 revealed that while the change of time of maximum of the diurnal component of the daily variation remained a worldwide effect through the entire period 1937 to 1952, the changes of amplitude of the diurnal component at Huancayo and Cheltenham were not correlated after 1946. Recently the present authors have reported[3] remarkable long term changes in the amplitude and the time of maximum of the semidiurnal component of the daily variation at Huancayo and Cheltenham. They have moreover emphasised that the study separately of the changes in the diurnal and the semidiurnal components of the daily variation does not reveal some important features of the physical process responsible for the changes. When the 12-monthly mean daily variations at Huancayo and Cheltenham during each year from 1937 to 1952 are examined, there is clear evidence that the changes are due to the addition or attenuation of a day contribution and a night contribution, each having principally only one maximum during 24 hours. While the night contribution has a maximum in the very early morning, the day contribution has one near noon. Normally both contributions are added or subtracted simultaneously during change from one year to another. However, just approaching sunspot minimum there is a year when only the day contribution is active in producing change. This is immediately followed by another year when only the night contribution is active. The pattern of addition or attenuation of the contributions appears to get reversed after a period of eleven years, so that the cycle of change is completed probably only in 22 years. A similar observation has been made by Thambyahpillai and Elliot[4] from another consideration.

With the mechanism of change described above, it is now possible to calculate and specify the extent of change $\Delta\overline{M}$ of the 12-monthly mean daily variation of meson intensity in terms of standard day and night contributions which are taken as units. We use here nomenclature explained by us elsewhere[3] in detail. Fortunately it is possible to derive the form and magnitude of the unit contributions from Huancayo data where the two contributions are more distinctly observed than at the middle latitude station of Cheltenham. Moreover the derivation is further facilitated because only the day contribution is active for the change from 1943 to 1942, or from 1952 to 1951, in the 12-monthly mean daily variations centered at June of each of these years at Huancayo. The mean of differences $\Delta\overline{M}$ (43.VI - 42.VI) and $\Delta\overline{M}$ (51.VI - 52.VI) is adopted by us as the unit contribution. It is specified by 12 bihourly percent deviations from mean intensity. [redacted] When the maximum positive deviation from mean is made to coincide with the hours 1100 or 1300, we designate the unit contribution by the symbols D_{11} and D_{13} respectively. Similarly, when the maximum is made to coincide with the hours 0100 or 0300, we designate the unit contribution by the symbols N_1 and N_3 respectively.

We then express the difference in the 12-monthly mean daily variations, centered at epochs x, y and x'y', in terms of unit day contribution D and unit night contribution N as follows :-

$$\Delta \overline{M} \ (xy - x'y') = aN + bD$$

For each difference $\Delta \overline{M}$, we determine the value of the coefficients 'a' and 'b' by conducting partial correlation analysis of $\Delta \overline{M}$ with either N_1 or N_3 and either D_{11} or D_{13}. The calculated curve for aN + bD is then correlated with $\Delta \overline{M}$ and the correlation coefficient r and the regression coefficient β are calculated. The choice between N_1 and N_3, and between D_{11} and D_{13} is made so as to give the highest values, approaching unity, for r as well as for β. In Table I we indicate for each $\Delta \overline{M}$ at Huancayo and at Cheltenham the most appropriate D and N, and the corresponding values of 'a' and 'b'. We also give values of r and β , which indicate how well the curve built up from the two contributions fits the experimental curve. The differences $\Delta \overline{M}$ are taken from epochs between which there is similar type of change occurring in $\overline{M}$ at both Huancayo and Cheltenham. It is satisfactory that the values of the coefficients r and β are never less than 0.83. Thus, subject to the maximum of the day contribution D and of the night contribution N each occurring at definite times constant to within 2 hours, it is seen that the two contributions can account for all features of the differences $\Delta \overline{M}$. It is to be noted that the pattern of addition and attenuation of the N and D contributions is a worldwide effect observable at equatorial as well as at middle latitudes. By considering the changes occurring in the daily variation in terms of N and D rather than i terms of the parameters of the diurnal and semidiur ponents of the variation, we are able to see the tr ide character of the changes.

It is questionable whether there is physical justification for allowing ourselves the freedom of shifting the maximum of each contribution by upto two hours, as we have done here by choosing N_1 or N_3 and D_{11} or D_{13}, to give the best fit with the experimentally observed change in $\overline{M}$. At Huancayo we always have N_1 for the night contribution. The day contribution is at D_{11} except during sunspot minimum when it appears to shift to D_{13}. At Cheltenham the behaviour is not so clear cut. It may be that there is a real shift of time of maximum of the day contribution by an hour or two during different periods of the solar cycle. However, the observed effect may just as well be caused by statistical uncertainty and by the lack of refinement in analysis.

We have used the same form of unit contribution for N as was derived for D. However the physical processes responsible for the two types of contributions may be quite different and the form appropriate for N may therefore be different from what we have assumed. The close agreement between $\Delta\overline{M}$ and the curve built up from N and D seems to indicate that if there is an error in this respect, it is small. However, a refinement of the present analysis may be possible by taking for N a slightly different form of unit contribution.

The present analysis demonstrates that the concept of day and night contributions is useful not only in understanding the physical basis of changes in the daily variation of meson intensity but in providing a means for quantitatively specifying such changes. We shall describe elsewhere in detail further implications of this study. We are indebted to the Atomic Energy Commission of India for valuable support.

Table 1.

$\Delta\bar{M}$		aN	bD	r	β
42-38	H	-2.20 N_1	-3.01 D_{11}	0.99	1.00
	C	-0.86 N_1	-1.76 D_{11}	0.96	1.00
43-42	H	+0.02 N_1	+0.78 D_{13}	1.00	1.03
	C	+0.65 N_1	+1.15 D_{13}	0.91	1.00
44-43	H	+2.50 N_1	+0.86 D_{13}	0.90	0.92
	C	+1.74 N_3	+0.40 D_{13}	0.83	0.99
47-44	H	-3.85 N_1	-3.60 D_{11}	0.96	1.00
	C	-3.66 N_3	-3.10 D_{13}	0.91	1.01
51-47	H	+2.80 N_1	+3.74 D_{11}	0.87	1.00
	C	+3.77 N_3	+4.61 D_{13}	0.91	0.85
52-51	H	+0.01 N_1	-1.22 D_{13}	1.00	1.00
	C	-0.02 N_3	-0.31 D_{13}	0.88	0.94

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TIME VARIATIONS OF PRIMARY COSMIC RAYS[1,2]

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I. INTRODUCTION

The subject of time variations of cosmic rays has grown in importance in recent years with increasing realisation that it will give some clue to the origin of cosmic radiation and of the electromagnetic fields in interplanetary and interstellar space. The close relationship of many of the variations with events occurring on the sun is of great interest in the understanding of solar physics.

A comprehensive review of the status of knowledge concerning cosmic ray intensity variations has been prepared by Elliot (1), but is now about four years old. In the intervening period since the article was written, important experimental as well as theoretical contributions have been made. While individual authors such as Simpson (2), Forbush (3) and Sarabhai *et al.* (4) have reviewed particular aspects of the field principally in the light of work of their own groups, a review of progress in the subject as a whole has not been published recently. It is therefore the purpose of this article to cover principally the period 1952 to the close of 1955, and in treating the subject take over generally from the point where Elliot stopped.

The majority of experimental results dealing with the time variation of cosmic rays relate to studies performed on the surface of the earth after the primary cosmic rays have suffered deflection in the geomagnetic field and interacted with matter in the atmosphere. While experiments made at high altitudes in aeroplanes and balloons reduce the intervening mass of atmosphere, it is nevertheless necessary to make allowance for terrestrial effects before one can interpret the variations in terms of the primary component of the radiation. The highly labourious determination of orbits of charged particles in the earth's magnetic field can now be successfully conducted by the use of modern computing machines, and by elegant analogue experiments using a model terella to represent the magnetised earth. Very significant progress has taken place during the past three years in our understanding of the diffusion of cosmic ray intensity in the atmosphere, thus making it possible to relate with some confidence the intensity of secondary particles measured under specific conditions with mean energy of the primary spectrum of the radiation. Moreover it is now possible to appreciate the role of meteorological factors on cosmic ray intensity. This is of particular significance for the meson component measured at low levels in the atmosphere and enables corrections to be made for variations of atmospheric origin.

[1] The survey of literature pertaining to this review was completed in March, 1956.

[2] The following abbreviations are used throughout the text: mb. = millibar; m.w.e. = meters water equivalent; L.S.T. = local sidereal time; UM region = unipolar magnetic region

This review therefore deals firstly with these advances which provide a background for the interpretation of studies on the time variations of primary cosmic rays.

The solar and sidereal daily variations of cosmic rays, which arise from solar and galactic anisotropies of the primary radiation as viewed from an apparatus fixed to the spinning earth, have often been referred to in literature without making a distinction with true variations of primary intensity. These daily variations are of interest in connection with the theories of origin of cosmic radiation and of electromagnetic fields in space. Furthermore, the solar anisotropy undergoes changes which are considered with other time variations of the radiation and we therefore devote a section of this review to current knowledge on the anisotropy of primary radiation where new experimental evidence has drastically changed some earlier concepts.

This brings us finally to the subject of time variations observed in primary cosmic rays. Here a mass of new experimental data have become available during the past two or three years. In this review we consider the time variations firstly from the standpoint of the time scale involved. Thus long term changes over periods of one or more years are grouped together. These are followed by an account of short term changes extending from one day to a year. Finally, we describe the solar flare effect which produces changes lasting for some hours. The division is primarily phenomenological in character and does not imply a common physical basis for the effects dealt with in each group.

We next discuss the interpretation of the variations with particular reference to their dependence on the mean energy of primaries, and to their solar and terrestrial relationships. We also consider the important question whether the different types of intensity variations represent increases or decreases or both kinds of changes. At the present moment there are a number of models which have been proposed to explain the established facts concerning cosmic ray time variations. It is impossible within the confines of this review to do adequate justice to all of them. The subjective approach of the authors is responsible for the emphasis on various alternative theories proposed. It is, of course, not claimed that there is unanimity of opinion amongst workers in this field concerning the views expressed in this and a later section of the review dealing with the implications of anisotropy and time variations on theories of the origin of cosmic rays.

2. ADVANCES IN ASSOCIATED FIELDS

2.1 Geomagnetic Effects

While early work on this subject by Lemaitre & Vallarta (5) and Stormer (6) involved labourious numerical calculations of the orbits of charged particles in the dipole field of the earth, the main concern of later investigators was to explain the experimentally observed geomagnetic effects such as the latitude effect and the azimuthal variation of cosmic ray intensity.

Through the use of Liouville's theorem and assuming isotropy of primary radiation it was possible to derive a satisfactory theory which no longer needed the calculation of individual particle orbits. A summary of the results is furnished in an admirable review by Alpher (7). However in the interpretation of the anisotropy of cosmic radiation, and of variations such as the solar flare effect where the isotropy of cosmic radiation is no longer observed, it becomes necessary to revert to a calculation of the orbits of charged particles.

We have to determine the asymptotic coordinates of the velocity vector of a charged particle of given rigidity which arrives in a given direction at a location specified in respect of its geomagnetic coordinates. Schluter (8) and Firor (9) have approached this problem by conducting numerical calculations with electronic computing machines and have confined themselves to primaries of energies extending up to 10 Bev for protons and therefore to observing stations in the middle latitudes. Brunberg & Dattner (10) by an experimental method have conducted a comprehensive investigation covering all primary energies greater than 2 Bev for protons and observing stations situated at different latitudes from equator to the poles. With a well collimated beam of electrons of specified but variable velocity emitted from a miniature gun mounted on a magnetised model of the earth, they have at each latitude determined the asymptotic coordinates of the velocity vector of particles of known rigidity which can arrive at specified angles with respect to zenith in the N-S and E-W planes at the observing station. The values of these coordinates can be read out from graphs published by these authors covering each 10° of latitude. From these coordinates they have prepared diagrams such as the one shown in Figure 1 relating to Kodaikanal on the magnetic equator, wherein the asymptotic coordinates can be read out for various rigidities and directions of arrival on a representation of the celestial sphere. A comparison of some of the results of the terella experiments with those derived from numerical calculations has demonstrated the great accuracy of the former. Brunberg & Dattner's study now forms a most valuable and essential basis for the interpretation of work not dealing with isotropic radiation. For most purposes their results are completely adequate. However, for certain effects it is desirable to have knowledge, which is presently not available relating to directions of arrival in azimuths other than in the E-W and N-S planes.

In the interpretation of high altitude balloon and rocket experiments one has to consider the appreciable contribution of the cosmic ray albedo, and interesting but as yet unpublished work in this direction has been conducted by Vallarta and his co-workers.

2.2 The Diffusion of Cosmic Rays in the Atmosphere

The discovery of new unstable particles and their alternative modes of decay indicates that complicated processes must come into play in the transition of the primary radiation to the secondary radiation observed at various

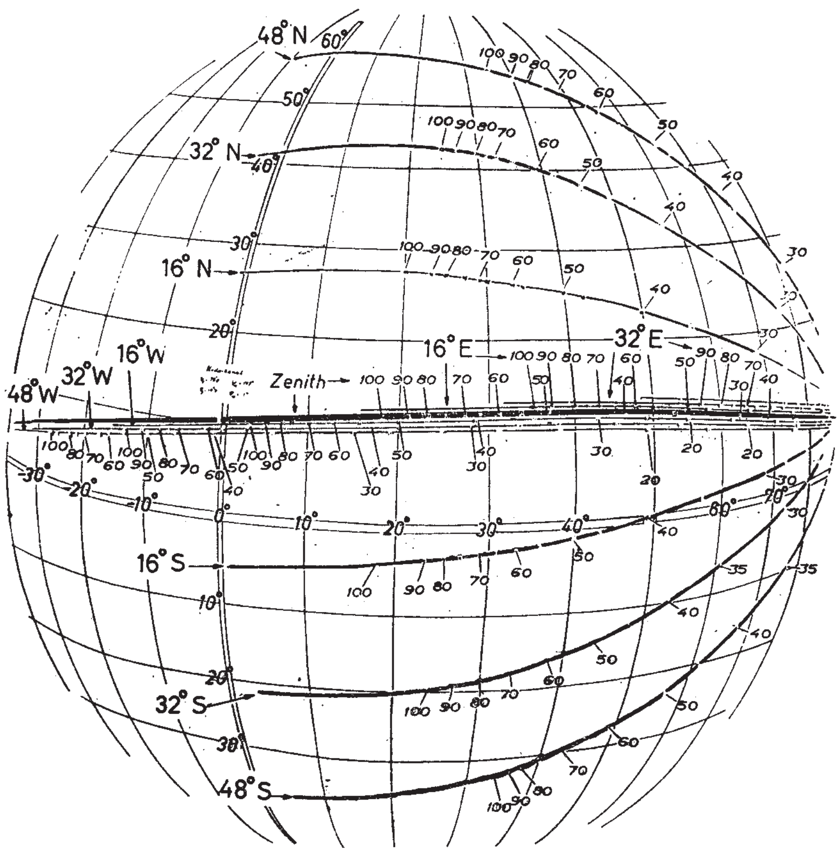

FIG. 1. Diagram showing the asymptotic coordinates of velocity vectors of protons incident at Kodaikanal (geomagnetic latitude 0.3°N). [Brunberg & Dattner (10)].

depths in the atmosphere. Estimates of the energy spectrum of primaries have been made by taking into account the total energy brought in by cosmic radiation at the top of the atmosphere at different latitudes. The primary spectrum has to be related through a specific yield or a generating function to the spectrum of secondaries which are measured at various depths of the atmosphere. Fortunately, for latitude sensitive primaries, it is possible by study of the latitude effect of the measured secondary component at different atmospheric depths, to derive this function without taking specific account of the intervening physical processes.

The latitude effect of the charged particle component at various altitudes in the atmosphere has been studied by the Pasadena workers (11), Pomerantz (12), Berry & Hess (13) and Rao *et al.* (14). Simpson (15) has compared the latitude effect at 310 g./cm.[2] depth for the nucleonic component as measured in a neutron monitor and for the meson intensity measured with a counter-telescope. His results are shown in Figure 2. From these data, various workers such as Treiman (16), Fonger (17), Nagashima (18), Dorman (19) and Olbert (20) have calculated the yield of secondaries in a particular energy range at specified depths in the atmosphere produced by primaries of specified energy. The most important conclusions may be summarised in the re-

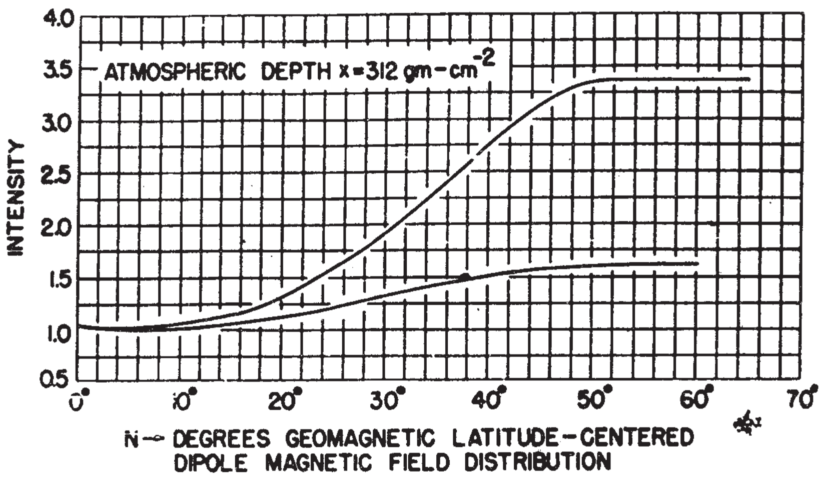

FIG. 2. The upper curve is the neutron latitude effect, the lower curve represents the charged particle component [Simpson (2)].

sults indicated in Figure 3 taken from Fonger. Reasonable extrapolation has been made in order to extend the results to primary energies beyond the latitude sensitive spectrum. The curves enable the intensity measured at 48° latitude in neutron monitors at mountain elevations and in charged particle detectors at sea level to be related to mean primary energy. It would be observed that the nucleonic component as measured by the local production of neutrons at Climax corresponds to a mean primary energy of 7.3 Bev, while the ionization chamber at sea level corresponds to a mean primary energy of 46 Bev. Dorman has made similar calculations and furnished figures from which can be read out the values of coupling coefficients for total ionizing intensity, hard component intensity and neutron intensity at sea level and the total intensity at 4300 meters altitude for the latitudes 0°, 30° and 50° up to primary energies of 1000 Bev.

Since the mean energy of primaries to which a neutron monitor responds is much lower than that for a meson telescope, the dependence of time variations on mean primary energy can be studied by comparing the changes ob-

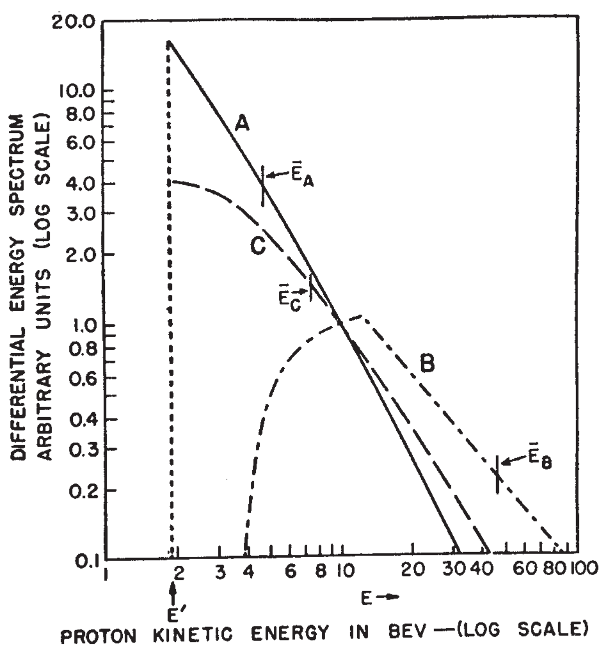

FIG. 3. Time average differential energy spectrum of primary protons arriving from the vertical at geomagnetic latitude $\lambda = 48°$ (Curve A) and the effective primary proton spectra in ionization chamber (Curve B) and neutron detector (Curve C) at the same latitude in the lower atmosphere. All three spectra are normalised to unit amplitude at proton kinetic energy E = 10 Bev. The mean energies of spectra A, B and C are $\bar{E}_A$, $\bar{E}_B$ and $\bar{E}_C$, respectively [Fonger (17)].

served in the two types of instruments. In making this comparison, allowance should be made for difference in the sensitivity of the instruments to radiation in inclined directions to the vertical and for the zenith angle dependence of the observed variation.

2.3 Variations of Atmospheric Origin

A great deal of effort has been devoted to study the effect of meteorological changes on cosmic ray meson intensity. By partial correlation analysis of day to day changes, Duperier was able to derive a regression equation

$$100 \frac{\Delta I}{I} = \alpha_P \Delta P + \alpha_H \Delta H + \alpha_T \Delta T$$

connecting the per cent change of meson intensity with the change of barometric pressure ΔP, the change of height of the 100 mb. level ΔH, and the change of temperature of atmosphere between the 100 mb. and 200 mb. levels. Duperier interpreted the barometer coefficient α_p as arising from a mass absorption effect, the decay coefficient α_H as arising from the change of survival probability of μ mesons when the mean height of meson formation alters, and the positive temperature coefficient α_T as arising from competition between the processes of $\pi-\mu$ decay and the nuclear capture of π mesons which depends on the density of the atmosphere near the level of creation of μ mesons. This equation and the physical meaning ascribed to the coefficients has met with two major difficulties. It was found that the values of the coefficients experimentally determined were not constant. They varied from period to period for the same instrument and they differed according to whether day to day or seasonal changes were considered. Furthermore there was a discrepancy between the lifetime for $\pi-\mu$ decay derived from α_T and what was estimated from other evidence.

Barret *et al.* (21) have pointed out that there is often a relationship bebween ΔH and ΔT. It is then not appropriate to treat these as independent variables. They suggest the adoption of a mean atmospheric temperature which is derived by a process of weighted averaging of the temperatures of successive isobaric levels from ground upwards. They have made observations at a depth of 1574 m.w.e. and since the contribution of $\mu-e$ decay was negligible for mesons corresponding to an energy at production exceeding 10^{11} ev, they were able to study the positive temperature effect arising only due to $\pi-\mu$ decay. They were then able to reconcile the observed positive temperature effect of 0.46 per cent per °C. with the calculated effect using for π mesons a mean lifetime $T=2\times10^{-8}$ seconds in conformity with evidence from other sources. Sherman (22) finds at a depth of 846 m.w.e. an α_T which is smaller than what was expected according to the calculation of Barrett *et al.* for an appropriate energy of μ mesons. Even though this constitutes some evidence for a $\kappa-\mu$ decay process he points out that within the statistical accuracy of the determination the value is not inconsistent with a $\pi-\mu$ decay scheme alone.

The differences in the estimates of α_H and α_T when meteorological changes of a day to day and seasonal character are considered, have been examined by a number of workers. Neglecting $\pi-\mu$ decay, and with a production spectrum of μ mesons as given by Sands (23), Olbert (24) has studied the change of survival probability of μ mesons. He has pointed out that even if the mean height of meson formation remains constant, the survival probability of the mesons depends on the distribution of mass along their path. If there is a proportionately greater mass encountered towards the end of the range, there is correspondingly a reduced ionisation loss and degradation of energy during the earlier part of the path of the meson, thus increasing the survival probablity in the atmosphere. Since there is often an increase of density in the lower layers accompanied by a decrease of temperature in these layers and an increase of temperature at high levels, this effect due to the change of distribution of mass in the atmosphere shows itself as an apparent positive temperature effect of the type observed by Duperier. Olbert has shown that such an effect can be as large as half the value of α_T observed by Duperier. Olbert has further demonstrated that when one considers a regression equation connecting ΔI with ΔH and ΔP only, neglecting the role of ΔT, the contribution of ΔT gets included in the term containing ΔH. As the relationship between ΔH and ΔT differs in seasonal and day to day changes, he was able to reconcile the apparent differences in the values of α_H when two different types of variations were considered by Elliot & Dolbear (25).

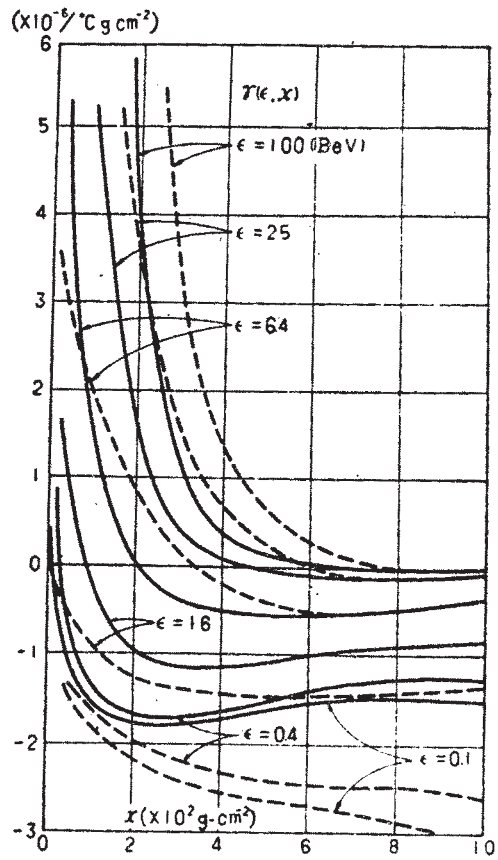

FIG. 4. The coefficient of partial temperature effect at different depths in the atmosphere [Maeda & Wada (26)].

Maeda & Wada (26) have extended Olbert's work by taking into account the process of $\pi-\mu$ decay. They have calculated the contribution to α_T of $\pi-\mu$ and $\mu-e$ decay processes taking into account the temperature variations at successive levels in the atmosphere. They find that the contribution of $\mu-e$ decay is almost constant irrespective of depth from the 50 mb. level downwards. However, the contribution of $\pi-\mu$ decay decreases exponentially with increasing atmospheric depth. They have presented the results graphically in a very convenient form as shown in Figure 4. It should be kept in mind that the values of α_T that one derives are to be used in conjunction with mass temperature of the atmosphere, and not with the temperature of individual layer as used by Duperier.

Hayakawa *et al.* (27) have extended the work of Maeda & Wada by considering the effect of nucleonic cascades on the production of μ mesons. They find that for the purpose of the $\pi-\mu$ decay process, it is more appropriate to consider the temperature of the 200 mb. level than the average temperature between 50 mb. and 200 mb. They furnish more accurate estimates than Barret *et al.* for the increase of α_T with increasing energy of μ mesons. The calculated values of α_T agree better with observations than the estimates of Maeda & Wada.

Trefall (28) has analysed the implications of various assumptions made in Duperier's regression equation in terms of the interpretation given to the coefficients that are derived from it. He points out that an apparent positive temperature effect can be obtained if the chosen level at which one considers ΔH differs from the true mean level of meson production. If for instance ΔH is taken in relation to the height of the 50 mb. level and the true mean level of production is below it, the distance between the true level of meson production and ground is not only controlled by the height of the assumed level of 50 mb. but by the temperature between it and the 50 mb. level. Thus an apparent positive temperature effect results from the change of survival probability of μ mesons. Thus Trefall was able to explain Duperier's observation that α_T was larger when ΔH was taken at the 50 mb. than at the 100 mb. level.

Trefall (29) has recently pointed out that the survival probability of μ mesons would alter with change of pressure due to ionisation loss. This loss would make a contribution to the barometric coefficient α_p just as Olbert had shown earlier that it would make a contribution to the temperature coefficient α_T. Thus the interpretation of α_p as being due to a pure mass absorption effect requires modification. Trefall estimates that up to a third of this coefficient may arise from the change of survival probability.

It is evident now that the regression equation of the type used by Duperier is inadequate to describe fully the atmospheric effects. In physical terms, his coefficient α_p includes effects due to mass absorption and $\mu-e$ decay, the coefficient α_H relates to $\mu-e$ decay while α_T relates to $\pi-\mu$ decay as well as to $\mu-e$ decay. Wada & Kudo (30) have suggested that by taking the height H to represent the difference between the height of mean level of meson production and an isobaric level near the ground, the mean temperature of the lower atmosphere is taken care of. Moreover this H is independent of sea level pressure. Using this H and a mean atmospheric mass temperature in conjunction with an appropriate temperature coefficient, a satisfactory modification to the original regression equation can be derived. This modified equation has the advantage of being applicable to diverse types of changes of pressure and temperature in the atmosphere, without requiring change of values of coefficients.

The correction of the daily variation of meson intensity for the removal of the effects of atmospheric origin has been considered by several workers. Sarabhai *et al.* (4, 31) have discussed the expected contributions due to daily variation of pressure, of heights of isobaric levels and of temperatures of various levels in the atmosphere. Except at very high altitudes the diurnal heating of the atmosphere is important only up to about 2 Km. above the ground. Near the mean level of meson production there is nonsignificant and small diurnal change of temperature or of the height of isobaric levels. The amplitude of the semidiurnal oscillation of the atmosphere at this level does not exceed a few meters even at the equator. Thus in the daily variation there is expected to be little contribution of the change of height of isobaric levels or of upper air temperature. Maeda (32) has also examined this problem from a number of different aspects. He concludes that there is a small diurnal variation of amplitude about 0.05 per cent with maximum at 1400 hours which he considers to be of atmospheric origin. This is in addition to the contribution of the barometric pressure.

The effect of meteorological factors on the nucleonic component is relatively less complicated than for the meson component where diffusion in the atmosphere involves unstable particles of short life time. Simpson *et al.* (33) have shown that the contribution to the counting rate of a neutron monitor from the local production of neutrons by π and μ mesons is negligible compared to the contribution of nucleons within the nucleonic cascade in the atmosphere. The temperature coefficient due to secondary mesons has been estimated to be less than -0.02 per cent per °C. at the equator and less than -0.006 per cent per °C. at the latitude of 50°. This leaves a mass absorption effect to be corrected for, and Simpson *et al.* have determined the value of 0.96 per cent per mm. of Hg in good agreement with the values reported by Adams & Braddick (34), van Heerdan & Thambyahpillai (35) and Rose & Katzman (36).

2.4 Anisotropy of Primary Cosmic Radiation

2.41 *Solar anisotropy*.—In the past there has been a great deal of misinterpretation of the experimental determinations of the daily variation of meson intensity. This has led to erroneous estimates of the anisotropy of the primary radiation. The daily variation was generally determined with instruments measuring intensity from as wide a range of directions as was possible. This helped to increase the measured intensity and reduce sampling errors. To improve the statistical significance of the determinations, it was customary to take the average of data extending over as large a period as was possible. A small effect with an amplitude of about 0.2 per cent was then observed. However, uncertainties in regard to corrections to be made for the daily variation of meteorological elements led many workers to question the validity of drawing any conclusions regarding the anisotropy of the radiation. Attempts were made by Malmfors (37) and by Elliot & Dolbear (25) to overcome this difficulty by making studies with directional telescopes point ing to two different directions inclined equally with respect to the vertical. From the difference observed in the daily variations in the North and South directions, it was concluded that there was an anisotropy of primary radiation. On assuming that the North telescope pointing to a fixed direction in space would not be affected by the anisotropy, the difference between north and south telescopes at stations like Manchester and Stockholm was erroneously interpreted as the daily variation corresponding to the anisotropy in the south direction. Sarabhai & Kane (38) have drawn attention to this and suggested that the observed N-S difference can arise from a geomagnetic effect.

As far back as 1950, experimental evidence was not lacking to show that an over-simplification was being made in dismissing evidence connected with the daily variation of meson intensity as being mainly due to effects of terrestrial origin. Ehmert & Sittkus (39) had revealed the difference in amplitude between the daily variations simultaneously measured by an ion chamber of omnidirectional sensitivity and by a vertical counter telescope having a more limited directional sensitivity. Sekido *et al.* (40) had pointed out that the amplitude of the daily variation increased from 0.19 per cent to 0.24 per cent when the semiangle of the measuring telescope in the East-West plane was reduced from 40° to 12°. During the past five years, a series of investigations have been made by workers at Ahmedabad with the object of studying the influence of experimental conditions, such as the characteristics of the apparatus and the latitude and elevation of the observing station, on the nature of the daily variation of meson intensity. Sarabhai *et al.* (4) have shown that at low latitudes the 12 month mean daily variation of meson intensity measured with telescopes with semiangles of 22° in the E-W plane had at different periods of time a diurnal amplitude of 0.3 to 0.8 per cent which is considerably greater than the amplitude observed with the ion chamber at Huancayo. As explained earlier a daily variation of meson intensity of comparable amplitude is hardly expected to be of atmospheric origin. Thus it was concluded that the observed daily variation could in fact be attributed to the anisotropy of cosmic radiation.

Sarabhai *et al.* (41) have conducted experiments where the reduction of the semiangle of the telescopes in the E-W plane may be considered to have been pushed to a practical lower limit. Conscious of the long term changes in the nature of the daily variation, these authors have taken care to ensure that comparisons are made only for data from instruments which have operated for a common period of time. Simultaneous measurements made with instruments with differing semiangles of opening from 15° to 2.5° in the E-W plane reveal a remarkable increase from 0.6 per cent to 1.2 per cent in the amplitude of the daily variation with decrease of semiangle from 15° to 5°. The daily variation measured with each apparatus is shown in Figure 5.

Firor *et al.* (79) have examined the daily variation of the nucleonic component measured with neutron monitors at different latitudes. Averaged over a large number of days, the daily variation has peak to peak amplitude of about 1.0 per cent which is comparable to the amplitude observed at low latitudes in meson telescopes of moderate semiangle. There is no great latitude dependence of the amplitude of the daily variation. In this respect experience derived from ion chambers of the Carnegie Institution is similar.

Working on the tenative conclusion that the daily variation of meson intensity, after making suitable correction for the barometric effect, can be related to the anisotropy of primary cosmic radiation which is under solar control, Sarabhai & Kane (42) tried to discover whether, as in the many other effects connected with the sun, there is any relationship of the 12

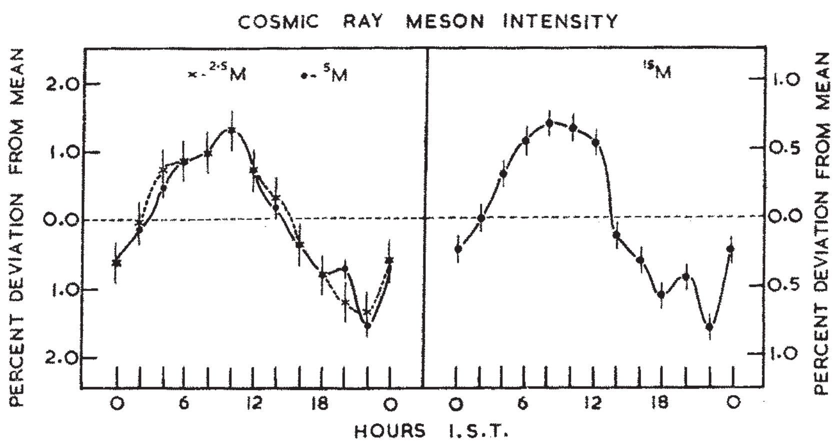

FIG. 5. Comparison of daily variations measured with telescopes of 2.5°, 5° and 15° semiangles in the E-W plane with 19° semiangle in the N-S plane in each case. Indian Standard Time (I.S.T.) is 40 minutes in advance of local time [Sarabhai, Nerurkar & Bhavsar (41)].

month mean anisotropy with the solar cycle of activity. The large changes first observed by them in the 12 month mean daily variation, which are discussed elsewhere in this review, constitute weighty evidence that the association of the daily variation of meson intensity with the anisotropy of primaries is substantially correct. It would indeed be difficult to associate any large contribution of atmospheric origin to the daily variation of meson intensity since meteorological elements are not known to undergo large long term changes of the type observed in cosmic rays.

Concerning the solar anisotropy of the high energy spectrum of the primary radiation, evidence is available from measurements made at great depths underground and with large atmospheric showers. The intensity of the measured radiation being very small, the statistical significance of the determinations is poor in most cases. MacAnuff (43) has reported at a depth of 60 m.w.e. an amplitude of about 0.2 per cent while Sherman (22) at a depth of 846 m.w.e. and Barrett *et al.* (21) at 1574 m.w.e. exclude the existence of a diurnal variation exceeding 1 per cent in amplitude. Farley & Storey (44) have shown that the daily variation has an amplitude of 1.4 per cent ± 0.25 per cent in investigations on large atmospheric showers. This confirms the absence in the primary spectrum extending upwards from 10^{12} ev of any large solar anisotropy which could produce a daily variation greater than one or two per cent.

The anisotropy of heavy primaries has been studied in balloon experiments by Anderson *et al.* (45), McClure & Pomerantz (46) and Yngve (47). The anisotropy of the very low energy spectrum has similarly been studied by Bergstralh & Schroeder (48) and Dawton & Elliot (49). The experiments are difficult to perform and present even greater difficulties of interpretation. While a daily variation as large as 25 per cent was reported by Yngve, other authors have failed to find a daily variation of amplitude larger than about 1.4 per cent. Since there is great variability of anisotropy from day to day, as is described later, observations made in balloon flights are not strictly comparable amongst themselves and with results reported from ground level stations which relate to the average of data over a large number of days.

2.42 *Galactic anisotropy.*—The study of the sidereal time variation of cosmic rays is related to the search for a galactic anisotropy in the primary radiation. If cosmic rays come from great distances, it would be most appropriate to examine the sidereal time variation of particles which travel almost with the velocity of light and constitute the very high energy region of the primary spectrum. Barrett *et al.* (21) at a depth of 1600 m.w.e. and Sherman (22) at a depth of 846 m.w.e. have estimated that the sidereal daily variation does not have an amplitude exceeding 2.0 per cent and 0.5 per cent respectively. With extensive air showers of primary energy greater than 10^{14} ev, Hodson (50) at Manchester reports an amplitude of 1.15 ± 0.61 per cent and a maximum at 2330 hours L.S.T. Daudin & Daudin (51) for an energy of 6×10^{14} ev indicate an amplitude of 0.39 ± 0.13 per cent at 2200 hours L.S.T. Cranshaw & Galbraith (52) indicate an amplitude of 4.9 ± 1.5 per cent at 1030 hours L.S.T. for an energy of 5×10^{16} ev but an amplitude less than 0.6 per cent for energy up to 10^{16} ev. The most significant result comes from Farley & Storey (44) from Auckland at 37°S. latitude. They get an amplitude of 1.5 ± 0.23 per cent at 1700 hours L.S.T., within half an hour of passage overhead of the galactic plane. The observation of the galactic centre is most favourable in the southern hemisphere and this may account for the discovery of the large sidereal time variation at Auckland. These results taken in conjunction with the observations at Manchester and the Pic du Midi and neglecting those of Cranshaw & Galbraith may be taken to indicate that there is now some evidence for an anisotropy along the plane of the Milky Way, and directed towards the galactic centre. However it is important to realise that in an investigation made by Clark (53) at Boston, no evidence could be found for the existence of any preferred regions or point sources from which there was enhanced intensity of cosmic radiation within the statistical significance of the observations. It is important to try to confirm the results at Manchester and at the Pic du Midi with more observations at Boston which is also at an intermediate latitude in the Northern hemisphere.

Sekido *et al.* (54) have reported remarkable results in their search for point sources with narrow angle alti-azimuth telescopes inclined to the vertical at 80° to 85°. They give the first reported evidence for a point source of cosmic radiation. The source is in the region of declination 0° and right ascension 5h 30m with an intensity which is 20 per cent of background intensity in the same direction.

3. TIME VARIATIONS

3.1 Long Term Changes of Primary Radiation

3.11 *Changes of total intensity.*—One of the most remarkable variations that has been discovered recently is the change of general intensity of cosmic radiation correlated with the change of solar activity of sunspot numbers. This change of 12 month mean intensity measured by the Carnegie Institution stations was shown by Forbush (3) and by Glokova (55) to be of the order of four per cent between sunspot minimum and sunspot maximum and to be present to almost an equal degree in all four stations ranging in latitude from the equator to 80°N. Figure 6 taken from Forbush demonstrates this

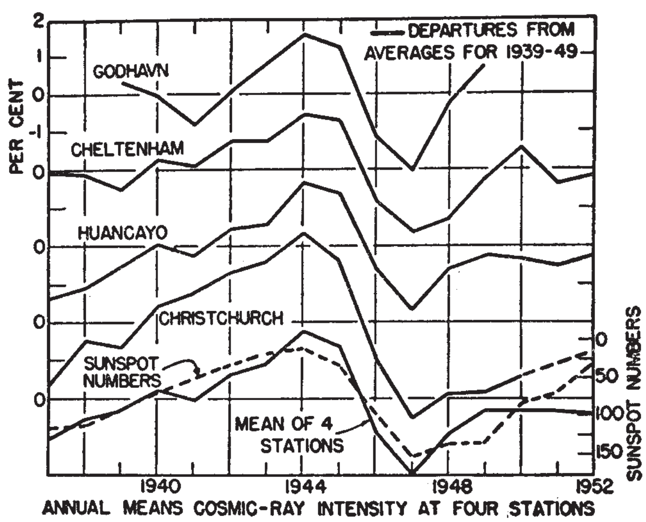

Fig. 6. Annual mean cosmic ray intensity at four stations [Forbush (3)].

change. Forbush has separated his data for magnetically quiet and disturbed days and shows that the change of intensity is present almost equally in both the groups. This is indicative of the fact that the change is not produced in a simple way by a series of magnetic storm type decreases occurring with varying frequency during different periods of the solar cycle.

Evidence of similar changes at high altitudes is provided by balloon experiments conducted by Neher (56). Corresponding to the change of only four per cent observed at sea level, Neher shows that at the latitude of 85° to 88°N. there was a change in total ionisation of about 50 per cent at an altitude of 70,000 feet from the sunspot maximum year of 1937 to the sunspot minimum year of 1954. Meyer & Simpson (57) in aeroplane flights at 30,000 feet have reported a change of 13 per cent in intensity measured by neutron monitors from 1948 to 1951 compared to a 1 per cent change observed at sea level.

Since high altitude experiments do not provide continuous data of the type that are available at sea level, it is impossible to follow the detailed trend of changes in the low energy component that can only penetrate at high levels of the atmosphere at intermediate latitudes. However, it is worthwhile to draw attention to the fact that flights made by Neher (58) at Bismarck in 1940, when the sun was by no means near the minimum of its activity, reveal an intensity in the upper atmosphere even greater than during the year 1954 of minimum activity. A possible solution of this difficulty has been suggested by Nerurkar by pointing out that while the solar activity during the flights in the years 1940 and 1954 was no doubt higher in 1940 than in 1954, there were periods about three months prior to the flights in each year, for which the solar activity was greater in 1954 than in 1940. Since the high altitude experiments refer to the intensity for a few days and not to the time average of intensity over a period of one year as taken by Forbush, it is conceivable that the anomaly referred to above may only be an apparent one, provided that there is a time lag of about three months between solar activity and changes of intensity. Nerurkar has looked for a time lag of this nature at Huancayo during sunspot minimum when it is expected to be most detectable because day to day fluctuations of cosmic ray intensity are not prominent. He finds that the correlation between monthly mean cosmic ray intensity and monthly mean K_p, indicative of solar activity in the equatorial plane, improves from 0.5 to 0.9 during 1944 and 1945 when the cosmic ray time series is shifted earlier by three months with respect to the K_p time series.[3] The above explanation must be considered tentative until it is confirmed by comparison over longer periods.

3.12 *Change of "knee" of the latitude effect.*—Neher (59) has summarized experimental data extending up to 1950 concerning the measurement of the latitude effect of cosmic rays at various altitudes. A most remarkable feature that emerged from these studies was the absence of a low energy component

[3] K_p is the geomagnetic three-hour-range index introduced by the International Association of Geomagnetism and Aeronomy. It is expressed on a scale of 28 steps and is currently computed from the K-indices of 11 magnetic observatories spread all over the earth. It gives a measure of disturbance in the earth's magnetic field over a three hour interval (IATME Bulletin No. 12e, 1951).

of primary cosmic radiation. The "knee" in the latitude effect indicated that beyond a latitude of about 55° there was no further change in the total cosmic ray intensity even at the highest altitudes that could be reached with balloons. The sharp cut off in the cosmic ray primary spectrum at an energy of about 0.8 Bev for protons corresponding to this "knee" has presented a difficult problem for interpretation.

In attempting to study the finer features of the latitude variation of intensity at high altitudes in high latitudes beyond the "knee," Neher *et al.* (60, 61) profiting by experience gained about the appreciable day to day changes in the intensity of cosmic rays, have since 1951 made simultaneous flights of balloon borne instruments at different latitudes. Thus they have developed a technique to study the "knee" independently of general fluctuations in cosmic rays. Determinations of the "knee" carried out by workers such as Pomerantz (12) and Van Allen & Singer (62) have not involved simultaneous observations at various latitudes and therefore are subject to an appreciable uncertainty as to the conclusions that can be drawn. Figure 7 from Neher shows the "knee" of the intensity versus latitude curves for an atmospheric depths of 15 g./cm.^{2} during 1937, 1951, and 1954. The figure illustrates clearly the shift of the "knee" to higher latitudes from 1937 to 1951. The low energy cut off for protons at 0.8 Bev during 1951 is absent during 1954 when a very large intensity of soft particles down to energies of 0.15 Bev for protons is measured and there is no evidence of a "knee." Meyer & Simpson (57) have reported that from 1948 to 1951, the "knee" of the latitude effect has shifted by 3° from 55 to 58°N. Simpson did not observe much change between 1951 and 1954, but since the results of Neher *et al.* show that this change was almost entirely due to the influence of particles, if protons between 0.15 and 0.8 Bev, it is to be expected that these would produce little effect at 30,000 feet altitude where Simpson's observations were carried out.

The investigation of very low energy particles in the range of 20 Mev to 170 Mev by means of single counters sent aloft in rockets has been done by Meredith *et al.* (63). At the present moment, interpretation of their results is beset with difficulties on account of uncertainty in the contribution of the albedo and of the geomagnetic effects as applied to streams of low energy particles at very high latitudes. Ellis *et al.* (64) point out that during 1953 there was a cut off for heavy primaries at about the same latitude as for protons. This indicates a cut off dependent on the rigidity rather than the energy of the primaries. The results, which require confirmation during other years, therefore favour a mechanism involving magnetic fields as being responsible for the cut off.

3.13 *Changes of solar anisotropy.*—Within the past three years large worldwide changes of the 12 month mean daily variation of meson intensity have been discovered by Sarabhai & Kane (42). By an examination of data from 1937 to 1946 of Forbush & Lange (69) they drew attention to correlated changes of amplitude and of time of maximum of the diurnal component of the daily variation at Christchurch, Cheltenham, and Huancayo. They pointed out the relationship of these changes with the 11 year cycle of solar activity and with the magnetic character figure, and showed that correlations improved during sunspot minimum. From this they concluded that the changes of daily variation were related mainly to activity in the equatorial belt of the sun. They also suggested that the anisotropy of the radiation was connected with continuous emission of cosmic rays from the sun, but this view does not now appear tenable in the light of further evidence to be discussed later.

Thambyahpillai & Elliot (65) have confined attention to the time of

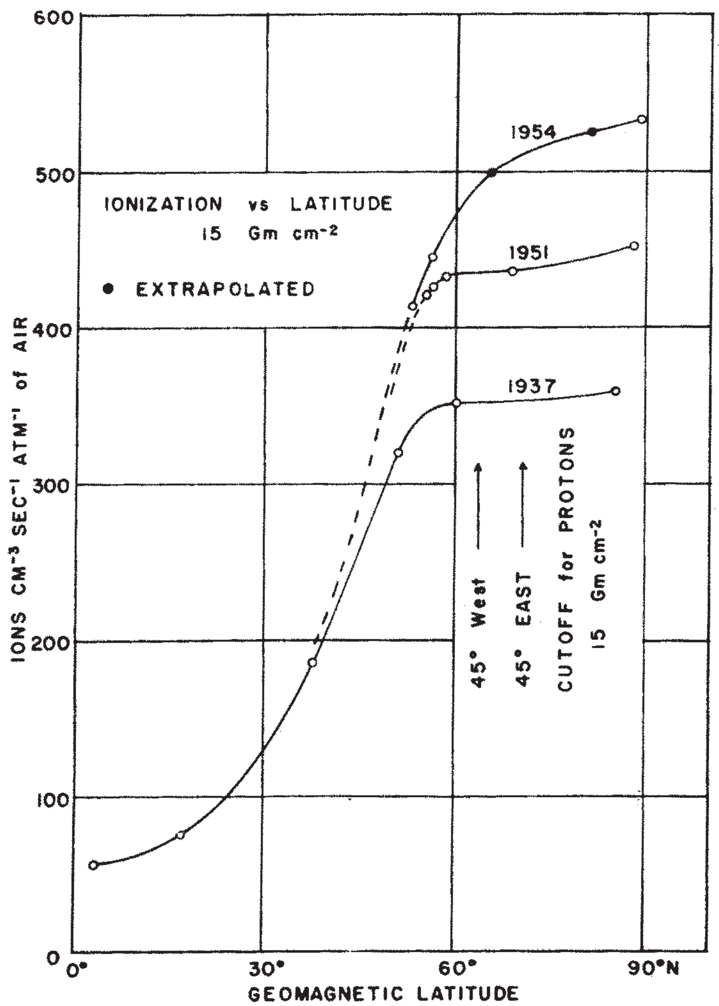

FIG. 7. Long term change of latitude effect at 15 gm./cm.^{2} atmospheric depth. Neher (56).

maximum of the diurnal component of the daily variation. After showing the correlated changes occurring in it at the Carnegie Institution stations, they have combined data from various sources to study the trend of change from 1932 to 1952. The data relate to different types of instruments and in putting them together no allowance has been made for a possible difference in the magnitude of the effect that would be recorded under the differing experimental conditions. However they were led to a general conclusion that the change probably followed a 22 year cycle of solar activity.

Steinmaurer & Gheri (66) have recently compared data taken over groups of years over the past 23 years. They show that during sunspot minimum in 1933, the time of maximum of the diurnal component was at about 7:00 A.M., comparable with the time of maximum about 20 years later in 1953–54, but was earlier than the time of maximum 11 years later in 1944. This indicates again a relationship with the 22 year cycle of solar activity. It is noteworthy that a maximum as early as 2:00 A.M. in 1954, has never before been observed.

Sarabhai *et al.* (67) have extended their earlier analysis of changes at the Carnegie Institution stations by examining further unpublished data from 1946 to 1953 supplied by Forbush. They find that while changes of amplitude at the different stations are not correlated in the new solar cycle, the changes

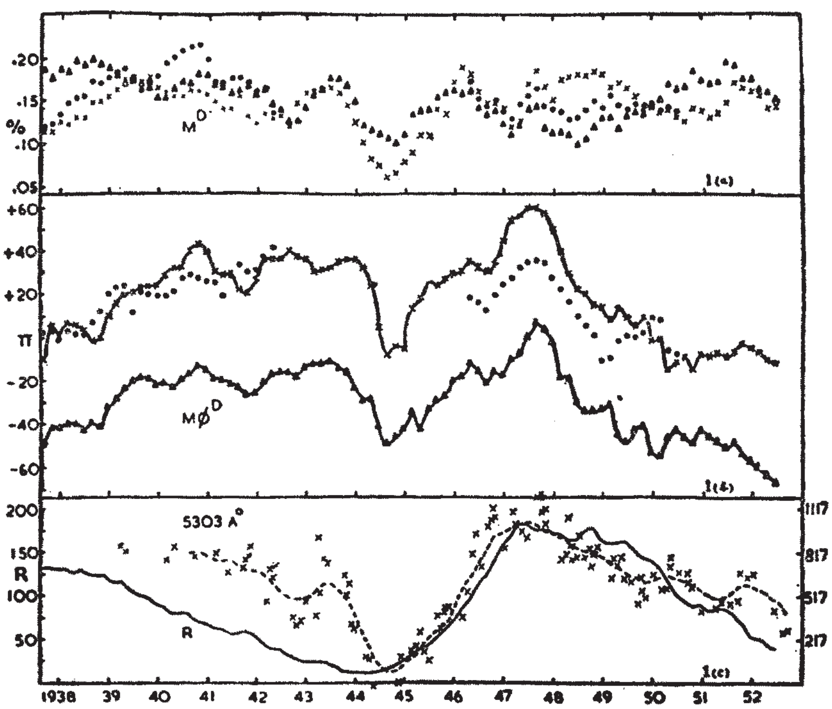

FIG. 8A

of time of maximum continue to exhibit worldwide characteristics. Furthermore they are better correlated with activity of 5303 Å coronal emission than with the relative sunspot number or the magnetic character figure.

The shift of time of maximum of the diurnal component has been shown

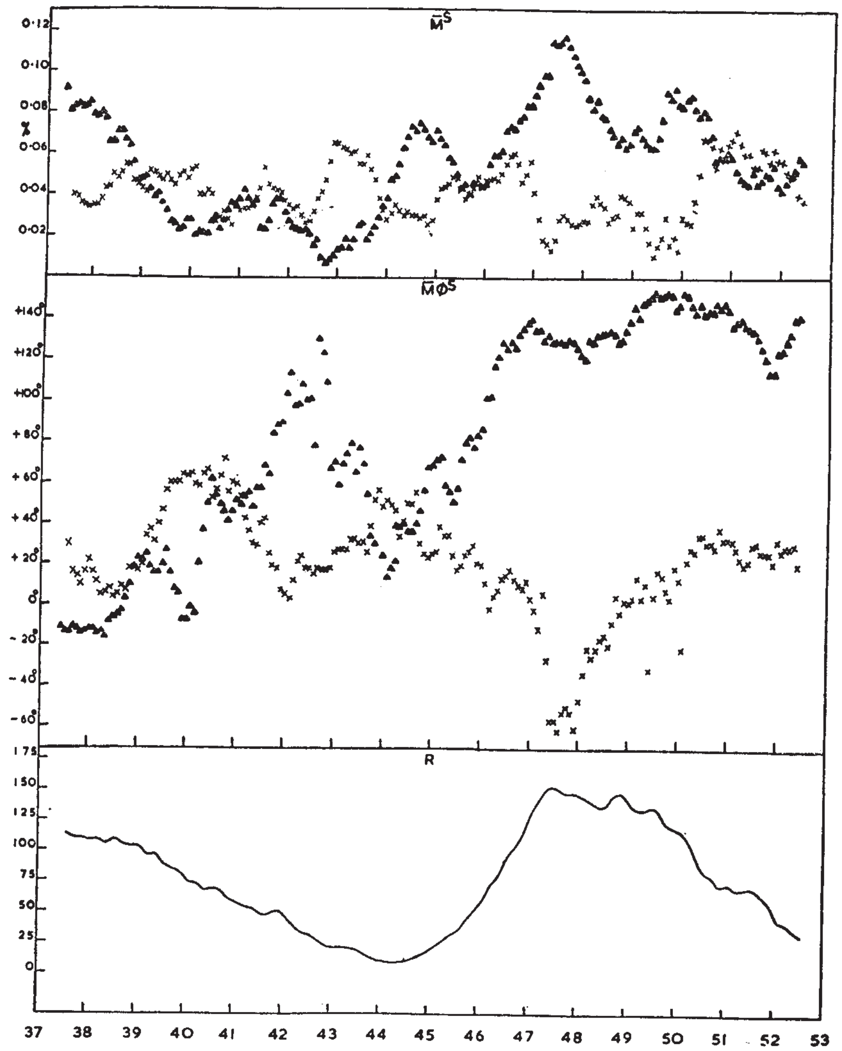

FIG. 8B

FIG. 8. Long term changes of diurnal component. (Fig. A, upper) and semidiurnal component (Fig. b, lower) of the daily variation at Huancayo (▲), Cheltenham (×) and Christchurch (●). M^D and M^S represent amplitude and $M\phi^D$ and $M\phi^S$ the times of maxima of the two components respectively [Sarabhai, Desai & Venkatesan (4, 67)].

by Sandstrom (68) to be independent of the direction of arrival of the particles and of the magnetic disturbance of the days characterised by K_p indices. Sarabhai *et al.* (4) have compared the changes in time of maximum of the 12 monthly mean daily variation studied simultaneously by an ion chamber at Huancayo and a vertical counter telescope at Ahmedabad. For these stations in low latitudes, the changes are well correlated for the short period considered, but the magnitude of the change with the counter telescope is about 2.5 times greater than the change with the ion chamber. Thus the semiangle of the detecting instrument influences not only the amplitude of the daily variation but the long term changes observed in the variation.

Sarabhai *et al.* (4) have demonstrated that in addition to long term changes in the diurnal component of the daily variation, significant changes also take place in the semidiurnal component. The changes occurring at the Carnegie Institution stations are shown in Figures 8(A) and 8(B) which relate to the diurnal and the semidiurnal components respectively. When the daily variation is considered as a whole instead of in terms of its harmonic components, a very remarkable sequence of changes is revealed as shown in Figure 9. At Huancayo, the 12 month mean daily variation which exhibits one maximum near noon from 1937 to 1943, changes over by 1952 to a variation exhibiting one maximum early in the morning. In the intervening period, there is clear evidence of the progressive increase of the early morning maximum followed by a decrease of the noon maximum. During the period 1945 to 1950 the daily variation therefore exhibits two maxima instead of one. Sarabhai and co-workers thus conclude that to follow the physical process of change of the daily variation, it is clearly necessary to discard individual consideration of only the diurnal component of the variation. The most appropriate manner of studying the changes is by examination of the daily variation unresolved into its harmonic components. As shown in Figure 9, only half the cycle of change appears to be completed in 11 years. This is again indicative of a 22 year cycle of change of the anisotropy.

Sarabhai *et al.* (4) have suggested that changes of the daily variation could be considered in terms of the contributions of two distinct types of variations. Both have one principal maximum. For the 'd' contribution the maximum occurs near noon and for the 'n' contribution at about 0300 hours. It has been shown by them that the pattern of addition or subtraction of the day and night contributions of the daily variation is worldwide in character and can satisfactorily explain the observed changes from year to year at Huancayo as well as at Cheltenham. The activity of the two contributions is closely related to the solar cycle of activity. In general, the day and the night contributions are simultaneously added or attenuated. However, just preceding sunspot minimum, there is a brief period when only the day contribution appears to be active. This is immediately followed by an equally brief period when only the night contribution is active. The pattern of addition and attenuation of the contributions appears to be reversed after 11 years.

3.2 Short Term Changes

3.21 *Magnetic storm type changes.*—Large worldwide decreases of cosmic ray intensity associated with magnetic storms have been reported in the past. These decreases have several remarkable features. All magnetic storms are not associated with decrease of cosmic ray intensity, and when effective storms take place, the ratio of change of magnetic field strength to the change of cosmic ray intensity is not constant from event to event. In storms such as the large storm on March 1, 1942, there is almost no latitude

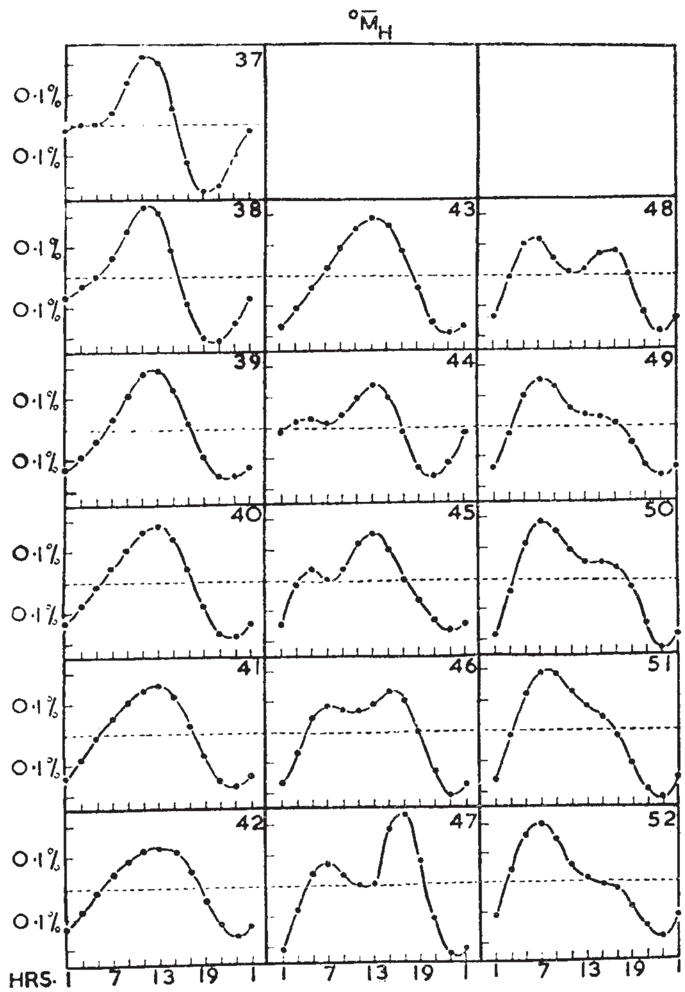

Fig. 9. The 12-month mean daily variation of meson intensity at Huancayo during different years [Sarabhai, Desai & Venkatesan (4)].

effect observable in the magnitude of the decrease at different stations extending from the equator to high latitudes. On the other hand in some storms, the low energy component of the primary cosmic radiation appears to be disturbed more than the high energy component. Neher & Forbush (70) have compared a storm type decrease observed at 70,000 feet over Texas with the decrease in the ion chamber at Mt. Wilson and have showed that the effect was about four times more pronounced in the former case.

During the past three years, further work has been done in studying the solar and terrestrial relationships of magnetic storm type decreases in cosmic ray intensity. Chasson (71) has shown that decreases of intensity occurred on two occasions an appreciable time before measurable geomagnetic disturbances. Trefall (72) has concluded that magnetic storms with a dominent positive peak and a negative peak which is small or absent, produce no change of intensity. Trumpy (73) and Kitamura (74) have examined the characteristics of some magnetic storms. Sekido *et al.* (75) have studied the solar relationship of cosmic ray effective and noneffective magnetic storms, which they designate as S and M type storms respectively. They have found that the frequency of S type storms varies in step with the 11 year cycle of solar activity, but this is not the case with M type storms which they associate with the supposed M regions on the sun. There is correlation between the occurrence of S type storms and the central meridian passage of large sunspot groups. This feature is absent for M type storms. The 27 day recurrence tendency as seen with Chree diagrams, shows sharp peaks for M type storms but sinusoidal changes for S type storms. The authors conclude that S type storms are caused by wide corpuscular clouds ejected from sunspot groups, but the M type storms are caused by narrow corpuscular beams from M regions.

3.22 *Day-to-day changes of intensity.*—The day to day changes of intensity, some of which are of the 27 day recurring type, have been extensively studied in recent years. Early work related to small changes noticed in ionisation chambers, but a significant step forward was possible with data from Simpson's neutron monitors in which it was quite obvious that large and significant changes of intensity of a few per cent in amplitude were occurring almost continuously from day to day. Simpson *et al.* (76) showed the association of the increases with the central meridian passage of active solar regions, and particularly of regions of green coronal emission on the sun. These increases were often seen to be followed within two to three days by increased geomagnetic activity. Recently Simpson *et al.* (77) have shown the close association of the central meridian passage of unipolar UM regions with cosmic ray increases during 1953. These regions as well as the increases of intensity persisted for several solar rotations.

Several workers have now demonstrated that the day to day changes are worldwide in character. Fonger (17) has found that changes in the neutron monitor at Climax are similar to simultaneous changes observed in the ion chamber at Freiburg, but on the average are five times greater in amplitude. Neher & Forbush (70) have demonstrated the correlated changes occurring in the ion chambers at Huancayo and Cheltenham, the neutron monitor at Climax and the ionisation at 70,000 feet over Bismarck. These are shown in Figure 10 which reveals the difference in amplitude of changes in

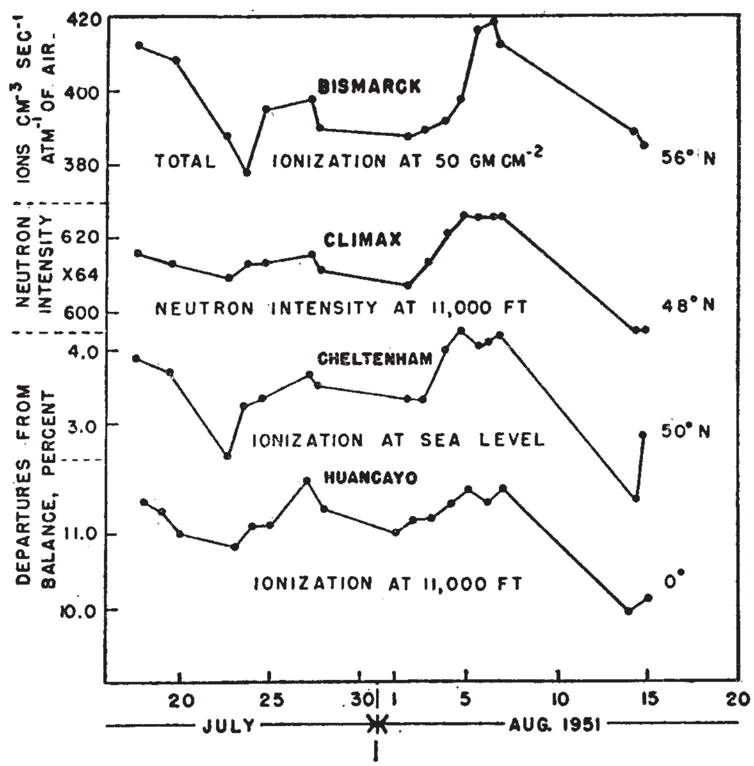

FIG. 10. Correlated day-to-day changes of cosmic ray intensity [Neher & Forbush (70)].

each case. Neher *et al.* (60) have demonstrated that the changes at high altitude over Bismarck and near the north geomagnetic pole are correlated amongst themselves and with changes in an ion chamber at ground level. van Heerdan & Thambyahpillai (35) have recently investigated the correlated changes measured with a neutron monitor and a counter telescope at London. In the study of the 27 day recurrence of these changes, they find a decrease of mean intensity connected with the increase of amplitude of the fluctuations. They have thus come to the conclusion that the changes represent decreases of intensity. Meyer & Simpson (78) have studied the 27 day recurrence tendency in the ion chamber data of Huancayo and the neutron monitor at Climax, and have demonstrated that the recurrence tendency is altered during the solar cycle. It is more pronounced during sunspot maxima, when incidentally the general intensity is low, and is weak at sunspot minimum when the general intensity is maximum.

Meredith *et al.* (63) have made rocket measurements with a single counter capable of responding to radiation of intensity as low as 20 Mev. They find that on many days during 1954 there is, at an altitude above 40 km, a large intensity of radiation of energy between 20 Mev and 140 Mev. It is of course debatable whether radiation of this type can legitimately be classed in cosmic radiation. But the observations show that just like the day to day variations of high energy radiation, there is also a day to day variation of large magnitude occurring in much softer radiation which can only be observed at very high altitudes.

3.23 *Day-to-day changes of anisotropy.*—The change of the diurnal component of the daily variation of cosmic rays during magnetically disturbed days has been extensively studied (39, 68, 73, 79 to 83). It is found that on days with high K_p, the amplitude of the diurnal component increases and its time of maximum becomes earlier. Sekido & Kodama (81) have shown that this effect is present to a greater degree in measurements made with narrow angle telescopes than with instruments with wider directional sensitivity. Sekido & Yoshida (84) have moreover demonstrated that the semidiurnal component which is normally present to a greater extent in the daily variation measured with narrow angle telescopes than with telescopes of large semiangle, gets reduced on magnetically disturbed days.

Sekido *et al.* (85) have made an intensive study of the mean storm type vector representing the difference in the diurnal components of the disturbed period daily variation and the quiet period daily variation during each year. They have shown that the disturbance vector representing a storm type anisotropy points on the average towards the radially outwards direction from the sun, and undergoes a long period change from year to year, broadly in step with the 11 year cycle of solar activity.

Following the discovery of long term changes in the anisotropy of the primary radiation as revealed by changes in the 12 month mean daily variation of cosmic ray intensity, various attempts have been made to study the short term changes of the anisotropy, not necessarily connected with magnetic disturbances. Firor *et al.* (79) have pointed out that the daily variation of the nucleonic component as revealed by the neutron monitor is highly variable in character. They found groups of days on which there was a large diurnal variation with a maximum during the day. There were other days on which there was no appreciable daily variation, and indeed on others, the daily variation appeared to have a maximum in the night. Sittkus (86) has looked at the amplitude of the diurnal variation measured by an ion chamber on individual days and he has noticed the tendency for a variation of large amplitude with a maximum near noon to occur during groups of days. He has found a 27 day recurrence tendency for these groups but compared to the rest of the days, the days with large noon time amplitude are not associated with a significantly different magnetic character figure. Remy & Sittkus (87) have shown that during 1954, the occurrence of days on which there was a large day time maximum of intensity was rarer than in 1953. They have moreover noticed a great variability of the time of maximum of the diurnal component of the daily variation.

Weighty evidence concerning the change of anisotropy from day to day comes from the investigations with narrow angle telescopes reported by Sarabhai & Nerurkar (88). With telescopes having semiangles of 2.5° and of 5° in the E-W plane, the combined data for each type of telescope for every day were examined.

On about 75 per cent of the total days the daily variation exhibited only one maximum. For these days they have found, as shown in Figure 11, a marked tendency for the diurnal maximum during the year 1954 to occur either at 12:00 noon or in the early morning at about 0300 hours local time. On the basis of a phenomenological classification of days according to whether they exhibit a maximum during the day, a maximum during the night or they exhibit two maxima instead of one, the days have been desig-

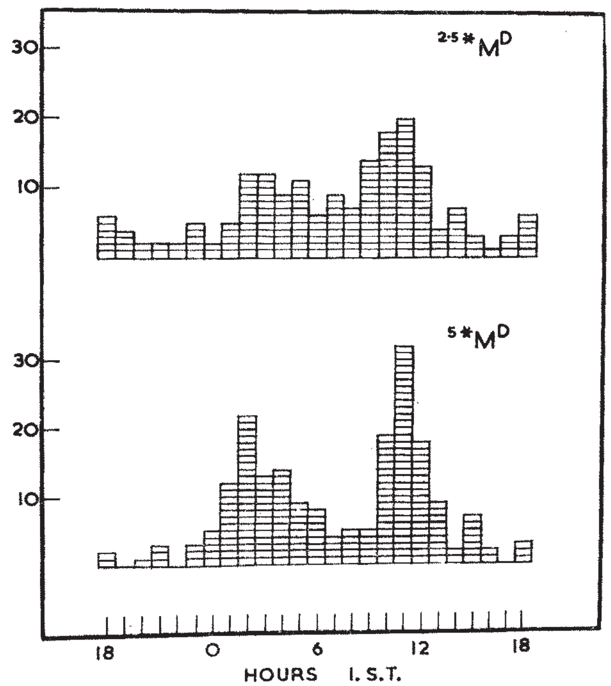

FIG. 11. The distribution of occurrence of the diurnal maxima for each of 24 hours of a day. The upper and the lower histograms refer to telescopes of 2.5° and 5° semiangles respectively in the E-W plane [Sarabhai & Nerurkar (88)].

nated as 'd', 'n' & 's' respectively. The three types of daily variations obtained for data averaged for days of each type are shown in Figure 12. The results indicate that there are at least two preferred orientations of the anisotropy and that on any particular day which does not belong to the 's'

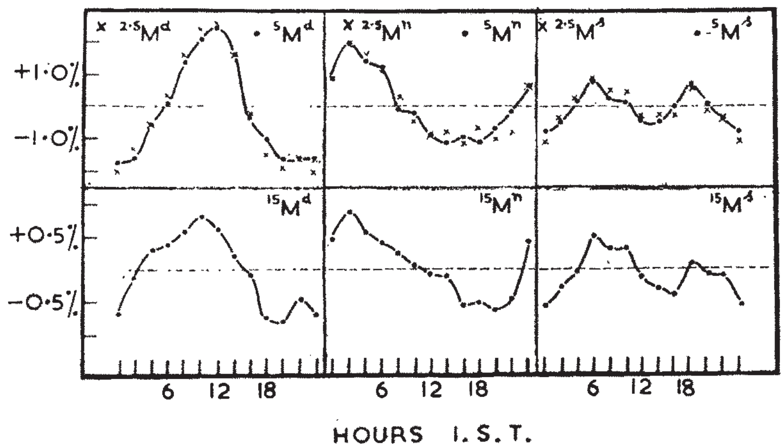

FIG. 12. The average daily variation of meson intensity measured with telescopes of 2.5°, 5° and 15° semiangles on 'd', 'n' and 's' type days [Sarabhai & Nerurkar (88)].

type, there is present either one of these two types of orientations. The amplitude of the daily variation occurring on each of these types of days is large and is of the order of 1.5 per cent to 2.0 per cent as observed with a narrow angle telescope at low latitudes. These days, particularly of the 'd' type, have a 27 day recurrence tendency and usually occur in groups as observed by Sittkus.

The recurrence tendency of the anisotropy observed in the ion chamber data at Huancayo has been studied by Yoshida & Kondo (89). They found a strong recurrence tendency, extending to two solar rotations, which was more marked than the recurrence tendency in either the general cosmic ray intensity or in the magnetic character figure during the same period. Kane (90) has studied the recurrence tendency in the daily variation measured by neutron monitors at several stations and by the Freiburg ion chamber for the years 1951, 1952, and 1953. He has shown that the recurrence tendency in the daily variation, unlike the tendency in the general intensity, remains almost unaltered during the three years.

3.3 Solar Flare Effect

Since the detailed review by Elliot (1) no major solar flare effect was observed in cosmic radiation until recently on February 23, 1956. In the four early events large increase of intensity was seen to occur simultaneously in instruments at stations situated in latitudes higher than 25°. The increases lasted from one to three hours and in three cases followed the visual observation of the flare within an hour. They were larger in neutron detectors than in instruments measuring meson intensity and the absence of recorded increases at low latitudes suggested that the radiation responsible for them was much more strongly energy dependent than normal cosmic ray intensity. There was no evidence for increases in the rate of extensive air showers (91).

During the last three years much further examination and analysis of earlier data has been done. Graham & Forbush (92) have confirmed in the records of an ion chamber at Thule on July 25, 1946 the occurrence of a polar type increase as reported earlier from Resolute and Godhavn. On the assumption that the flare effect is caused by the emission of solar particles of cosmic ray energy, Schluter (8) and Firor (9) have examined the trajectories of charged particles in the geomagnetic field. Figure 13 shows the impact zones of solar particles in the rigidity range two to ten Bev in terms of local time at the place of observation. The impact zone theory, on assum-

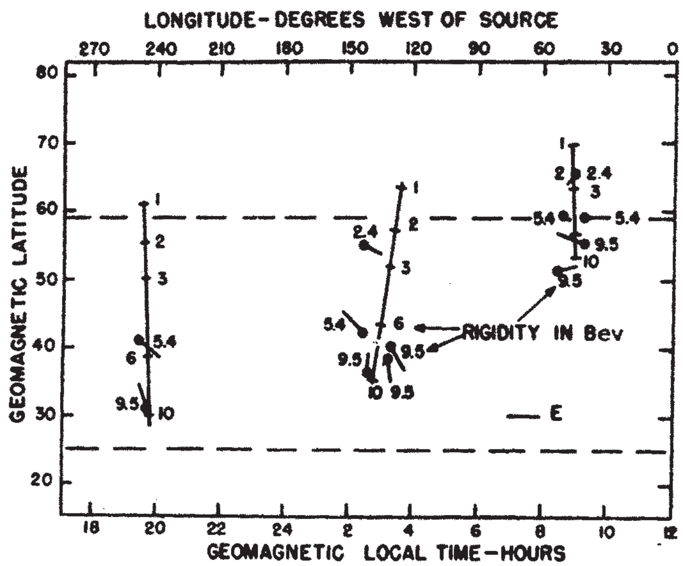

FIG. 13. Impact points on the earth for one to ten Bev particles approaching in the equatorial plane from a source situated at noon local time [Firor (9)].

ing a solar diameter of about 30° as viewed from the earth, satisfactorily explains the principle features of the increases observed in middle latitudes. However there is difficulty in explaining polar type of increases at latitudes higher than 65° on the basis of direct orbits from the sun.

Sekido & Murakami (93) have analysed the amplitude and the duration of the solar flare increases observed at different stations during each of the four early events. They distinguish between the effect occurring within the impact-zones from the polar type of effect, which has a longer duration and a less steep rise of intensity than the former. This is suggestive of a different mode of travel of particles for the polar type increases as compared to the direct trajectories for arrivals within the impact zones. These authors suggest that the flare radiation has a spectrum such as E^{-5}. However there is a varying amount of averaging of the solar flare increases at different stations and there is also a difference in the geometry of recorders at various stations. Hence a derivation of any definite power law spectrum at the present moment appears premature, particularly because of the imperfect understanding of the polar type increases.

Treiman (94) has calculated that the solar magnetic moment should not exceed 5×10^{32} gauss-cm.^{3}, if the calculations of the impact zones by Firor are to be retained. Kraushaar (95) has made a similar calculation concerning the galactic magnetic field and puts an upper limit of 3×10^{-6} gauss for it. Kraushaar (96) has offered an interesting suggestion involving deflections in a galactic field of this magnitude and emission of particles from the sun over a wide range of angles for explaining the polar type of increases. A verification of this explanation would be possible from the seasonal dependence of the flare effect at polar latitudes, but it is difficult at present to confirm the validity of his hypothesis from the few instances which have been recorded.

Firor (9) has looked for flare type of increases associated with small flares of magnitude 1^+. As shown in Figure 14, he finds about 1.0 per cent increase in the intensity on days when the Climax recorder was in an appropriate impact zone to be able to receive particles from the sun. This he compares with no increases on days when the Climax recorder was not in one of the impact zones, during the occurrence of flares. Neher *et al.* (60) have reported in the records of a flight made on July 23, 1951, an increased intensity during the descent as compared to the ascent of the instrument. A flare of magnitude 1 occurred about an hour before the commencement of the flight. This is the solitary reported instance when an instrument was aloft soon after a flare, and the authors indicate that in terms of solar protons the increase would have to be due to arrival of 0.6 Bev particles. It is perhaps significant to note that the low energy cut off at the time was about 0.8 Bev for general cosmic ray intensity.

The most recent flare of February 23, 1956 has been remarkable in many respects. It was of magnitude 3^+ and apparently more pronounced cosmic ray increases have been recorded than during the earlier events. An increase of about 4500.0 per cent has been reported in a neutron monitor at latitude 57°N. by Marsden *et al.* (97). Moreover an average increase of 5.7 per cent at stations near the magnetic equator in India is reported by Sarabhai *et al.* (98). On the assumption that the increase is caused by solar protons travelling along more or less direct paths, they suggest from Brunberg & Dattner's calculations that only solar protons in the energy range 30 to 67.5 Bev could have been responsible for the increases at the Indian stations. These particles could only come from restricted directions inclined to the zenith towards south and hence the small per cent change of intensity is indicative of a large flux of protons of about 50 Bev energy which they estimate is nearly 1.5 times the flux of the background cosmic rays in the same energy range. Thus the upper limit of energy of particles responsible for flare type increases is much higher than has been hitherto believed.

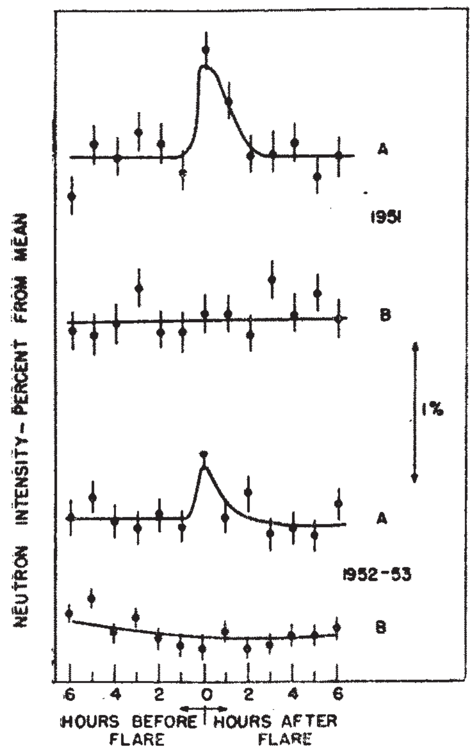

Fig. 14. Cosmic ray intensity during times of small solar flares. Curves A and B show behaviour when detector was within and outside respectively of the morning impact zone [Firor (9)].

4. THE INTERPRETATION OF VARIATIONS

4.1 Dependence on Mean Energy of Primaries

From various experiments which have been referred to in the earlier section, we have attempted to summarise data of significance to the evaluation of the dependence of the variations on the mean energy of primary radiation. These are presented in Table I.

TABLE I

RATIO OF AMPLITUDES OF VARIOUS TYPES OF CHANGES RECORDED BY DIFFERENT RECORDERS*

Type of change	Recorder A	Recorder B	Recorder C	Ratio of amplitude A:B or A:B:C	Ref.
Long term change	IC 50°N. sea level	IC 1°S. 11,000 ft.	IC 43°S. sea level	1:1:1	(3)
	IC 50°N. 90,000 ft.	IC 1°S. 11,000 ft.		12:1	(56)
Magnetic storm type change	NM 48°N. 11,000 ft.	IC 49°N. sea level		5:1	(100)
	NM 42°N.	IC 1°S. 11,000 ft.		2.7:1	(3)
	IC 1°S. 11,000 ft.	IC 50°N. sea level	IC 80°N. sea level	1:1:1	(91)
	CT(±12°) 25°N.	CT(±40°) 25°N.	CT(±85°) 25°N.	3:1.7:1	(40)
	CT(±45°) 47°N.	IC 49°N.		1.5:1 to 2.4:1	(38)
	IC 70,000 ft.	IC sea level		4:1	(70)
Day-to-day change	NM 48°N. 11,000 ft.	IC 49°N. sea level		5:1	(17)
	IC 1°S. 11,000 ft.	IC 50°N. sea level		1:1	(70)
	IC 50°N. 70,000 ft.	NM 48°N. 11,000 ft.	IC 1°S. 11,000 ft.	7:3:1	(70)
Diurnal variation	NM 48°N. 11,000 ft.	NM 1°S. 11,000 ft.		1:1	(79)

* The recorders are designated by IC for ionization chamber, CT(±x°) for counter telescope of semiangle x° in the E-W plane and NM for neutron monitors. The geomagnetic latitude and the elevation of the observing station are indicated by numbers immediately following the abbreviation used for recorders.

TABLE I—(*Continued*)

Type of change	Recorder			ratio of ampli- tude A:B or A:B:C	Ref.
	A	B	C		
	IC 1°S. 11,000 ft.	IC 50°N. sea level		1.1:1	(42)
	CT(±45°) 47°N.	IC 49°N.		1.5:1 to 2.4:1	(38)
	CT(±12°) 25°N.	CT(±40°) 25°N.		1.3:1	(40)
	CT(± 5°) 13°N.	CT(±15°) 13°N.		2:1	(41)

It will be noticed that the long term changes of intensity, the magnetic storm type decreases and the day to day changes of intensity exhibit certain common features. The amplitude of variations studied with omnidirectional instruments is generally smaller than with counter telescopes where the amplitude becomes progressively larger with a dimunition of angle of opening of the telescope. There is often a larger change of intensity of particles of energy less than 10 Bev than of those above it. The ratio, however, of the changes observed in the two cases is variable. Moreover, there are occasions when, as shown by Neher, the reverse is true, and there can be increase of intensity at intermediate energies without corresponding change at low energies. It is remarkable that the fluctuations are not as latitude dependent as a comparison of the neutron monitor studies with charged particle detectors at the same latitude would seem to suggest. It appears that the difference between the semiangles of the meson detector, which is usually an ion chamber or a wide angle telescope, and the effective directional sensitivity of the neutron monitor, is perhaps responsible for this discrepancy. It has been discussed earlier that the energy spectrum of solar primaries associated with flares is considerably steeper than the spectrum of normal cosmic ray primaries.

The amplitude of the diurnal component of the daily variation of intensity has frequently been considered an index of the degree of anisotropy of primary radiation. However, the amplitude depends very much on the directional sensitivity of the measuring instrument and on the period for which data are averaged. At the present moment we have no available data where the amplitude of the daily variation observed with a neutron monitor can be compared directly with the amplitude of the daily variation in meson intensity measured with a telescope of equivalent effective directional sensitivity. Until this is done, it would be difficult to conclude whether the anisotropy is greater in respect of the spectrum in the mean energy range of about 7 Bev which is measured in a neutron monitor at middle latitudes and in the spectrum with a mean energy of about 40 Bev which would be measured at a similar station with a meson intensity recorder.

Some evidence on the energy dependence of the anisotropy is obtainable from the latitude effect of the amplitude of the daily variation observed with similar instruments. Huancayo is at a mountain elevation at the geomagnetic equator compared to Cheltenham which is at sea level at 50°N. geomagnetic latitude. Over a period of several years, the per cent amplitude at Huancayo is about ten per cent larger than at Cheltenham. Between Huancayo and Climax there is no appreciable difference in the amplitude of the neutron daily variation over 13 months. Thus within the latitude sensitive spectrum of primaries there appears to be no marked change in anisotropy. Experimental data for high energy primaries from experiments made with large atmospheric showers or at great depths underground establish only an upper limit to the magnitude of the anisotropy at these energies and in consequence do not reveal the dependence of the anisotropy on primary energy.

4.2 Solar and Terrestrial Relationships of Cosmic Rays

There is now a vast amount of evidence to show that the sun strongly influences the cosmic rays that are measured on the earth. Most of these influences have been revealed through relationships with the activity of the sun which changes markedly from time to time. Some activity persists through several solar rotations and produces characteristic 27 day recurrences. General solar activity changes with an 11 year period, while the state of magnetic polarity of bipolar sunspots has a periodicity of 22 years.

The sun appears to influence the low energy cut off of the primary spectrum over an 11 year cycle. Independently of the change of cut off, it is known to also produce a general change of intensity, with a cycle of 11 years. It produces changes of intensity of shorter duration. Many of these are related to the central meridian passage of regions of solar activity such as sunspot groups, unipolar regions and regions of intense coronal 5303 Å emission. The occurrence of the regions at low heliographic latitudes appears to favour their effectiveness in influencing cosmic rays.

The sun produces an anisotropy of the cosmic radiation. The 12-monthly average anisotropy illustrates a change which is consistent with a cycle of 22 years and perhaps constitutes the first solar influence detected so far on the earth which has a period corresponding to what may be considered the true solar cycle of activity. This requires to be verified by observations extending over several cycles. The sun also produces day to day changes of anisotropy, some of which are related to the central meridian passage of active regions as in the case of variations of intensity.

The sun emits cosmic rays in association with flares, and these are now believed at least sometimes to have particles of energy exceeding 50 Bev, if they are protons which have travelled in direct paths to the earth.

The terrestrial relationships of cosmic ray variations with geomagnetic activity arise from the latter being themselves associated with solar activity. Similar is the case with some ionospheric disturbances. For instance Dolbear *et al.* (99) have shown the association of cosmic ray increases with ionospheric disturbances during day time hours. Also flare type increases of cosmic rays are associated with ionospheric disturbances and radio fade outs.

4.3 The Mechanisms of Variations

The close relationship of cosmic ray variations with solar activity has prompted various workers to investigate whether these changes are caused by the emission of cosmic rays from the sun. At the present moment there is general agreement on solar emission only in respect of the flare type increases. The view is tending towards the modulation of cosmic ray intensity to explain the other variations because of the combined weight of one or more of the following arguments which by themselves do not warrant an unequivocal answer.

(*a*) At minimum of solar activity, as judged by visual evidence on the solar disc or by comparative absence of terrestrial effects such as magnetic and ionospheric disturbances and auroral activity, there is an absence of "knee" with the presence of many low energy particles with energy down to about 150 Mev. Associated with these particles, there is an increase in general intensity, not only because of the absence of the low energy cut off but, due to enhanced intensity, throughout the whole spectrum. This result suggests that turbulent magnetised clouds produce a screening of the earth probably by scattering of cosmic rays. The characteristics of the screen are governed by the solar activity. At sunspot minimum the screen is either temporarily removed or is made less impervious.

(*b*) Magnetic storms on many occasions are accompanied by decreases in cosmic ray intensity, but never with increases. Heerdan & Thambyahpillai (35) have shown that an increase in the general intensity is associated with the reduction of amplitude of 27 day recurrences, thus suggesting that the 27 day recurrent changes are decreases. They are therefore similar to the magnetic storm type changes and indicate that screening of cosmic ray intensity has occurred. This is in general agreement with the minimum of amplitude of 27 day recurrences occurring at minimum solar activity when there is general enhanced total intensity.

The only evidence for an increase in cosmic ray intensity associated with visible solar disturbances is that put forward by Simpson *et al.* (76, 77). Figure 15 illustrates the sharp peaks of intensity which coincide with the central meridian passage of active regions. It is not clear at the present moment that there is any reasonable argument to minimise the significance of this type of observation. Therefore there is at the present moment a real difficulty in assuming that all variations under consideration here are in the nature of decreases. More data on the association of increases with the central meridian passage of regions of solar activity are required to settle this point.

Because of close relationships with geomagnetic disturbances, early workers tried to explain the variations in terms of a modulation of cosmic ray intensity by changes in the geomagnetic field. Simpson (100) has shown that the variations in the neutron intensity at latitudes above the "knee"

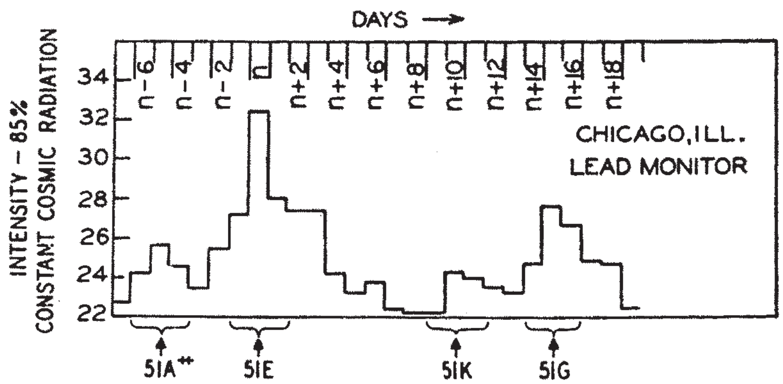

FIG. 15. Association between intensity maxima in neutron pile at Chicago and the central meridian passage of local active regions on the sun. Simpson, Fonger & Wilcox (76).

of the intensity versus latitude curve were very similar to those observed at low and middle lattitudes. Hence these variations in the nucleonic and the ionizing component are not produced by geomagnetic field disturbances. Nagashima (18) has proposed a static electric field surrounding the earth and assumes changes in it to explain the worldwide nature of the intensity variations. His model explains fairly well the altitude dependence of the variations reported by Neher *et al.* (60) and by Fonger (17), as well as their latitude dependence examined by Yoshida & Kamiya (101). However, Simpson (100) has examined the effect on cosmic ray intensity of axially symmetric geoelectric fields at different distances from the earth. He finds that in the range 45°N. to 60°N., the latitude dependence of the fractional changes in neutron intensity during different periods does not agree with the latitude effect calculated for different distances of the field. He concludes that no accelerating or decelerating geoelectric field is responsible for these variations. In addition, such a mechanism will be unable to account for large cosmic ray changes during periods when there are no geomagnetic disturbances and presumably no perturbing geoelectric fields. Simpson therefore suggests that the mechanism responsible for the changes is of extraterrestrial origin and its association with solar phenomena is independent of the earth's system.

Alfvén (102) has suggested that the emission of corpuscular matter from the sun which is responsible for magnetic storms is also responsible for cosmic ray fluctuations. An electric field is set up due to the polarisation of the neutral beam which takes place in the presence of a trapped magnetic field carried with it. The acceleration and deceleration of cosmic rays traversing the field may be expected to cause increases or decreases. This model has been considered in greater detail by Brunberg & Dattner (103), to explain the decreases observed with magnetic storms. They consider the orbits of cosmic rays in a general dipole field in the solar system and require a magnetic field of 10^{-5} gauss in the vicinity of the earth, if only decreases are to be observed.

Davis (104) has discussed the influence of the emission of ionized matter from the sun on solar or galactic magnetic fields within the solar system. He explains that the tendency would be to sweep the magnetic fields away and leave a field free cavity of a mean radius of about 200 astronomical units around the sun. Cosmic rays of rigidity less than 10^{12} volts would be trapped within the cavity and their intensity would depend on its volume. He has tried to show that a 1.0 per cent change of the mean radius of such a cavity with the 11 year solar cycle could explain the 4.0 per cent change of intensity as observed by Forbush (3). However this mechanism fails to explain the much larger long term changes of intensity for low energy than for high energy primaries, as observed by Neher (55) and by Meyer & Simpson (57).

Morrison (105) has recently proposed a model which attempts to explain most of the principal features of various types of fluctuations observed in cosmic ray intensity which he believes to be decreases of intensity. He supposes that clouds of ionized matter are emitted more or less continuously from active regions of the sun. These clouds have within them turbulent magnetic fields instead of trapped coherent magnetic fields visualised by Alfvén (102). The clouds would be free of cosmic ray intensity when they are emitted, but intensity will slowly build up in them as cosmic rays diffuse into them. The intensity of cosmic rays at any time within the cloud, would be governed by the age of the cloud and the rate of diffusion of cosmic rays into it. The diffusion time depends on the scale of turbulence and the strength of the magnetic field and is therefore greater for low energy particles than for high energy particles. As the earth gets enveloped in one of these clouds, it experiences decreases of cosmic rays intensity depending on the intensity within the cloud at that moment.

Morrison expects that at great distances from the sun of the order of 100 astronomical units, there would be a fairly uniform diffuse cloud in place of the discrete structures seen at closer distances of the sun equivalent to the distance of the earth. Scattering in the distant diffuse clouds is expected to produce the general change of intensity as well as the change in the low energy cut-off accompanying the solar cycle. This scattering would be more effective for low energy particles than for high energy particles and thus explains the experimental observations in this regard.

Morrison has suggested the possibility of being able to explain a cosmic ray intensity increase associated with the central meridian passage of a UM region by postulating the presence of streams on either side of the UM region which would have more turbulence and therefore less intensity than the stream from the UM region. However not all cosmic ray increases have been associated with UM regions, and there might be difficulty in explaining the day to day increases on Morrison's model.

An attractive feature of Morrison's theory is that turbulent chaos and not a highly ordered model is called upon to explain the observed facts. Morrison thus comments on his model "it lacks the specific details of other proposals, but this weakness perhaps allows better experimental agreement." Morrison does not explain the wide variability of the energy dependence of different variations on different occasions. Perhaps another drawback with the model is that it fails to explain solar anisotropy of radiation revealed by the diurnal variation and its changes.

5. THE INTERPRETATION OF THE SOLAR ANISOTROPY OF COSMIC RADIATION

Explanations of the daily variations of cosmic rays in terms of a solar magnetic field or the variations of a geomagnetic field became untenable quite early, because of the failure to detect the expected large latitude dependence of the variations. Brunberg & Dattner (106) have pointed out that seen from a fixed coordinate system, the rotating sun would be strongly polarised so that there would be a voltage difference between the poles and the solar equator of the order of 10^9 volts. The combined action of the electric field produced by polarisation and the solar magnetic field will make charged particles within the solar system partake in a general rotation with the sun so that the earth will receive an excess of particles in the 18 hourly direction. They thus get a tangential anisotropy. Alfvén (107) on the other hand, has shown the possibility of an outward radial flow of energy depending on the accelerating processes within the solar system. This will impart a radial anisotropy to cosmic rays, which will change with the 11 year cycle of solar activity. These explanations require a general magnetic field of the sun having an intensity of about 10^{-5} gauss at the earth's orbit to account for a diurnal variation whose amplitude was believed to be about 0.2 per cent.

Nagashima (108) has recently examined the possibility of explaining a diurnal variation of the order of 0.2 to 0.5 per cent on the basis of the electric field theory suggested by him to explain the magnetic storm type change of total intensity. There would however be a large latitude dependence of the daily variation which is not observed.

Because of the neglect of the following experimentally determined features of the daily variation averaged over periods of one year or longer, it is difficult to attach much importance to any of the above mentioned theories to explain the observed facts.

(*a*) The daily variation cannot at all times be satisfactorily described in terms of the diurnal component only. For several years in the past the daily variation had two significant maxima.

(*b*) A shift of the principal maximum of the daily variation by as much as ten to twelve hours takes place over a period of years. The implication of this shift is that during some years, the daily variation exhibits a principal maximum during the day while in others, the maximum is shifted to the night.

(*c*) The amplitude of the daily variation is markedly determined by the directional sensitivity of the recording instrument. The change of amplitude of the daily variation with change of semiangle of the telescope is very much more than can be normally expected. Large amplitudes of the order of 1.2 per cent have been observed with narrow angle telescopes at low latitudes.

The occurrence of the storm type anisotropy and the frequent day to day variations of anisotropy make it necessary to evaluate the physical meaning to be attached to the anisotropy derived from data averaged over a long period. The daily variations of the 'd' and the 'n' type, which occur on groups of days, have times of maxima which coincide with those of the two contributions which are found to play a determining role in producing long term changes in the 12 month mean daily variation. This raises the question whether there is in fact a permanent anisotropy in addition to the variable types of anisotropy present on groups of days. If we accept the existence of a permanent anisotropy, its features and characteristics are at the present moment not known. It would appear that these have been masked by a more prominent anisotropy which is of a highly variable character. At the present moment, no satisfactory place can be found to fit in the above picture the semidiurnal type of variation observed on certain days at low latitudes.

At the present juncture it is important to find explanations for the two main types of variable anisotropies. In this connection theories which have been advanced by various workers to explain the characteristics of the storm type anisotropy assume a special significance. Elliot & Dolbear (83) and Alfvén (102) have suggested that electric fields are produced within beams of ionized particles emitted from the sun in the presence of the solar magnetic field. Acceleration of cosmic ray particles traversing these beams produces an anisotropy in particular directions depending on the relative position of the beam and the earth. Nagashima (108) has examined the detailed implications of this model taking into consideration the deflection within the beam of particles in the trapped magnetic field which is derived from the solar dipole field. A feature of his theory is that associated with every beam there is a minimum energy below which no anisotropy would be produced. For higher energies, the per cent anisotropy would progressively decrease with increasing energy. Nagashima has shown that the maximum anisotropy would be produced in the direction pointing towards the sun. This agrees with the experimental determination of the storm type vector by Sekido *et al.* (85). Nagashima's theory also explains the 11 year cycle of variation of the storm type anisotropy as being due to a change in the density of the solar streams and of the strength of the trapped magnetic fields during the solar cycle of activity.

Nagashima's theory does not explain a night time maximum as observed in the daily variation on groups of days. Recently Nerurkar (109) has extended Nagashima's work by admitting the possibility of random orientation of the magnetic field trapped within the beam. This could arise if the orientation of the field in the beam is not determined by the solar dipole field but by the field in the direct vicinity of the regions from which the beams are emitted. Since the daily variation reveals an anisotropy in the E-W plane, the component of the trapped field perpendicular to the equatorial plane has to be considered. Thus a modification of Nagashima's theory whereby the direction of the effective magnetic field can be reversed is possible. Nerurkar has demonstrated that there can then be anisotropy in the 0800 and in the 1600 hour directions depending on the orientation of the magnetic field. Due to the effect of the geomagnetic field these anisotropies can produce at low latitudes maxima of intensity in the daily variation at 0300 and 1100 hours respectively in agreement with observations. The most satisfactory scheme of things would be, to be able to explain intensity fluctuations as well as anisotropy on a unified theory. Further work is now required in this direction.

6. IMPLICATIONS ON THEORIES OF THE ORIGIN OF COSMIC RAYS

The presence of heavy nuclei and the isotropy of the primary radiation have a direct bearing on our concepts of the origin of cosmic radiation and of the properties of interplanetary and interstellar space. The composition of the primary radiation in terms of the relative abundance of nuclei with different atomic numbers sets an upper limit to the number of collisions, and to the mean life time of the primaries. This, coupled with knowledge of the density of matter in interstellar space gives an estimate of the volume in which the radiation could be confined. The containing of the cosmic rays within a specified volume is required from energy considerations of the universe as a whole, as also from the necessity to produce a high degree of isotropy through a state of equilibrium reached within this volume.

As we have discussed earlier, the existence of a permanent solar anisotropy may be considered to be uncertain at the present moment. If it is present, it is not likely to cause an amplitude of the daily variation larger than 0.5 per cent. A solar anisotropy of a highly variable character which may on occasions have large magnitude of the order of one or two per cent does exist, but this appears to be caused by the modulation of particles in the neighbourhood of the earth in their passage through streams of ionized particles emitted from the sun with magnetic fields trapped within them.

There is some evidence for a galactic anisotropy pointing to an excess of particles coming from the direction of the milky way, and particularly from the galactic centre. Davis (110) has discussed the implications of these results in terms of the galactic magnetic field along the spiral arm in which the solar system is situated, and in terms of various mechanisms proposed for the acceleration of particles to cosmic ray energies. He calculates the anisotropy to be expected through three processes in the very high energy primaries as studied in extensive air shower experiments. He comes to the conclusion that excepting for the results of Daudin & Daudin (51), the observations of Cranshaw & Galbraith (52) and of Farley & Storey (44) favour acceleration by Fermi's mechanism and the diffusion of cosmic rays along the spiral arm.

A theory of variations and of origin of cosmic rays within the solar system has been proposed by Alfvén (107). This requires the presence of a permanent solar field of the order of 10^{-5} gauss at the earth. Particles get accelerated to cosmic ray energy by repeated traversals through disturbed electromagnetic fields produced in the solar system by storm producing beams. By circulation in the trapping field the radiation would become almost isotropic up to 10^{14} ev. The absence of anisotropy of any large magnitude for primaries of 10^{16} ev energy as shown by experiments with extensive air showers would be contrary to the predictions of this theory.

Evidence for the stellar origin of cosmic rays comes from the solar flare effect and from the discovery of a point source reported by Sekido *et al.* (54). Firor *et al.* (111) have estimated from the frequency of the occurrence production of 4 Bev protons at the rate of 10^{23} particles per second. Sarabhai *et al.* (98) have recently estimated that at the time of a large flare of intensity 3^+, about 10^{28} protons have been accelerated to energies of about 50 Bev. The estimate of Firor *et al.* (111) is compatible with the intensity of cosmic rays in the 4 Bev region if all solar particles are trapped in a region of mean radius of the order of 10^{15} cm. At the present moment, it would appear that stellar bodies could perhaps provide an adequate mechanism for injecting into the galaxy particles which through other accelerating mechanisms of the type suggested by various workers (112 to 116) could contribute to the overall flux of intensity.

7. CONCLUSION

New experimental facts concerning cosmic ray variations and the anisotropy of the radiation have given a great stimulus to theories of origin of cosmic rays and of cosmical electrodynamics. We now accept the existence of large changes of primary intensity. We have good reason to believe that many of the changes represent modulations of primary intensity occurring at some distance from the earth. The changes therefore provide a new and valuable tool to study electromagnetic fields and distribution of matter in interplanetary and interstellar space. There appears a possibility of being able to understand these changes in terms of the chaotic turbulent condition of matter in such space. The changes also furnish fresh insight into problems of solar physics. However, interpretations of results of observations have been seriously handicapped by the paucity of data simultaneously obtained from observing stations widely distributed on the earth, and by non-standardised experimental techniques followed at various places. It is fortunate that this state of affairs is now being remedied through the newly created Sub-Commission for Cosmic Ray Intensity Variations (SCRIV) and the programme in cosmic rays for the International Geophysical Year 1957–58. It is obviously important that worldwide studies should be continued without interruption through several solar cycles and that in future there should be several studies comparable with those made by Forbush at the Carnegie Institution of Washington.

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Changes of Solar Anisotropy and of the Intensity of Cosmic Radiation.

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1 – Introduction.

Realization has grown in recent years that the solar anisotropy of cosmic radiation which is detected by the measurement of the solar daily variation of meson intensity corrected for atmospheric influence, is of a highly variable character [1-8]. The solar and terrestrial relationships of the changes of anisotropy have been studied and theories have been advanced [9-11], to explain the creation of the anisotropy by a modulation of the cosmic ray intensity incident in particular directions. A confirmation of these experimental observations and tests of the proposed models for the modulation of cosmic rays are of crucial significance to the theories of the origin of cosmic rays and of the electromagnetic state of interplanetary space.

To undertake this task we want firstly an experimental technique which permits us to select days on which significant daily variations of different types occur. It has been shown earlier [6] that days on which the daily variation has a significant amplitude, can broadly be classified into three groups. On the so called « *d* » type days, the daily variation has one maximum near noon, on « *n* » type days it has one maximum early morning and on « *s* » type days it has two maxima instead of one. It is also known that the 3 different types of daily variations are more clearly revealed in observations with vertical narrow angle telescopes, having semiangles of about 5°, than with ionization chambers or wide angle telescopes. Not only is the amplitude of the variation larger, but the separation of maxima of « *d* » and « *n* » types is greater for narrow angle observations than for omnidirectional studies. However, since the magnitude of the solar anisotropy and the consequent amplitude of the daily variations changes from day-to-day, it is important to have an instrument with as high a counting rate as possible so that even days on which the amplitude is small can be significantly classified. Therefore the experimental technique should involve the use of narrow angle telescopes of as large aperture as is possible.

The second aspect of the study should relate to the examination of the worldwide character of the changes in anisotropy. While it has been shown that some aspects of changes in the 12-month mean anisotropy are correlated for a station at the equator (Huancayo) and at stations in the middle latitudes (Cheltenham or Christchurch) it has also been noticed [8] that day-to-day changes which are correlated for Ahmedabad, Freiburg and Amsterdam are not correlated with the day-to-day changes in the equatorial station of Kodaikanal. Classification of days according to the nature and magnitude of the anisotropy occurring on each day is an important task which is meaningful only if changes of the daily variation exhibit certain global characteristics.

Finally, having classified days in terms of the character of the anisotropy, it is worthwhile to study the solar and terrestrial relationships of the changes of anisotropy. For this, we can examine the values of physical quantities such as I, the mean cosmic ray intensity, C_p the daily planetary magnetic character figure and the indices for solar activity on the solar disc on days of different classifications.

We present here the first results of an investigation being conducted since July 1955 at Ahmedabad (Lat. 23°01′ N, Long. 72°36′ E, Geomagn. Lat. 13° N, Alt. 180 ft.).

2 – Experimental technique.

A cubical meson telescope conforming to the specifications of the standard instrument to be used during the International Geophysical Year has been modified to provide additional data. The instrument has three counter trays of area 85 cm × 85 cm, each tray made up of 20 Geiger counters. The vertical separation of the extreme trays is 85 cm and 96.5 g/cm^2 of iron are kept between the two lower trays. In each tray, pairs of adjoining counters are operated with a common electronic quenching unit. 10 vertical triple coincidence telescopes ^{5}T of semiangle 5° in the E-W plane are formed by using separately each pair of counters in a tray. The output of five such pairs is also combined and used to provide 2 vertical triple coincidence telescopes ^{26}T of semiangle 26° in the E-W plane. Finally, the triple coincidences of the complete trays provide the standard telescope ^{45}T of semiangle 45° in the E-W plane. The semiangle in the N-S plane of all telescopes is 45°. The characteristics of the different telescopes are indicated in Table I.

In practice, the records of the 10 narrow angle telescopes ^{5}T are not separately registered, but they are combined into 4 groups, 2 of 3 telescopes each, and 2 of 2 telescopes each. While on a large number of days data from all 10 telescopes are available, there are a number of days when due to instrumental failures some of the telescopes are not in operation. When this happens the useful data on any particular day relate to fewer than 10 narrow angle telescopes and to one or to none of the two 26° telescopes ^{26}T.

TABLE I.

Semi-angles		Number of telescopes available	Bihourly counting rate per telescope	Total bihourly counting rate N	% standard deviation for bihourly rate $100/(N)^{\frac{1}{2}}$
E-W	N-S				
5°	45°	10	1300	13000	± 0.9 %
2 °	45°	2	29000	58000	± 0.4 %
45°	45°	1	100000	100000	± 0.3 %

The satisfactory functioning of the telescopes is verified by comparison of the changes in their daily mean rates. For each day, a daily variation and a daily mean intensity for ^{5}T and ^{26}T telescopes is derived by averaging the data of similar telescopes that are satisfactorily in operation on that particular day. The standard deviation of the data varies according to the number of telescopes in operation on each day. Therefore, in considering the significance of a variation measured on a day, we have to relate it to the standard deviation appropriate to the number of similar telescopes which are in operation.

The daily variation data on each day are first corrected for the influence of the daily variation of barometric pressure using a coefficient of -2.2% per cm of Hg. The appropriateness of using this coefficient has been discussed by SARABHAI *et al.* [4, 16]. The data are then harmonically analysed and the amplitudes and times of maxima of the diurnal and the semidiurnal components of ^{5}T and ^{26}T are calculated.

3 – Types of daily variations.

In the present study, a 2σ level of significance has been adopted when examining the types of daily variations that occur on different days. The amplitude and time of maximum of the diurnal component are physically meaningful only on days on which the daily variation curve is essentially diurnal in character and exhibits one principal maximum during 24 hours. Similarly the amplitude and the time of maximum of the second harmonic are physically meaningful when the daily variation is semi-diurnal in character with two maxima in 24 hours. By examining the daily variation formed by superposition of diurnal and semidiurnal components having a ratio of amplitudes M^D/M^S ranging from 0.2 to 2.0, it is clear that when this ratio is less than 0.75 the final curve always exhibits two pronounced maxima in 24 hours. On the other hand when the ratio is larger than 1.5 the daily variation exhibits only one maximum.

For ^{5}T, in Fig. 1*a* is given the histogram showing the frequency of occurrence of the diurnal maximum for each of 12 bihourly intervals of a day for 103 days on which the diurnal amplitude $M^D \geqslant 2\sigma$. If we now impose the condition that $M^D/M^S \geqslant 1.5$, the resulting histogram is shown in Fig. 1 *b*. This relates to 71 days on which we can conclude from the ratio of the amplitudes of the diurnal and the semidiurnal components that the daily variation has one maximum only. It is observed that by restricting attention to significant days which have only one maximum during 24 hours, the histogram clearly reveals the tendency for the diurnal maximum to occur in one of two preferred periods of the day, at 0700 and at 1500 hours IST. We can therefore distinguish days on which the maximum of the diurnal variation occurs between midnight and noon from those on which the maximum occurs between noon and midnight. A similar classification into « *n* » and « *d* » type days was undertaken by SARABHAI and NERURKAR [6] who observed during an investigation in 1954-55, the tendency for narrow angle telescopes to exhibit daily variations with one of two preferred times of maxima for the diurnal component, when the semidiurnal component was small compared to it. However, at that time, the maxima occurred at 0300 hours and at 1100 hours instead of at 0700 hours and at 1500 hours respectively, during 1956. The shift to later hours of both maxima during the period of about two years from 1954 to 1956 is probably connected with the shift to later hours observed in the time of maximum of the diurnal component of the 12 month mean daily variation since the last minimum of solar activity in 1954.

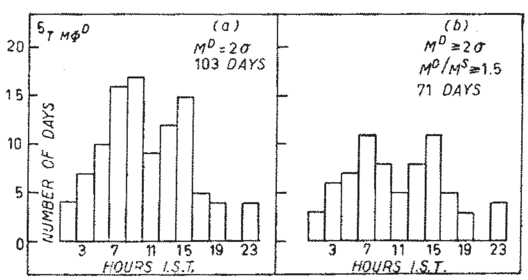

Fig. 1. – The distribution of occurrence of the diurnal maximum for ^{5}T for each of 12 bihours of a day, (*a*) when $M^D \geqslant 2\sigma$, and (*b*) when $M^D \geqslant 2\sigma$ and $M^D/M^S \geqslant 1.5$. M^D and M^S are the per cent amplitudes of the diurnal and the semidiurnal components of the daily variation.

On days when the ratio $M^D/M^S \leqslant 0.75$ and $M^S \geqslant 2\sigma$, we have a daily variation which has a significant semi-diurnal component, predominating over the diurnal component. On such days, the daily variation exhibits two maxima instead of one and we can classify the day as an « *s* » type day.

In order to study the nature of the daily variation on days when the diurnal and the semidiurnal components are of comparable amplitude, i.e. $1.5 > M^D/M^S > 0.75$, and the diurnal component is significant at the 2σ level, we can consider separately the harmonic components of the mean daily variation on such days when the diurnal component has a maximum occurring between midnight and noon, and between noon and midnight.

In Table II are indicated the amplitude and time of maximum of the diurnal and the semidiurnal components for the mean daily variations during

TABLE II.

No.	Character of the variation on each day	Average percentage amplitudes and the times of maxima (expressed in degrees) for the 1st and the 2nd harmonic components of the daily variation.				
		M^D	$M\Phi^D$	M^S	$M\Phi^S$	M^D/M^S
1	$1.5 > M^D/M^S > 0.75$ and $0° < M\Phi^D < 180°$	0.8 ± 0.2	120°	0.3 ± 0.2	− 24°	2.7
2	$M^D/M^S \geqslant 1.5$ and $0° < M\Phi^D < 180°$	0.98 ± 0.15	100°	0.12 ± 0.15	56°	8.2
3	1+2 combined	0.92 ± 0.10	107°	0.06 ± 0.10	18°	15.1
4	$1.5 > M^D/M^S > 0.75$ and $180° < M\Phi^D < 360°$	1.0 ± 0.3	180°+27°	0.4 ± 0.3	38°	2.5
5	$M^D/M^S \geqslant 1.5$ and $180° < M\Phi^D < 360°$	0.90 ± 0.18	18 °+59°	0.04 ± 0.18	− 9°	22.2
6	4+5 combined	0.92 ± 0.15	180°+52°	0.11 ± 0.15	+ 27°	8.4
7	$M^S \geqslant 2\sigma$ and $M^D/M^S \leqslant 0.5$	0.16 ± 0.15	110°	0.23 ± 0.15	48°	0.7

the two groups of days. Also indicated in the table for comparison are the characteristics of the diurnal and the semidiurnal components of the « *n* » and « *d* » type days when $M^D/M^S \geqslant 1.5$ and M^D is significant at the 2σ level. It is observed that even for days on which individually M^D/M^S is between 1.5 and 0.75, the average daily variation has a ratio much larger than 1.5. This indicates that while on individual days we have a semidiurnal component which is comparable to the diurnal component, there is no strongly preferred time of maximum of the semidiurnal component. In consequence, the resultant average daily variation for the 2 groups of days is diurnal in character. Moreover, the time of maximum and amplitude of the diurnal component of the average for the two groups do not differ significantly from those of the « *d* » and « *n* » type days respectively where even on individual days the ratio $M^D/M^S \geqslant 1.5$. The days relating to the two groups can therefore be grouped with « *n* » and « *d* » type days respectively. In effect therefore classification of days can be undertaken on the following criteria:

a) « *n* » type days are those days on which the daily variation has $M^D \geqslant 2\sigma$, $M^D/M^S > 0.75$ and the diurnal maximum occurs between midnight and noon.

b) « *d* » type days are those days on which the daily variation has $M^D \geqslant 2\sigma$, $M^D/M^S > 0.75$ and the diurnal maximum occurs between noon and midnight.

c) « *s* » type days are those days on which $M^S \geqslant 2\sigma$, $M^D/M^S <$ 0.75.

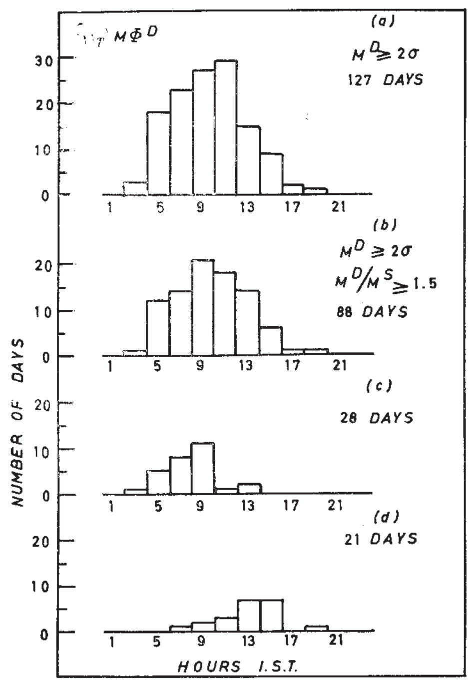

Fig. 2. – The distribution of occurrence of the diurnal maximum for ^{26}T for each of 12 bihours of a day: (*a*) when $M^D \geqslant 2\sigma$, (*b*) when $M^D \geqslant 2\sigma$ and $M^D/M^S \geqslant 1.5$, (*c*) for days on which ^{5}T has a daily variation of « *n* » type, and (*d*) for days on which ^{5}T has a daily variation of « *d* » type.

Fig. 2-*a* and 2-*b* show histograms for ^{26}T corresponding to the histograms shown in Fig. 1-*a* and 1-*b* for the ^{5}T telescopes. It will be observed that the separation of groups of days on which the daily variation is a maximum in the morning or in the afternoon is not as distinct in ^{26}T as for the narrow angle telescope ^{5}T. However, the reality of the occurrence of the daily variation with a diurnal maximum at one of two preferred times of maxima even in ^{26}T is seen by separating the days included in Fig. 2-*a* according to the type recorded by ^{5}T. Thus the histograms of occurrence of time of maximum of the diurnal component of ^{26}T on days on which ^{5}T has a maximum before noon or in the afternoon are shown in Fig. 2 *c*) and 2 *d*) respectively. It is clear that days on which

there is a morning maximum in ^{5}T are associated with an earlier time of maximum in ^{26}T than days on which ^{5}T has a maximum in the afternoon. The separation of the two groups in ^{26}T is however only by about four hours in place of about 8 hours for ^{5}T.

In Fig. 3 we show separately the daily variations for ^{5}T and ^{26}T averaged for all days on which

a) there is a significant « *n* » type of variation,

b) there is a significant « *d* » type of variation,

c) there is a significant « *s* » type of variation, and

d) there is any one of the above three types i.e. at least one of the harmonic component is significant but there is no other criterion to separate the days.

It is observed from the Fig. 3 *d*) that if all days with significant variation are considered, but no classification is undertaken, the average daily variations of ^{5}T and ^{26}T are not significantly different from each other. The amplitude of variation recorded by narrow angle telescopes ^{5}T is no greater than the amplitude from the wider angle telescopes ^{26}T. However, if we classify the variations into the « *d* », « *n* » and « *s* » types there is marked difference in the results from, ^{5}T and ^{6}T telescopes. The amplitude of the daily variation in narrow angle telescopes is much greater than in telescopes with wider angles. It has been pointed out by EHMERT [12] and by SARABHAI and NERURKAR [6] that the ratio of amplitudes of variations measured by narrow and wide angle telescopes is not constant. However, the average ratio of amplitudes of the diurnal components of ^{5}T and ^{6}T is 1.8 for the « *d* » type and 1.7 for the « *n* » type. The ratio of amplitudes for the semidiurnal components of narrow and wide angle telescopes is 2.9 for « *s* » type days. These ratios may be compared to the average ratios of 3.0, 2.0 and 1.0 reported by NERURKAR [13] for ^{5}T and ^{15}T telescopes for the period 1954 ÷ 55.

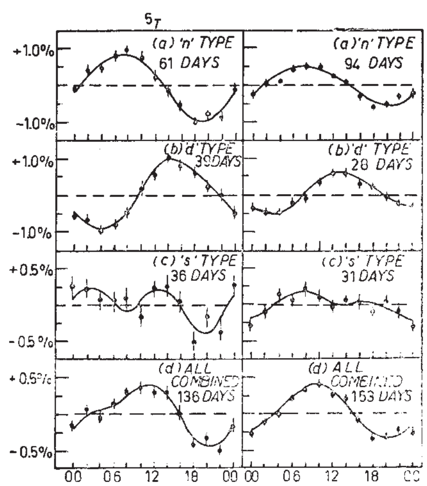

Fig. 3. – Average daily variation for « *n* », « *d* » and « *s* » type days for ^{5}T and ^{26}T telescopes and the average daily variation for all these types of days taken together.

By the side of the curves in Fig. 3 the number of days are indicated on which daily variations of significant amplitude of each type are observed by

^{5}T and ^{26}T telescopes during the period February 1956 to December 1956. Of the total number of days on which data are available, a significant daily variation is observed on 44.7% of days for ^{5}T and on 58.6% of days for ^{26}T. The « *n* » type of daily variation occurs most frequently. It accounts for 44.8% of the days of significant variation for ^{5}T and 61.4% for ^{26}T. The corresponding percentages for « *d* » type days are 28.7% and 18.3% respectively; while for « *s* » type days they are 26.5% and 20.3% respectively. The percentages given here do not indicate directly the relative frequency of occurrence of the daily variations of different types. This is because the amplitudes of « *n* », « *d* » and « *s* » type variations for the same telescopes are not equal; as can be seen from Fig. 3. The level of significance which establishes a lower limit of amplitude below which we disregard data for the purpose of classification, thus acts differentially in respect of the dsitribution of amplitude of each type of variation.

4 - Classification of days according to the character of the daily variation.

It has been demonstrated in the preceding section that there is a tendency for « *n* » and « *d* » type days records selected according to ^{5}T telescope to be respectively associated with earlier and later times of maxima of the diurnal component of ^{26}T telescopes. The validity of classification of days into « *n* » and « *d* » types is more clearly indicated in Fig. 4 where the time of maximum of the diurnal component of ^{5}T is plotted against the time of maximum of the diurnal component of ^{26}T on each day on which both the diurnal components are significant at their respective 2σ levels.

There are 49 such days, and it is clear that there is a remarkable association of the time of diurnal maxima recorded by the ^{5}T and ^{26}T telescopes. The correlation between the pairs of values in Fig. 4 relating to each day is $+0.86 \pm 0.04$. The regression lines indicate that narrow angle telescopes reveal larger changes than the wider angle telescopes, in confirmity with the observ-

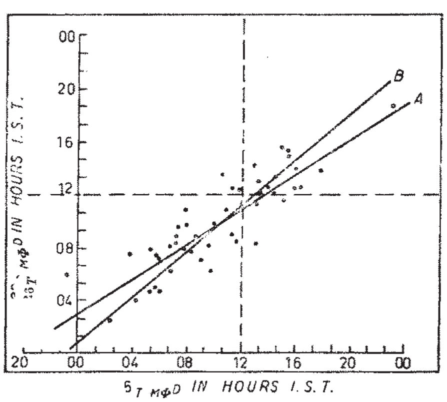

Fig. 4. – Diagram showing the relation between the times of maxima of the diurnal components of the daily variations measured on individual days by ^{5}T and ^{26}T telescopes. The line of regression A is of ^{26}T $M\Phi^{D}$ on ^{5}T $M\Phi^{D}$, and line B is of ^{5}T $M\Phi^{D}$ on ^{26}T $M\Phi^{D}$.

ation made by SARABHAI *et al.* [4] from a comparison of Huancayo ion chamber and Ahmedabad counter telescope data. The grouping of times of maxima around two epochs, one before noon and the other after noon, is clearly seen, as in the histograms of Fig. 1. The horizontal and vertical lines corresponding to noon indicate the boundary for the classification into « *n* » and « *d* » type days. There are only two points out of 49 where there is substantial disagreement between ^{5}T and ^{26}T telescopes in classifying according to « *n* » and « *d* » types. There are eleven days on which ^{5}T and ^{26}T telescopes simultaneously register significant « *s* » type daily variations. As against this, there are 20 days on which either ^{5}T or ^{26}T has a « *d* » or an « *n* » type variation, and the other has an « *s* » type variation. If we, therefore, consider all classifications, we have a total of 58 days on which both types of telescopes are in agreement. As against this, there are 22 cases of disagreement, most of them involving an « *s* » type classification. When one realises that a large semidiurnal component, significant at the 2σ level, can arise either as an adjunct to a main diurnal component, or by itself because the variation is truly semidiurnal in character, it is clear that the present system of classification into « *s* » type days requires further refinement.

In Fig. 5 we show on a Bartel's diagram, days classified as « *n* », « *d* » and « *s* » according to the daily variation recorded by ^{5}T telescopes. Also indicated on the diagram are those days on which no data are available for evaluating daily variation. It will be observed that there is a tendency for at least the « *n* » and « *d* » type days to occur in groups of 2 to 3 days. There is also evidence of a 27 day recurrence tendency, particularly for « *d* » type days.

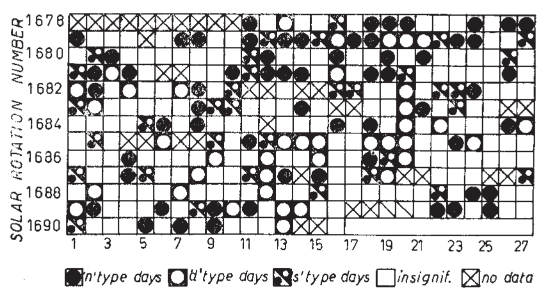

Fig. 5. – Bartel's diagram showing the dates of occurrence of « *n* », « *d* » and « *s* » type of daily variation. Days on which ^{5}T is inoperative are indicated as « no data » days.

5. – Correlated changes of anisotropy, mean intensity and C_p, the daily magnetic planetary character figure.

For studying correlated changes it is convenient to use the method of superposed epochs. We consider as an epoch each day when a particular type of daily variation occurs, and compute the average of daily mean intensity I and C_p on days of epoch as well as on 5 days on either side of epoch.

Such analysis is conducted separately for « *n* » type, « *d* » type and « *s* » type days indicated in the Bartel's diagram in Fig. 5.

In studying the correlated changes of the daily variation and of the daily mean intensity *I*, the latter is first corrected for the influence of change of daily mean barometric pressure using a coefficient $\alpha_B = -1.8\%$ per cm Hg, derived experimentally from the present data. The corrected daily mean intensity still exhibits changes of a long term character due to seasonal and other factors. The long term changes are next removed, without eliminating short time fluctuations of *I* over periods of 5 to 10 days, by taking moving averages of *I* over a period of 13 days and applying correction for the variation of the moving averages. In Fig. 6 *a*), *b*) and *c*) are indicated the values of *I*

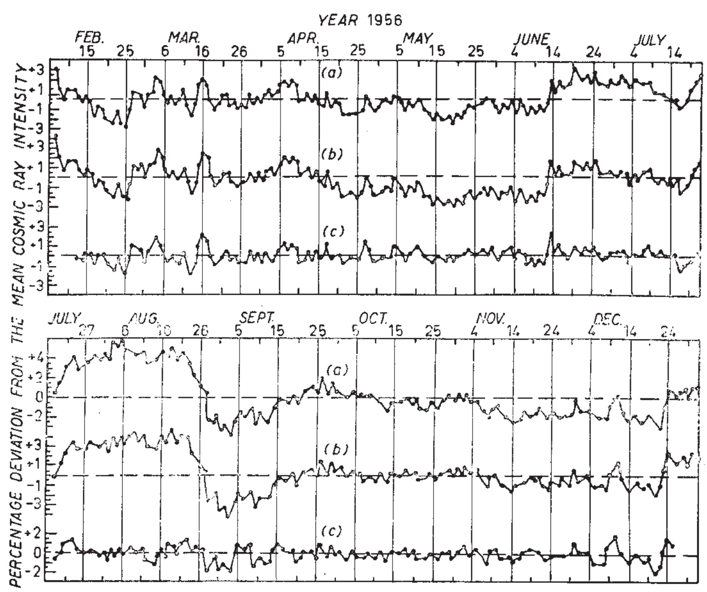

Fig. 6. – The day to day change of the daily mean intensity *I* of cosmic rays as observed by ^{5}T, (*a*) uncorrected intensity, (*b*) corrected for the day to day changes in barometric pressure, and (*c*) corrected for long term changes (see text).

before applying pressure correction, after applying pressure correction and after removing long period variations respectively. The latter values of *I* are used in the analysis of correlated changes.

The result of this analysis for the daily mean intensity measured by ^{5}T is shown separately in Fig. 7 *a*), *b*) and *c*) for « *n* », « *d* » and « *s* » type days respectively. The change of C_p in each case is also shown.

A remarkable result of this analysis is that « *n* » type days are accompanied by an increase of intensity of about $0.16 \pm 0.03\%$ from 3 days prior to epoch.

The intensity is normal on epoch, but decreases significantly after epoch to reach, 2 days later, a minimum value about ($0.27 \pm 0.03\%$) less than the average daily mean intensity for the entire period of observation. « *d* » type days on the other hand are associated with increase of mean intensity which remains about ($0.17 \pm 0.04\%$) above the average from epoch to $+2$ days. A slight decrease in intensity before epoch is not significant. For « *s* » type days, the mean intensity is nearly normal during the epoch period and on 3 days before and after it. For C_p, the values are high compared to the mean of the entire period, from -3 to $+1$ days of the « *n* » type epochs. For « *d* » type epochs this is also true for $+1$ and $+2$ days after the epoch day, but there is a C_p minimum in the interval 0 to -1 days before the epoch. For « *s* » type epochs, C_p values show a minimum near about the epoch day and an increase 4 days after the epoch.

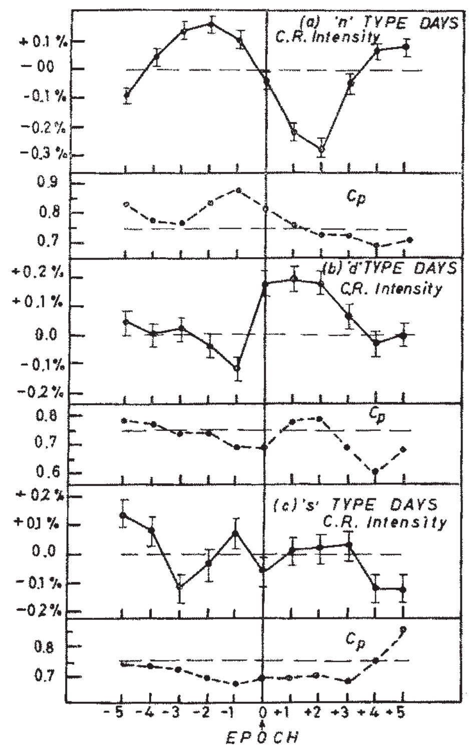

Fig. 7. – Average daily mean cosmic ray intensity changes on -5 to $+5$ days, (*a*) for « *n* » type days as epochs, (*b*) for « *d* » type days as epochs and (*c*) for « s » type days as epochs. The corresponding average change of magnetic character figure C_p in each case, is also shown.

6. – Discussion.

The results presented here are of a preliminary character and indicate certain tentative conclusion which can be drawn from the analysis of data from narrow angle telescopes operated over a period of 11 months in 1956.

It is seen that on a majority of days, which have a daily variation of significant amplitude, the variation can be designated as belonging to the « *n* », the « *d* » or the « *s* » type. The experimental technique at present does not permit a variation to be established at the 2σ level of significance unless it has a harmonic component of amplitude greater than 0.74% for ^{5}T and 0.34% for ^{26}T telescopes. With an improvement of technique involving a larger effective aperture of narrow angle telescopes than at present, it would be possible to extend the study to variations of smaller amplitude than is now possible. It is not known what characteristics would be shown by the daily variations of small amplitude.

The difference between « *d* » and « *n* » types of variations is more marked for narrow angle telescopes than for wide angle instruments. Thus in deriving an average of the daily variation over an extended period of days, the reduction of amplitude for ^{5}T is much greater than for ^{26}T. If we wish to compare the amplitudes of daily variations recorded by narrow and wide angle telescopes, the comparison should be made separately for each type of variation and not for an average variation having a combination of all types of variations. This point requires to be borne in mind when considering the results of other workers who have compared the amplitudes of the daily variations of narrow and wide angle telescopes without attempting to classify the different types of variations.

The shift towards later hours, by about four hours, from 1954 to 1956, of the time of maximum of « *n* » as well as of « *d* » type of variations seems to indicate that the striking changes observed in the 12 month mean daily variation can be due not only to the change of frequency of occurrence of days of each type, but to an intrinsic shift of time of maximum and of the anisotropy. Close study over an extended period with narrow angle telescopes is required to understand better the nature of the changes that occur.

The classification of days according to the character of the observed daily variation requires to be further refined so that when the classification is made, it relates to a characteristic of the anisotropy, and is therefore detectable on a global basis. In the present study the validity of the characterisation is tested only by comparison made of two types of telescopes operating at one station. It is important to extend this comparison to other instruments at the same station and at different stations.

One of the most important conclusions that can tentatively be drawn from the present study is the one concerning correlated day to day changes of anisotropy and the daily mean intensity. The main weakness in the evidence that is presented lies in the absence of upper air meteorological data with which the daily mean intensity could properly be reduced to standard atmospheric conditions. We have been unable to evaluate the extent of error which can be introduced on this account in our analysis. At low latitudes however, day to day changes are not as important as at high latitudes, and it is believed therefore that a more accurate correction for meteorological changes than we have been able to apply to our values of daily mean intensity, would not alter our conclusions substantially.

The observation that « *n* » type days are associated with decreases of intensity and « *d* » type days with increases of daily mean intensity after the respective epochs is one of great significance in the interpretation of processes responsible for the anisotropy and changes of cosmic ray intensity. An increase of intensity can result either by the presence of a source of cosmic rays within the solar system, or what is more likely, by a modulation process involving the increase of energy of cosmic rays incident from certain directions. In the latter case one would require the creation of an ordered electric field in appropriate regions of interplanetary space as viewed from the earth. Since the space is believed to be often filled with clouds of ionized solar matter, it would be difficult to sustain the field in the absence of trapped coherent magnetic fields within the ionized streams.

The present evidence, along with that of SIMPSON *et al.* [14], are the only ones in support of the existence of variations of intensity which represent not just decreases, as shown by HEERDAN and THAMBYAHPILLAI [15], but increases of intensity as well. Since, as discussed above, they are indicative of the existence of coherent magnetic fields and not just turbulent fields in interplanetary space, it is of great importance to confirm experimentally these findings with a large number of independent investigations extending over a long period of time. Our present study relates to only 11 months of observations and it is therefore necessary to take the present conclusions as tentative for the time being.

* * *

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A SOLAR FLARE TYPE INCREASE IN COSMIC RAYS AT LOW LATITUDES

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On 23rd February 1956, the occurrence of a large solar flare was associated with a number of remarkable events observed at different stations on the earth. In addition to ionospheric disturbance, a spectacular increase of cosmic ray intensity has been reported by a number of observing stations situated in the middle latitudes.

The Physical Research Laboratory has for some years been conducting a systematic study of the ionosphere and of cosmic ray intensity at low latitudes. Continuous measurement of cosmic radio noise has been started recently. A report by Ramanathan *et al.*[1] of the events observed at Ahmedabad on 23rd February by an ionospheric recorder and a 25 Mc/s cosmic radio noise monitor is published separately. We give here the results of measurements of cosmic ray meson intensity made with standard telescopes at

1.	Ahmedabad	..	A	—73° E,	23° N,	13° N	geomagnetic,	sea-level
2.	Kodaikanal	..	K	—77° E,	10° N,	1° N	,,	2,343 m.
3.	Trivandrum	..	T	—77° E,	8° N,	1° S	,,	sea-level

Ahmedabad and Trivandrum are stations at sea-level.

Trivandrum and Kodaikanal are stations on the geomagnetic equator, the latter being situated at a mountain elevation. Details of the standard telescopes have been published elsewhere.[2] The telescopes measure triple coincidences of cosmic rays that can penetrate 10 cm. of lead, and which arrive in directions inclined with the vertical at an angle not exceeding 22° in the E-W plane, and 37° in the N-S plane.

I. Solar Flare Type Increase on 23rd February 1956

During the period 21–2–1956 to 25–2–1956, three independent instruments were functioning satisfactorily at Ahmedabad, while at Kodaikanal and Trivandrum there were at each station one or two independent telescopes in operation. In Fig. 1 are shown the per cent. hourly deviations of meson intensity measured by each telescope on 22nd, 23rd and 24th February. No corrections of any kind have been applied to the data. For each station hourly data from the different telescopes have been combined and the average per cent. hourly deviations are plotted. The average per cent. hourly deviations of all 7 telescopes at the three stations are also shown. In Table I we give

TABLE

Per cent. average hourly deviations of meson intensity at Ahmedabad, Kodaikanal

75° L.M.T.	21—2—1956 A	K	T	Ave.	22—2—1956 A	K	T	Ave.
2330 to 0030	+1·58		+0·26	+0·92	−0·02	−1·17	+0·98	−0·07
0030 to 0130	+0·42		−2·23	−0·91	+0·05	+0·66	+4·35	+1·68
0130 to 0230	−0·02		−0·70	−0·36	+1·56	+0·83	+1·10	+1·16
0230 to 0330	−0·05		−3·07	−1·56	−1·19	−0·33	+0·55	−0·32
0330 to 0430	−1·86		−1·92	−1·89	+0·44	+1·50	−0·43	+0·50
0430 to 0530	+0·53		−1·67	−0·57	+0·11	−1·00	−0·51	−0·46
0530 to 0630	+1·01		−0·10	+0·46	+1·17	+0·34	+4·31	+1·94
0630 to 0730	+0·68		−1·51	−0·42	−3·06	+0·67	+0·74	−0·55
0730 to 0830	−2·36		−0·64	−1·50	−0·84	+0·34	+3·47	+0·99
0830 to 0930	−2·13		+2·70	+0·29	+1·23	+1·17	+0·25	+0·88
0930 to 1030	−1·09		+3·51	+1·21	+0·49	+4·33	+2·75	+2·52
1030 to 1130	+0·96		−1·25	−0·15	+0·19	−0·33	+5·76	+1·87
1130 to 1230	+2·38		+0·22	+1·25	−2·47	+2·34	+0·58	+0·15
1230 to 1330	+0·85		−1·76	−0·45	−1·58	−0·83	+0·41	−0·66
1330 to 1430	−1·12		+0·27	−0·43	+1·74	+2·67	+3·06	+2·49
1430 to 1530	−2·18		−1·75	−1·97	+1·79	+3·00	−1·61	+1·06
1530 to 1630	−0·60		+0·93	+0·17	−1·73	+1·00	+0·83	+0·03
1630 to 1730	+0·37		−0·57	−0·10	−0·52	−3·83	−4·08	−2·81
1730 to 1830	−3·17		−1·49	−2·33	−1·80	+0·50	−1·52	−0·94
1830 to 1930	+1·80		−0·02	+0·89	−1·90	+2·67	−1·96	−0·39
1930 to 2030	−0·95		−0·32	−0·64	+0·06	−2·35	−1·96	−1·41
2030 to 2130	−1·50		−1·38	−1·44	−2·13	+1·00	−2·39	−1·50
2130 to 2230	−2·98		+3·08	+0·05	+2·08	−0·34	−5·16	−1·14
2230 to 2330	+0·24		−2·91	−1·22	+2·40	+0·84	−2·50	+0·25

the average hourly deviations at A, K and T as well as the combined average hourly deviations for all three stations. Data commence from two days prior to the day of the solar flare and end two days following the flare. Since the

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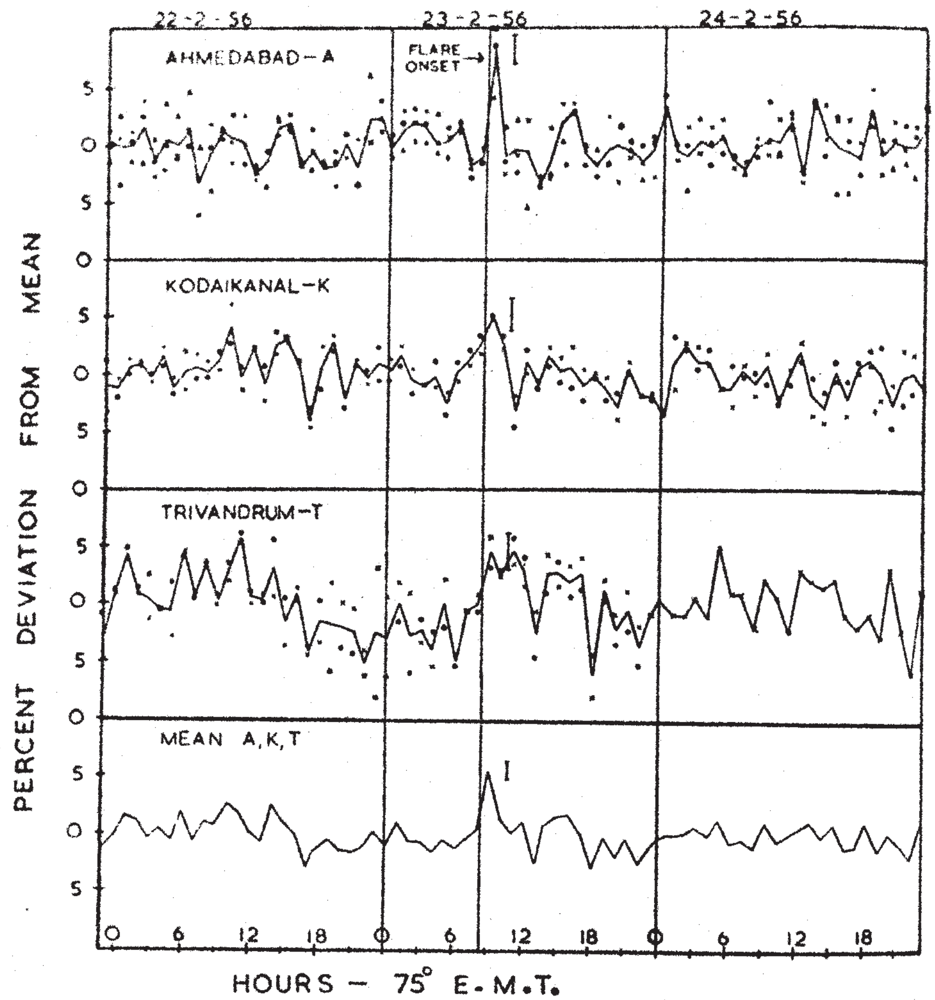
and Trivandrum and the per cent. average hourly deviations for the three stations

23—2—1956				24—2—1956				25—2—1956			
A	K	T	Ave.	A	K	T	Ave.	A	K	T	Ave.
−0·08	+0·33	−2·92	−0·89	+3·19	−3·45	+0·81	+0·18	+1·90	+0·83	+2·04	+1·59
+1·40	+1·50	+0·11	+1·00	−0·47	+1·00	−0·81	−0·09	−4·06	+0·83	−2·10	−1·78
+1·80	−0·67	−2·86	−0·57	−0·98	+2·33	−1·02	+0·11	+2·41	−0·66	−1·53	+0·07
+1·60	−1·00	−2·32	−0·57	+0·10	+1·33	+0·61	+0·68	−1·78	−2·00	−1·52	−1·77
0·00	−0·16	−4·15	−1·43	−0·16	+1·23	−1·22	−0·01	+3·16	+0·49	−2·40	+0·41
+0·30	−1·67	−0·02	−0·46	+0·70	−1·33	+4·89	+1·42	+1·23	+2·66	−2·13	+0·58
+1·60	+0·17	−5·10	−1·11	−1·48	−1·16	+0·81	−0·67	+0·38	+1·00	+0·06	+0·48
−1·70	+1·33	−0·75	−0·37	−2·15	+0·16	+0·81	−0·39	+0·73	−0·50	+1·18	+0·47
−1·30	+2·50	+0·06	+0·42	−0·32	−0·99	−2·24	−1·18	+0·46	+0·49	+0·69	+0·54
+7·60	+4·83	+4·57	+5·66	+0·94	+0·33	+2·24	+1·17	+0·43	+2·33	+3·62	+2·12
−0·91	+2·66	+2·60	+1·45	+0·07	−2·33	+0·61	−0·53	−0·35	−2·00	+4·76	+0·80
−0·47	−3·33	+4·61	+0·27	+2·08	−0·33	−2·44	−0·23	−1·22	+0·83	+1·97	+0·52
−0·59	+1·00	+2·89	+1·10	−2·68	+1·83	+2·85	+0·67	−0·47	−2·00	−0·17	−0·88
−3·31	−1·00	−2·60	−2·30	+3·02	−1·99	+2·24	+1·09	−0·92	−0·83	−0·66	−0·80
−1·40	+1·50	+2·60	+0·90	+0·86	−2·99	+1·43	−0·23	+1·19	+2·17	+3·91	+2·43
+1·86	+0·33	+2·66	+1·61	−0·01	+0·17	+2·24	+0·80	−1·86	+2·00	+0·98	+0·37
+2·95	+0·50	+1·86	+1·77	−0·72	−2·12	−1·02	−1·29	+1·00	+1·83	+0·25	+1·03
−0·84	−1·00	−2·61	+0·26	−1·24	+0·50	−2·24	−0·99	+3·89	+2·00	+0·74	+2·21
−1·78	−0·16	−6·26	−2·73	+2·94	+1·33	−1·02	+1·08	−0·40	+1·49	+2·36	+1·15
−0·38	−1·83	+1·24	−0·16	−1·00	+0·01	−2·85	−1·26	+1·37	−4·17	−1·46	−1·30
−0·15	−2·83	−2·13	−1·70	+0·11	−2·84	+3·05	+0·10	+0·30	+0·83	−3·15	−0·67
−0·53	−0·50	−0·54	−0·19	−0·11	−0·34	−2·44	−0·96	−0·10	−1·83	−0·73	−0·88
−1·65	−2·00	−3·56	−2·40	−0·24	−0·01	−6·11	−2·12	−0·47	−0·83	−2·31	−1·20
−0·68	−2·00	−0·81	−1·16	+1·58	−1·16	+1·99	+0·80	−0·80	+0·05	+1·55	+0·27

photographic records were made hourly at the half hours according to 75° EMT, which is almost local time at the three stations, and the onset of the flare was observed at Ahmedabad by the sudden absorption of cosmic



TEXT-FIG. 1. Per cent. hourly deviations of cosmic ray meson intensity at Ahmedabad, Kodaikanal and Trivandrum and the average of the hourly deviations at the three stations on 22nd, 23rd and 24th February 1956. The hourly deviations of each individual telescope are also indicated with appropriate symbols.

radio noise at about 0832 hours 75° EMT, we are fortunate in having the onset of the flare almost coincide with the commencement of the hourly interval over which the cosmic ray intensity is averaged.

At Ahmedabad during the hour immediately following the flare the average deviation is $+7 \cdot 6 \pm 1 \cdot 3\%$. During the same hour at Kodaikanal and at Trivandrum the average deviations are $+4 \cdot 8 \pm 1 \cdot 45\%$ and $+4 \cdot 6$

$\pm 1\cdot 64\%$ respectively. The average hourly deviation at Ahmedabad rarely exceeds $\pm 3\%$ and therefore the increase of $7\cdot 6\%$ after the solar flare on 23–2–1956 stands out clearly. At Kodaikanal and Trivandrum the hourly deviations are much larger than at Ahmedabad and consequently the increases during the hour following the flare are not equally striking even though at both stations there are large significant positive deviations. In the average of deviations of all seven telescopes we get the advantage of suppressing deviations which are not simultaneously present at all three stations. We then have a prominent average increase of $+ 5\cdot 7 \pm 0\cdot 8\%$ during the hour immediately following the solar flare. This is considerably larger than other hourly deviations throughout the period. The difference between the increase at Ahmedabad and the average increase at all three stations is not significant. It is therefore not possible to comment on the difference in the flare effect due to change from 0–13° geomagnetic North latitude. There is also no significance difference between the increases at Kodaikanal and Trivandrum, in spite of the difference in elevation of about 2,343 m. But in view of the standard error of the determination at each place, the existence of a difference cannot be excluded.

II. Interpretation

The present evidence establishes for the first time the existence of a solar flare increase in cosmic rays at low latitudes near the geomagnetic equator. During the four earlier observed instances of solar flare increases in cosmic ray intensity, no significant increase was noticed at stations in latitudes less than 25°. It is difficult to say whether the present flare is unique in producing measurable effects at the Equator, since equipment comparable to ours was not operating during earlier occasions at low latitudes. As discussed later in this communication, solar cosmic rays emitted during large flares can arrive only from certain restricted directions from the sky above the instrument. This effect becomes more pronounced at low latitudes and therefore the chance of recording a significant flare type event with an ionisation chamber with omnidirectional sensitivity is rather less favourable than with a telescope pointing to an appropriate direction. It is not known so far whether the Carnegie Institution ionisation chamber at Huancayo has registered an increase after the recent flare. A negative answer will leave ambiguous the position regarding the uniqueness of the present flare since its occurrence at a time when all three stations in India were near the impact zone appropriate to positive particles originating from the sun has perhaps favoured the observation of the increases at the Indian stations as compared to Huancayo.

From evidence prior to the recent flare, the generally accepted interpretation of the solar flare increase in cosmic ray intensity was that it is caused by a burst of positively charged particles from the sun which for the purpose of this effect, appears to have a diameter of about 30° as viewed from the earth. The particles were believed to have a maximum energy of about 10 Bev and an energy distribution much steeper than the distribution of the normal primary cosmic rays. Even though increases at stations at high latitudes, such as Godhavn, Resolute and Thule have presented difficulties, since the stations lie outside normal impact zones for particles of these energies from the sun, attempts have been made to retain the postulate of solar origin by invoking the aid of interplanetary magnetic fields. The discovery of the increase at low latitudes now makes it necessary to revise some of our thinking on this subject. If the effect is caused by positively charged particles from the sun, the following conclusions would appear to result from our observation of the increase at the magnetic equator and at 13° North geomagnetic latitude where the minimum cut-off rigidity for vertical particles is about 17·0 and 16·2 Bev/Zc respectively. In order to correct for the deflection in the geomagnetic field, and to determine the energies of positive particles originating from the sun which could play a role in causing the increase of intensity, we can use the most valuable results of Brunberg and Dattner.[3]

On 23rd February 1956, the declination of the sun was − 10°. At 0900 hours local time the position of the sun, with an angular diameter of 30° as viewed from the earth, is indicated in the diagrams kindly prepared by Brunberg and Dattner for Ahmedabad and Kodaikanal and reproduced in Figs. 2 (A) and (B) respectively. It will be observed that at Ahmedabad solar protons must have energies between 35 and 65 Bev. Furthermore these particles are incident at the top of the atmosphere at directions in the N-S plane which make angles with the zenith from about 16° S–50° S. Correspondingly at Kodaikanal or Trivandrum the solar particles would have to be within an energy range 35–70 Bev and would be incident in directions from about 8° S–45° S inclined to the vertical in the N-S plane. At all three stations no particles from the sun could arrive in the E-W plane. Between the stations at the magnetic equator and at 13° N geomagnetic latitude, there is no marked change in the limits of directions of arrival of the trajectories or of the energies of allowed protons of solar origin. Moreover we have not established a significant difference between the per cent. increase of meson intensity at the three stations after the flare. It is therefore appropriate to consider the average conditions for solar protons in low latitudes in conjunction with the average increase of 5·7%.

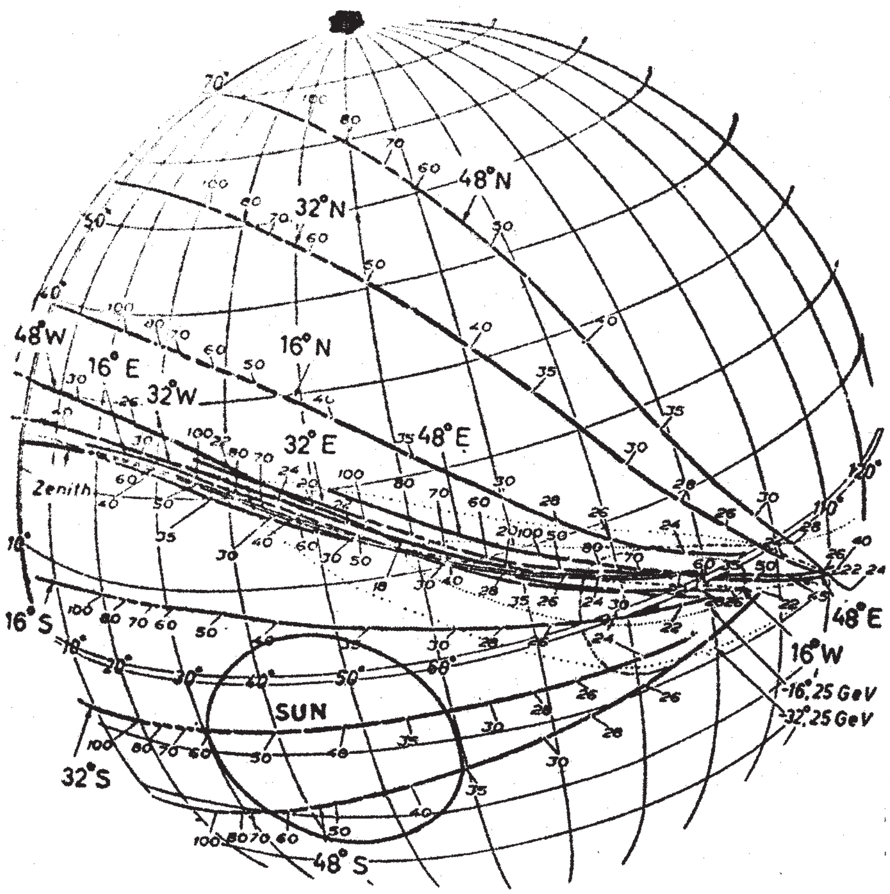
III. The Intensity of 50 Bev Solar Flare Protons

If N* be the number of primary solar protons in the energy range 35–67·5 Bev per sec. per cm.² area normal to the direction of incidence, and N be the number of background cosmic rays in the same energy range per sec. per cm.² per steradian, we would like to calculate the ratio $x = N^*/N$. At the present moment there are a number of uncertainties involved in relating N* and N to the corresponding counting rates n^* and n in our telescopes due to solar particles and background intensity respectively of primaries in the energy range 35–67·5 Bev. This is mainly because the published results of Brunberg and Dattner relate only to the E-W and N-S planes. We have therefore no precise way of determining the limiting directions in other azimuths which define the extent of cone which is available to the solar protons during this flare. From the interceptions of the cone on the N-S plane through zenith, and from the semi-angle of the telescopes in the same plane we estimate that solar protons can have not more than a fifth of the cone available to background intensity measured in our telescopes. Thus at the present moment we can calculate only a lower limit to the ratio x, indicative of the order of its magnitude. Under these circumstances it is appropriate to disregard a correction for the difference in the effective aperture of the telescope for solar protons and background intensity. Furthermore, since the mean primary energy for background intensity is comparable to the mean energy of 50 Bev for solar protons, we can also assume that the same multiplicity factor can be applied in each case to derive the sea-level intensity in terms of the intensity at the top of the atmosphere. Thus we have $x = N^*/N \approx 5\, n^*/n$. If n' be the counting rate due to background in the entire energy range from geomagnetic cut-off to infinity, and we assume an integral spectrum of the form $E^{-1 \cdot 7}$ for the primaries of background intensity, the proportionate increase of intensity

$$\cdot 057 = \frac{n^*}{n'} \approx \frac{x}{5} \frac{[E^{-1\cdot 7}]_{35}^{67\cdot 5}}{[E^{-1\cdot 7}]_{10\cdot 5}^{\infty}}.$$

We then have $x \approx 1 \cdot 5$, indicating that averaged over one hour following the flare, the flux of solar protons in the energy range 35–67·5 Bev is about 1·5 times the flux of background cosmic rays in the same energy range.

Visual records indicate that the flare on 23–2–1956 was of magnitude 3 and occurred at 22·5° heliographic north and 73° heliographic west. One

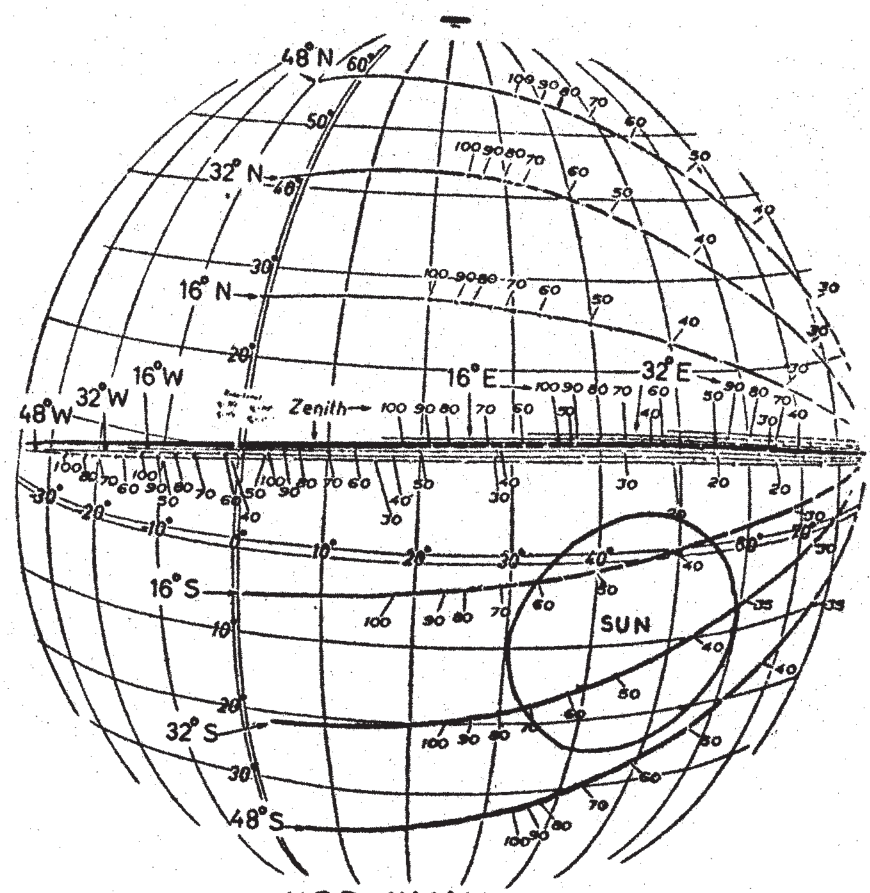


AHMEDABAD

A

TEXT-FIG. 2. Dagrams prepared by Brunberg and Dattner, showing the asymptotic co-
to the zenith in the North-South and East-West Planes at (A) Ahmedabad, (B) Kodaikanal.
at 0900 hours 75° EMT is marked in the diagrams. For further explanation, reference may be

accept the rather remarkable conclusion that protons of energies as great as 35–67·5 Bev can be ejected from the sun in a cone of semi-angle as large as 75°. A consequence of assuming throughout the cone a flux of solar protons as large as is observed near the earth would be that during the hour following the solar flare of magnitude 3 the sun emitted about 10^{38} protons of an energy of about 50 Bev. This may be compared with the estimate made by Simpson



KODAIKANAL

B

ordinates of velocity vectors of protons of different energies incident in various directions inclined
The position of the sun on 23-2-1956 with an assumed diameter of 30° as viewed from the earth,
made to the original paper.[8]

et al.[4] of 2×10^{23} protons per second of mean energy 4 Bev averaged over a solar cycle due to flares of magnitude equal to or greater than 1+.

IV. Conclusion

When we consider the sharp increase of intensity and its short mean life reported by other workers who have made continuous ionisation chamber records, we are forced to conclude that events occur on the sun which involve the acceleration of a very large number of particles to much higher energies than has been hitherto suspected or indeed thought possible. The alternative to such a conclusion might involve the abandoning of our present belief that during such events particles are actually emitted from the sun. Any modulation theory would run into the difficulty, amongst others, that the interval between the observed maximum of visual intensity of the flare and the maximum of cosmic ray intensity is only of the order of about 10–15 minutes.

We are indebted to Drs. Brunberg and Dattner for their proton-energy diagrams and to Professor H. V. Neher and Mr. Nerurkar, for helpful discussions. We are also grateful to Mr. Thakore and Mr. Vishwanath, for computational assistance. The present work is generously financed by the Atomic Energy Commission of India.

SUMMARY

During the hour following the big solar flare on 23–2–1956, an average increase of $+5\cdot7\pm0\cdot8\%$ has been observed in meson intensity measured with standard telescopes at Ahmedabad, Kodaikanal and Trivandrum. This is the first report of a significant solar flare type increase in cosmic rays near the geomagnetic equator. If the increase is due to solar protons travelling in approximately direct paths, the energy of the protons must extend from about 35–67·5 Bev. It is estimated that the average flux of such protons is approximately equal to 1·5 times the flux of general cosmic ray intensity in the same energy range. During the hour, the sun is estimated to have emitted more than 10^{28} protons of about 50 Bev energy.

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PAPER 39

THE ANISOTROPY OF PRIMARY COSMIC RADIATION AND THE ELECTROMAGNETIC STATE IN INTERPLANETARY SPACE

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ABSTRACT

Study of the anisotropy of cosmic rays from the measurement of the daily variation of meson intensity has demonstrated that there are significant day-to-day changes in the anisotropy of the radiation. New experimental data pertaining to these changes and their solar and terrestrial relationships are discussed.

An interpretation of these changes of anisotropy in terms of the modulation of cosmic rays by streams of matter emitted by the sun is given. In particular, an explanation for the existence of the recently discovered types of daily variations exhibiting day and night maxima respectively, can be found by an extension of some ideas of Alfvén, Nagashima, and Davies. An integrated attempt is made to interpret the known features of the variation of cosmic ray intensity in conformity with ideas developed above.

The study of the daily variation of cosmic ray intensity provides a unique tool for the evaluation of the anisotropy of the primary cosmic radiation, and changes occurring in it. Since the anisotropy is related to theories of the origin of cosmic radiation and to the electromagnetic state in interplanetary space, it is of importance to summarize the current status of our knowledge derived from measurements of the daily variation of cosmic ray intensity.

1. The daily variation of cosmic rays and the anisotropy of the primary radiation is of a highly variable character. This is seen in large long-term changes of the 12-monthly mean daily variation of meson intensity (Sarabhai and Kane [1], Sarabhai, Desai and Venkatesan [2], Thambyahpillai and Elliott [3], Steinmaurer and Gheri [4]), the day-to-day changes correlated with magnetic character figure and the occurrence of large amplitudes of the daily variation of meson intensity on groups of days

(Sittkus[5], Remy and Sittkus[6]). It is seen from Fig. 1 that on these same days the daily variation at Amsterdam (H. F. Jongen, private communication) at $\lambda = 54^\circ$ N, at Ahmedabad (U. D. Desai) $\lambda = 13^\circ$ N show similar features. However, Kodaikanal (D. Venkatesan) on the magnetic equator

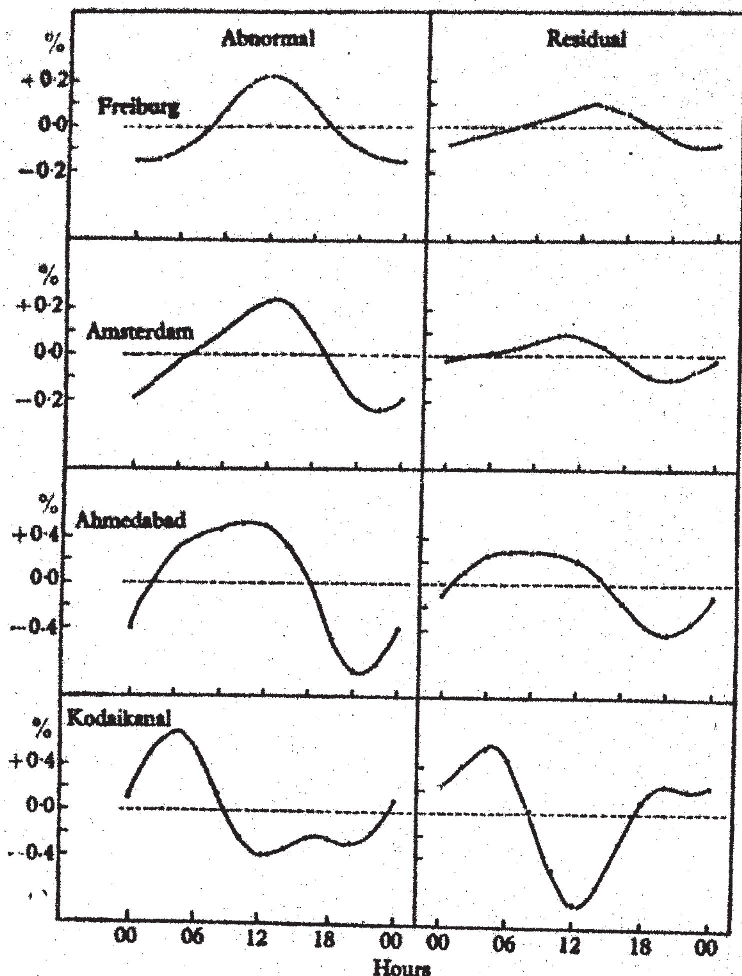

Fig. 1. Comparison of the daily variation at Freiburg (Sittkus), Amsterdam (Jongen), Ahmedabad (Desai) and Kodaikanal (Ventakesan) on days of abnormal amplitudes at Freiburg with the daily variation on residual days.

does not exhibit any marked difference on days on which Sittkus gets abnormal amplitudes.

2. During several years the daily variation, particularly at low latitudes, exhibits two maxima instead of one. This is seen not only in data from Huancayo during 1937–52 (Sarabhai, Desai and Venkatesan[9]) but also

in data at Ahmedabad, Kodaikanal (Venkatesan and Sastry) and Trivandrum (Duggal) during 1950–5 as shown in Fig. 2. The changes of the daily variation indicate that they are primarily due to two types of anisotropies

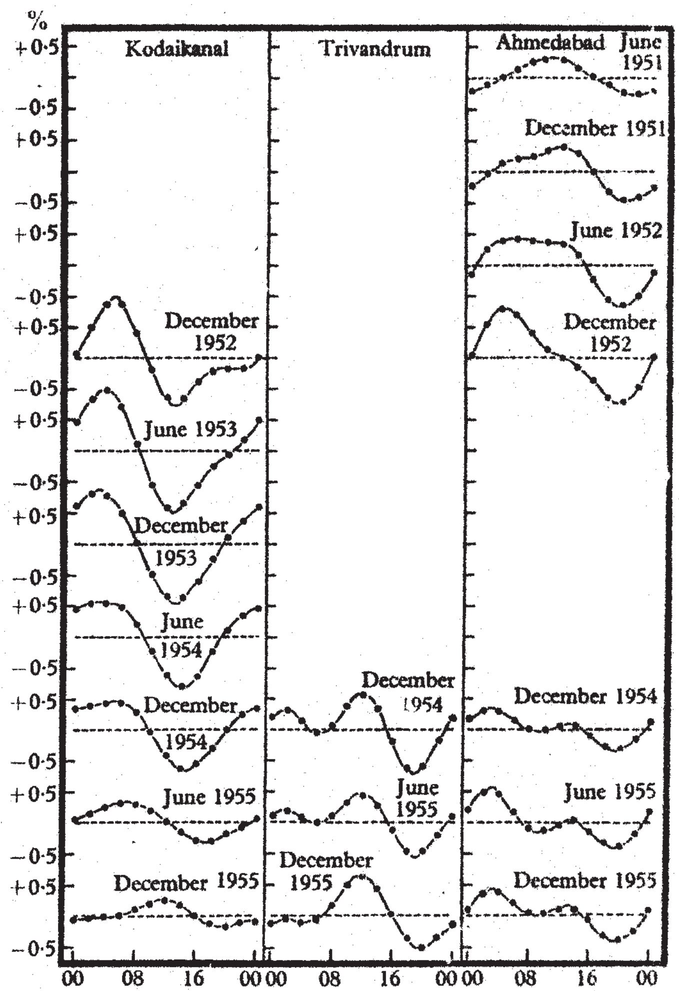

Fig. 2. Twelve-monthly mean daily variation of meson intensity at Ahmedabad, Kodaikanal and Trivandrum centred at six-monthly intervals 1950–5.

which correspond to maxima at 03.00 and 11.00 hours local time respectively (Sarabhai, Desai and Venkatesan [2]).

3. The daily variation of radiation incident in directions very close to the vertical is characterized by large amplitudes and undergoes large changes (Ehmert [7], Sarabhai and Nerurkar [8]). For stations in low

latitudes it exhibits maxima centred at 11.00 hours or 03.00 hours on a majority of days. On some days, which appear to be associated with low values of K_p, the daily variation has two maxima instead of one. The cone within which the radiation with large amplitude appears to be incident is restricted to a semi-angle of about 5° around the vertical. The semi-angle of the cone is however variable, so that during different periods the ratio of the amplitude in narrow angle and in wide angle telescopes varies, as shown in Table 1 (Elmert[7], Sarabhai and Nerurkar[8]).

Table 1. *The ratio of the diurnal amplitudes measured with telescopes of different semi-angles on identical days during different periods*

	1954					1955								
	Aug.	Sept.	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	June	July	Total	Reference
$\frac{CT(\pm 5^\circ)}{CT(\pm 15^\circ)}$	1·52	1·79	1·72	1·74	2·17	2·40	1·83	1·65	1·68	0·79	1·18	1·04	1·60	10
$\frac{CT(\pm 45^\circ)}{IC}$	—	—	—	—	—	—	—	—	—	—	—	—	1·5:1 to 2·4:1	7

The recorders are designated by IC for ionization chamber and CT ($\pm x^\circ$) for counter telescope of semi-angle x° in the east-west plane.

4. The comparison of the daily variations with telescopes pointing to the vertical, the east and the west directions indicates that the spread of times of maxima in the three directions is much less than is expected. This is seen in the curves of the daily variation and the harmonic components shown on harmonic dials in Fig. 3 (*a*) and (*b*). These relate to a study made by Nerurkar at Ahmedabad with telescopes pointing to directions inclined at 45° to the vertical.

5. The long-term changes appear to follow the 22-year cycle of solar activity (Thambyahpillai and Elliot[3], Steinmaurer and Gheri[4], Sarabhai, Desai and Venkatesan[2]). The occurrence of the anisotropy which gives a maximum near noon and the anisotropy which gives a maximum at night-time is on groups of days which have a 27-day recurrence tendency.

If we consider the above facts, the most important conclusion is that at the present moment our knowledge of the characteristics of a permanent anisotropy, if indeed such exists, is very meagre. Initially, it is appropriate to consider for interpretation only the variable anisotropy about which we have now a number of well-established experimental facts and solar and terrestrial relationships. Theories which have been advanced in the past to explain only the average characteristics of the diurnal component of the daily variation, and those which do not take into consideration the existence of the two types of anisotropies which produce daily variations with maxima separated by approximately 8–10 hr are clearly inadequate. A theory which explains the variable anisotropy by a modulation of the primary intensity seems most promising in this context.

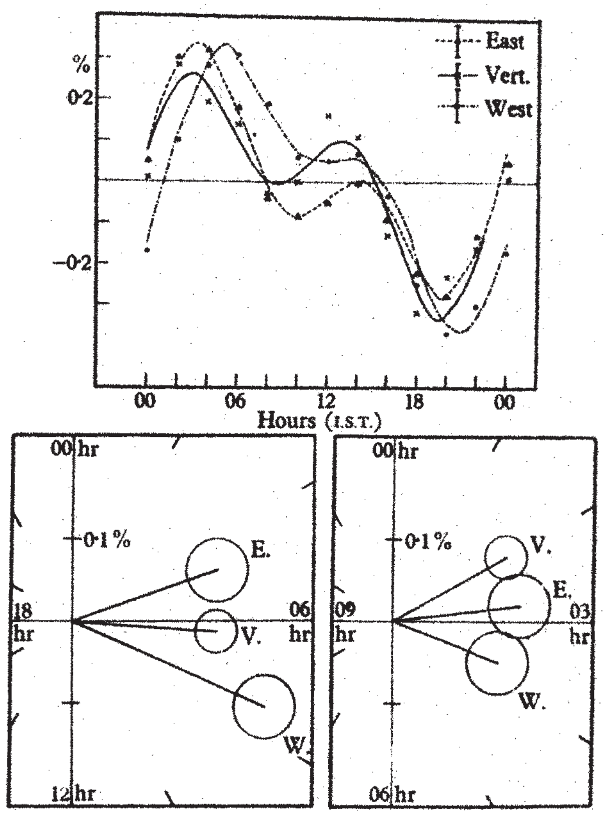

Fig. 3 (*a*, upper). The daily variation at Ahmedabad in the vertical, the east and the west pointing telescopes. (*b*, lower), harmonic dials showing the diurnal and the semi-diurnal components of the daily variation in the three telescopes at Ahmedabad.

Nagashima [9] has proposed a theory to explain the magnetic-storm type anisotropy which is directed towards the 12-hr direction. His theory postulates neutral beams of ionized particles ejected from the sun. These carry with them a trapped magnetic field derived from the solar dipole field. The charge separation which occurs in the beams as viewed from the earth, creates an electric field across the beams so that cosmic rays which traverse the beams and come to the earth suffer an acceleration or a deceleration depending on the orientation of the beam and the earth. Nerurkar[10] has studied the implications of an extension of Nagashima's ideas. If the magnetic field trapped within a beam is derived from the high local magnetic field in the neighbourhood of the active region from which the beam is ejected, it would be possible to expect a magnetic field frozen within the beam but having no preferred orientation in relation to the solar dipole field. For the purpose of the theory, the author has assumed that the solar beam would have an outward radial velocity of from 500 to 2000 km/sec, a width of about 5×10^{12} cm and a magnetic field of from 10^{-5} to 5×10^{-6} gauss at the distance of the earth from the sun. These values are consistent with theories of geomagnetic disturbances involving neutral but ionized streams of matter ejected from the sun.

With the daily variation of cosmic ray intensity which arises as an observational effect due to the spinning of the earth, it is only possible to study the anisotropy in the east–west plane. We have therefore to consider the electric field produced in the beam in the east–west plane due to the component of the magnetic field in the direction perpendicular to this plane. We have also to consider the situation that arises because the beam has an angular velocity derived from the spinning of the sun and it approaches the earth, envelops it and then recedes from it. These three cases are illustrated in Fig. 4 (*a*), (*b*) and (*c*) respectively. The top and the bottom series of diagrams of the figure relate to the reversal in direction of the component of the magnetic field perpendicular to the ecliptic. The diagrams illustrate the directions in space, as viewed from the earth, along which cosmic rays suffer acceleration or deceleration after traversing the beam. They also show in a schematic manner the increase or decrease according to local time of mean intensity of a definite primary region due to the spinning of the earth. Some of the consequences of the theory are as follows:

(1) While in the case of particles being accelerated we get an increase of intensity, there is a decrease when particles are decelerated. However, the time of occurrence of the increase and the decrease is separated by 12 hr. Therefore, the maximum of the daily variation occurs at approximately the same time irrespective of the relative position of the beam with respect to the earth.

(2) Depending on the negative or positive sign of the component of the trapped magnetic field, an anisotropy is produced which would give a maximum in the daily variation either at about 08.00 or at about 16.00 hours before deflexion in the geomagnetic field. The measured time of maximum depends on the correction to be applied for bending of the trajectories in the geomagnetic field.

(3) The magnitude of the anisotropy would vary in relation to the magnitude of the component of the trapped magnetic field in the direction perpendicular to the east–west plane. For different orientation of the trapped field of varying magnitude, we can expect the average anisotropy to correspond to a daily variation at low latitude having a most probable time of maximum 03.00 hours or 11.00 hours respectively, even though the

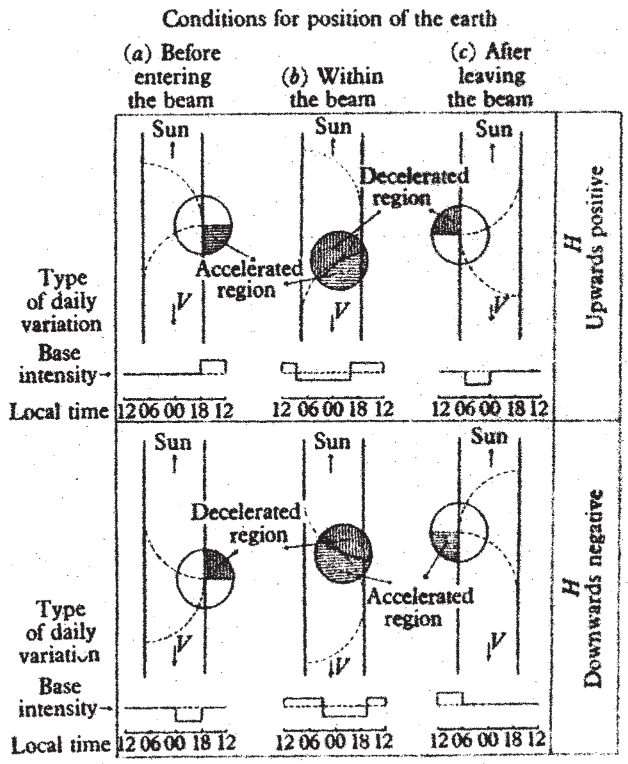

Fig. 4. Accelerated and decelerated regions and the type of daily variation for positive primaries of energy $= 2E_{min}$ when the earth is (a) on the right side, (b) within, and (c) on the left side of the beam. The component of the trapped magnetic field perpendicular to the plane of the paper is positive and towards the reader in upper figures and negative and away from the reader in lower figures.

time of maximum as well as the amplitude on each particular occasion would be different. Table 2 indicates the expected amplitude and time of maximum of the diurnal component of the daily variation at low latitudes.

(4) The anisotropy is only produced for primary cosmic rays of energy above a certain minimum value E_{min}. E_{min} depends on the width of the beam, the magnitude of the trapped magnetic field and its orientation in

Table 2. *The percent amplitude and the time of maximum of the diurnal component of the daily variation of meson intensity in equatorial latitudes.*

Width of the beam = 5×10^{12} cm				When H is positive		When H is negative	
H (gauss)	Velocity (cm/sec)	Change in energy (eV)	E_{min} (Bev)	Amplitude (%)	Time of maximum (hr)	Amplitude (%)	Time of maximum (hr)
10^{-5}	2×10^8	$1{\cdot}3 \times 10^8$	10	0·65	1030	0·65	0300
10^{-5}	10^8	$0{\cdot}65 \times 10^8$	10	0·33	1030	0·33	0300
10^{-5}	5×10^7	$0{\cdot}33 \times 10^8$	10	0·16	1030	0·16	0300
5×10^{-6}	2×10^8	$0{\cdot}65 \times 10^8$	5	0·44	1130	0·39	0130
5×10^{-6}	10^8	$0{\cdot}33 \times 10^8$	5	0·22	1130	0·20	0130
5×10^{-6}	5×10^7	$0{\cdot}17 \times 10^8$	5	0·11	1130	0·10	0130

respect to the east–west plane. No appreciable anisotropy is produced for cosmic ray particles of energy less than E_{min}, while for increasing energy above E_{min}, the per cent anisotropy goes on diminishing. This explains why averaged over long periods the amplitude of the daily variation measured with a neutron monitor is about the same at Huancayo as it is at Climax, even though the mean energy of primary radiation is 19 Bev and 7 Bev respectively (Firor, Fonger and Simpson [11]). Similarly there is almost no latitude effect observable in the amplitude of the daily variation measured with ionization chambers at Huancayo, Cheltenham and Christchurch. Comparison between a neutron monitor and a meson detector cannot be made directly on account of the differences in the response functions of the instruments with respect to directions of arrival of particles. The energy dependence of the anisotropy also reconciles with theory the experimentally observed small change in time of maximum of the daily variation measured in the east and the west directions.

The special properties of the daily variation of intensity measured with narrow angle telescopes pointing towards vertical require much further consideration for experimental study and interpretation.

Our grateful thanks are due to the other research workers of the Physical Research Laboratory whose efforts have contributed to continuous cosmic ray recordings at Ahmedabad, Kodaikanal and Trivandrum and to the Atomic Energy Commission of India for financial assistance.

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PAPER 39

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An interpretation of these changes of anisotropy in terms of the modulation of cosmic rays by streams of matter emitted by the sun is given. In particular, an explanation for the existence of the recently discovered types of daily variations exhibiting day and night maxima respectively, can be found by an extension of some ideas of Alfvén, Nagashima, and Davies. An integrated attempt is made to interpret the known features of the variation of cosmic ray intensity in conformity with ideas developed above.

The study of the daily variation of cosmic ray intensity provides a unique tool for the evaluation of the anisotropy of the primary cosmic radiation, and changes occurring in it. Since the anisotropy is related to theories of the origin of cosmic radiation and to the electromagnetic state in interplanetary space, it is of importance to summarize the current status of our knowledge derived from measurements of the daily variation of cosmic ray intensity.

1. The daily variation of cosmic rays and the anisotropy of the primary radiation is of a highly variable character. This is seen in large long-term changes of the 12-monthly mean daily variation of meson intensity (Sarabhai and Kane [1], Sarabhai, Desai and Venkatesan [2], Thambyahpillai and Elliott [3], Steinmaurer and Gheri [4]), the day-to-day changes correlated with magnetic character figure and the occurrence of large amplitudes of the daily variation of meson intensity on groups of days

(Sittkus [5], Remy and Sittkus [6]). It is seen from Fig. 1 that on these same days the daily variation at Amsterdam (H. F. Jongen, private communication) at $\lambda = 54^\circ$ N, at Ahmedabad (U. D. Desai) $\lambda = 13^\circ$ N show similar features. However, Kodaikanal (D. Venkatesan) on the magnetic equator

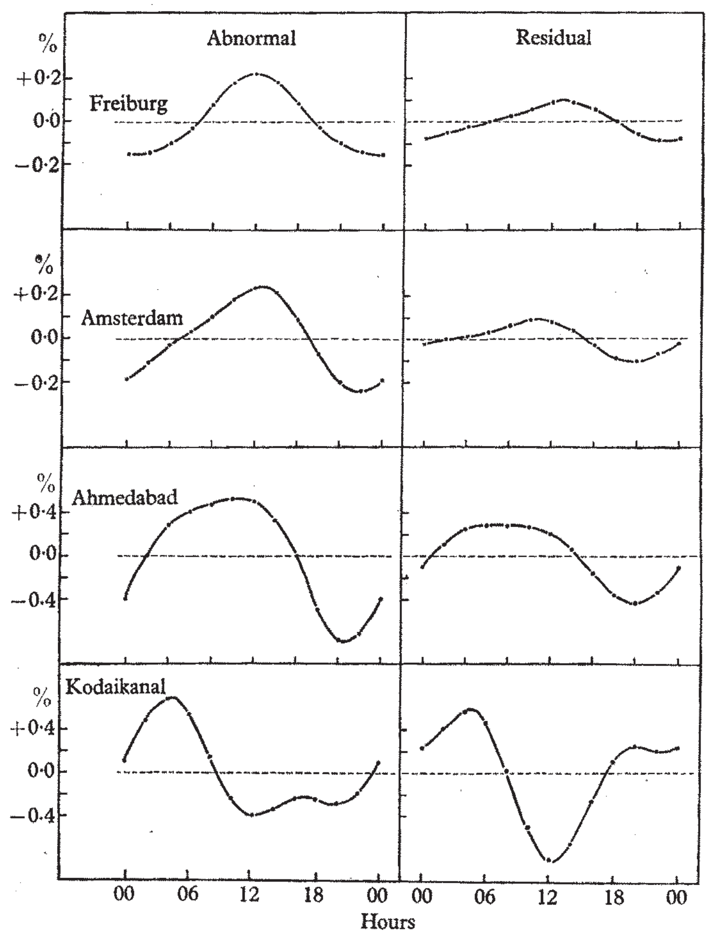

Fig. 1. Comparison of the daily variation at Freiburg (Sittkus), Amsterdam (Jongen), Ahmedabad (Desai) and Kodaikanal (Ventakesan) on days of abnormal amplitudes at Freiburg with the daily variation on residual days.

does not exhibit any marked difference on days on which Sittkus gets abnormal amplitudes.

2. During several years the daily variation, particularly at low latitudes, exhibits two maxima instead of one. This is seen not only in data from Huancayo during 1937–52 (Sarabhai, Desai and Venkatesan [2]) but also

in data at Ahmedabad, Kodaikanal (Venkatesan and Sastry) and Trivandrum (Duggal) during 1950–5 as shown in Fig. 2. The changes of the daily variation indicate that they are primarily due to two types of anisotropies

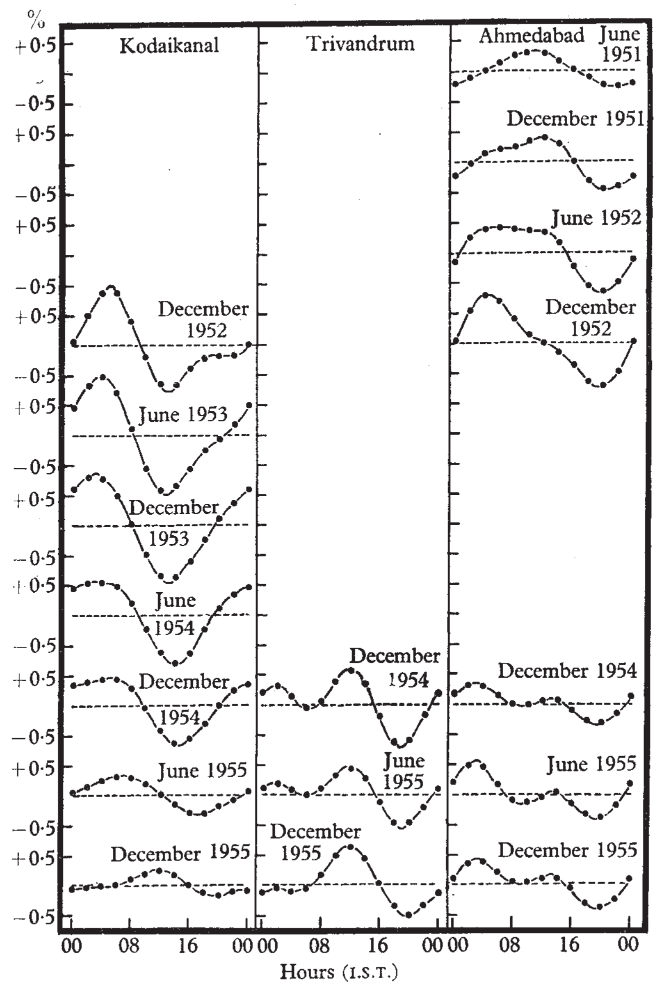

Fig. 2. Twelve-monthly mean daily variation of meson intensity at Ahmedabad, Kodaikanal and Trivandrum centred at six-monthly intervals 1950–5.

which correspond to maxima at 03.00 and 11.00 hours local time respectively (Sarabhai, Desai and Venkatesan [2]).

3. The daily variation of radiation incident in directions very close to the vertical is characterized by large amplitudes and undergoes large changes (Ehmert [7], Sarabhai and Nerurkar [8]). For stations in low

latitudes it exhibits maxima centred at 11.00 hours or 03.00 hours on a majority of days. On some days, which appear to be associated with low values of K_p, the daily variation has two maxima instead of one. The cone within which the radiation with large amplitude appears to be incident is restricted to a semi-angle of about 5° around the vertical. The semi-angle of the cone is however variable, so that during different periods the ratio of the amplitude in narrow angle and in wide angle telescopes varies, as shown in Table 1 (Ehmert [7], Sarabhai and Nerurkar [8]).

Table 1. *The ratio of the diurnal amplitudes measured with telescopes of different semi-angles on identical days during different periods*

	1954					1955								
	Aug.	Sept.	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	June	July	Total	Reference
$\frac{CT(\pm 5^\circ)}{CT(\pm 15^\circ)}$	1·52	1·79	1·72	1·74	2·17	2·40	1·83	1·65	1·68	0·79	1·18	1·04	1·60	10
$\frac{CT(\pm 45^\circ)}{IC}$	—	—	—	—	—	—	—	—	—	—	—	—	1·5:1 to 2·4:1	7

The recorders are designated by IC for ionization chamber and CT ($\pm x^\circ$) for counter telescope of semi-angle x° in the east–west plane.

4. The comparison of the daily variations with telescopes pointing to the vertical, the east and the west directions indicates that the spread of times of maxima in the three directions is much less than is expected. This is seen in the curves of the daily variation and the harmonic components shown on harmonic dials in Fig. 3 (*a*) and (*b*). These relate to a study made by Nerurkar at Ahmedabad with telescopes pointing to directions inclined at 45° to the vertical.

5. The long-term changes appear to follow the 22-year cycle of solar activity (Thambyahpillai and Elliot [3], Steinmaurer and Gheri [4], Sarabhai, Desai and Venkatesan [2]). The occurrence of the anisotropy which gives a maximum near noon and the anisotropy which gives a maximum at night-time is on groups of days which have a 27-day recurrence tendency.

If we consider the above facts, the most important conclusion is that at the present moment our knowledge of the characteristics of a permanent anisotropy, if indeed such exists, is very meagre. Initially, it is appropriate to consider for interpretation only the variable anisotropy about which we have now a number of well-established experimental facts and solar and terrestrial relationships. Theories which have been advanced in the past to explain only the average characteristics of the diurnal component of the daily variation, and those which do not take into consideration the existence of the two types of anisotropies which produce daily variations with maxima separated by approximately 8–10 hr are clearly inadequate. A theory which explains the variable anisotropy by a modulation of the primary intensity seems most promising in this context.

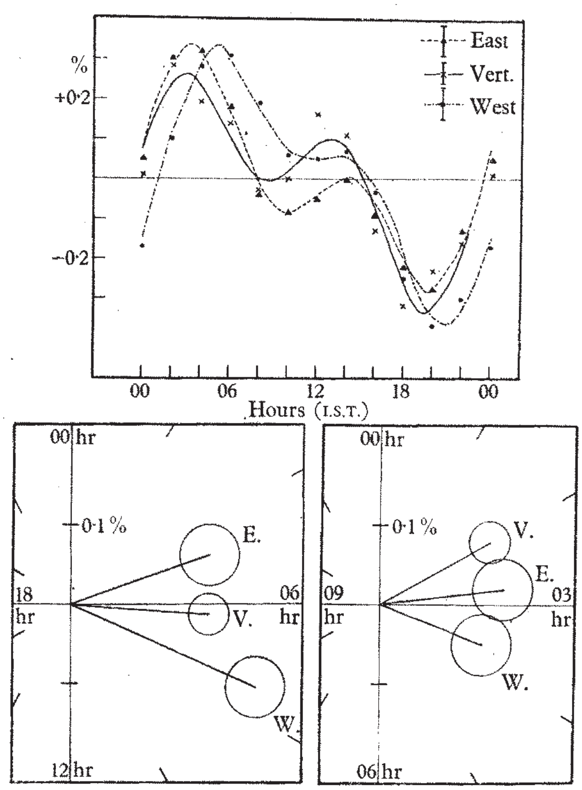

Fig. 3 (*a*, upper). The daily variation at Ahmedabad in the vertical, the east and the west pointing telescopes. (*b*, lower), harmonic dials showing the diurnal and the semi-diurnal components of the daily variation in the three telescopes at Ahmedabad.

Nagashima [9] has proposed a theory to explain the magnetic-storm type anisotropy which is directed towards the 12-hr direction. His theory postulates neutral beams of ionized particles ejected from the sun. These carry with them a trapped magnetic field derived from the solar dipole field. The charge separation which occurs in the beams as viewed from the earth, creates an electric field across the beams so that cosmic rays which traverse the beams and come to the earth suffer an acceleration or a deceleration depending on the orientation of the beam and the earth. Nerurkar [10] has studied the implications of an extension of Nagashima's ideas. If the magnetic field trapped within a beam is derived from the high local magnetic field in the neighbourhood of the active region from which the beam is ejected, it would be possible to expect a magnetic field frozen within the beam but having no preferred orientation in relation to the solar dipole field. For the purpose of the theory, the author has assumed that the solar beam would have an outward radial velocity of from 500 to 2000 km/sec, a width of about 5×10^{12} cm and a magnetic field of from 10^{-5} to 5×10^{-6} gauss at the distance of the earth from the sun. These values are consistent with theories of geomagnetic disturbances involving neutral but ionized streams of matter ejected from the sun.

With the daily variation of cosmic ray intensity which arises as an observational effect due to the spinning of the earth, it is only possible to study the anisotropy in the east–west plane. We have therefore to consider the electric field produced in the beam in the east–west plane due to the component of the magnetic field in the direction perpendicular to this plane. We have also to consider the situation that arises because the beam has an angular velocity derived from the spinning of the sun and it approaches the earth, envelops it and then recedes from it. These three cases are illustrated in Fig. 4 (*a*), (*b*) and (*c*) respectively. The top and the bottom series of diagrams of the figure relate to the reversal in direction of the component of the magnetic field perpendicular to the ecliptic. The diagrams illustrate the directions in space, as viewed from the earth, along which cosmic rays suffer acceleration or deceleration after traversing the beam. They also show in a schematic manner the increase or decrease according to local time of mean intensity of a definite primary region due to the spinning of the earth. Some of the consequences of the theory are as follows:

(1) While in the case of particles being accelerated we get an increase of intensity, there is a decrease when particles are decelerated. However, the time of occurrence of the increase and the decrease is separated by 12 hr. Therefore, the maximum of the daily variation occurs at approximately the same time irrespective of the relative position of the beam with respect to the earth.

(2) Depending on the negative or positive sign of the component of the trapped magnetic field, an anisotropy is produced which would give a maximum in the daily variation either at about 08.00 or at about 16.00 hours before deflexion in the geomagnetic field. The measured time of maximum depends on the correction to be applied for bending of the trajectories in the geomagnetic field.

(3) The magnitude of the anisotropy would vary in relation to the magnitude of the component of the trapped magnetic field in the direction perpendicular to the east–west plane. For different orientation of the trapped field of varying magnitude, we can expect the average anisotropy to correspond to a daily variation at low latitude having a most probable time of maximum 03.00 hours or 11.00 hours respectively, even though the

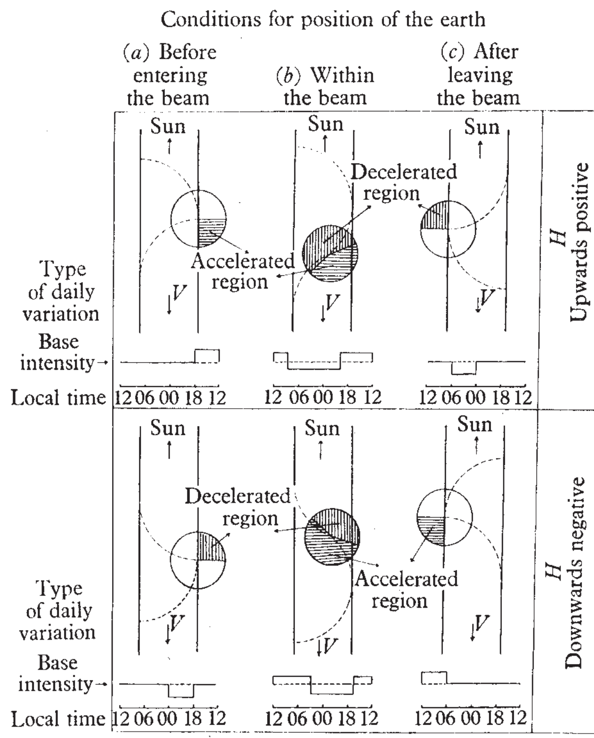

Fig. 4. Accelerated and decelerated regions and the type of daily variation for positive primaries of energy $=2E_{\min}$ when the earth is (a) on the right side, (b) within, and (c) on the left side of the beam. The component of the trapped magnetic field perpendicular to the plane of the paper is positive and towards the reader in upper figures and negative and away from the reader in lower figures.

time of maximum as well as the amplitude on each particular occasion would be different. Table 2 indicates the expected amplitude and time of maximum of the diurnal component of the daily variation at low latitudes.

(4) The anisotropy is only produced for primary cosmic rays of energy above a certain minimum value $E_{\min}$. $E_{\min}$ depends on the width of the beam, the magnitude of the trapped magnetic field and its orientation in

Table 2. *The percent amplitude and the time of maximum of the diurnal component of the daily variation of meson intensity in equatorial latitudes.*

Width of the beam $= 5 \times 10^{12}$ cm				When H is positive		When H is negative	
H (gauss)	Velocity (cm/sec)	Change in energy (eV)	E_{min} (Bev)	Amplitude (%)	Time of maximum (hr)	Amplitude (%)	Time of maximum (hr)
10^{-5}	2×10^8	1.3×10^8	10	0·65	1030	0·65	0300
10^{-5}	10^8	0.65×10^8	10	0·33	1030	0·33	0300
10^{-5}	5×10^7	0.33×10^8	10	0·16	1030	0·16	0300
5×10^{-6}	2×10^8	0.65×10^8	5	0·44	1130	0·39	0130
5×10^{-6}	10^8	0.33×10^8	5	0·22	1130	0·20	0130
5×10^{-6}	5×10^7	0.17×10^8	5	0·11	1130	0·10	0130

respect to the east–west plane. No appreciable anisotropy is produced for cosmic ray particles of energy less than E_{min}, while for increasing energy above E_{min}, the per cent anisotropy goes on diminishing. This explains why averaged over long periods the amplitude of the daily variation measured with a neutron monitor is about the same at Huancayo as it is at Climax, even though the mean energy of primary radiation is 19 Bev and 7 Bev respectively (Firor, Fonger and Simpson [11]). Similarly there is almost no latitude effect observable in the amplitude of the daily variation measured with ionization chambers at Huancayo, Cheltenham and Christchurch. Comparison between a neutron monitor and a meson detector cannot be made directly on account of the differences in the response functions of the instruments with respect to directions of arrival of particles. The energy dependence of the anisotropy also reconciles with theory the experimentally observed small change in time of maximum of the daily variation measured in the east and the west directions.

The special properties of the daily variation of intensity measured with narrow angle telescopes pointing towards vertical require much further consideration for experimental study and interpretation.

Our grateful thanks are due to the other research workers of the Physical Research Laboratory whose efforts have contributed to continuous cosmic ray recordings at Ahmedabad, Kodaikanal and Trivandrum and to the Atomic Energy Commission of India for financial assistance.

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NORTH–SOUTH ANISOTROPY AND ANTICIPATORY INCREASE OF INTENSITY ASSOCIATED WITH THE COSMIC-RAY STORM OF FEBRUARY 11, 1958

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THE time variations of cosmic rays have been measured during the International Geophysical Year with standard instruments at a large number of places on the Earth, and several studies have been made of the energy dependence of the primary variations and the anisotropy which is often associated with primary variations of intensity. From an examination of Forbush-type decreases, Fenton, Fenton and Rose[1] have come to the conclusion that the cause of the transient intensity decreases is variable in its energy dependence from a few BeV. to more than 30 BeV. The variation in response to transient decreases observed with similar equipment at different stations suggests that a primary anisotropy is present at these times. Lockwood[2] has examined the detailed structure of several Forbush-type decreases in the intensity of local neutrons during 1955–58. He finds that in most of the decreases there was a magnetic storm at the onset. Flare activity during the preceding 30 hr. was high and there was some indication of an intensity maximum during the 12-hr. period preceding the start of the decrease. He comments that such an anticipatory effect might be due to the albedo of the moving magnetic gas cloud, but that further results are needed to substantiate any anticipatory effect. McCracken and Parsons[3] have made a very interesting analysis of a Forbush-type event which occurred on October 21, 1957. They found that there was a preliminary depression prior to the commencement of the Forbush decrease and they comment that it

* Sometime guest of the Massachusetts Institute of Technology.

Table 1. CHRONOLOGY OF EVENTS ASSOCIATED WITH THE FORBUSH DECREASE OF FEBRUARY 11, 1958

ΔC and ΔH respectively indicate the change of cosmic-ray intensity (CR) and of the horizontal component of geomagnetic field at Virginia

Date	U.T.	Solar event	U.T.	Terrestrial effect:	Cosmic ray features
9-2-58	0207	*2+ Flare		Radio fade-out	
	2053–	Type III and			
	2120	Type I radio bursts			
	2139	*2+ Flare $E04.S20$		Radio fade-out	
10-2-58	1325	*2+ Flare with major burst radio noise $W67, S12$		Radio fade-out	
			2100	CR maximum $+\Delta C \approx +1$ per cent	(1) Anticipatory increase at equator only related to high energy
11-2-58			0120	S.C. storm	
			0126	$+\Delta H, -\Delta C$	(2) Decrease starts at high latitudes
			0130	Aurora	
			0154	$+\Delta H, -\Delta C$	
			0300	CR minimum	(3) 0300 minimum at equator
					(4) 0500 minimum in mesons
			0622	X-ray $\Delta H = 0$	
			0635	Maximum absorption, galactic noise of 18 Mc./s.	
					(5) 0700 minimum at high latitudes
			0730	X-ray ends	
			0850	X-ray and ΔH	(6) Increase commences
			1000	Maxima aurora	
			1100	CR maximum	Seen in instruments with high and low energy response. Not observed in stations in 120° E. belt, nor in the southern hemisphere

Table 2. PARTICULARS OF COSMIC-RAY NEUTRON MONITOR STATIONS USED IN ANALYSIS

Code	Station	Geog. Lat.	Geomag. Lat.	Long.	Investigator
A	Murchison Bay	80° N.	76° N.	18° E.	Dr. A. E. Sandstrom, Sweden
B	Churchill	59° N.	69° N.	94° W.	Dr. D. C. Rose, Canada
C	Leeds	53° N.	57° N.	0°	Dr. J. G. Wilson, England
D	Sulphur Mt.	51° N.	58° N.	115° W.	Dr. D. C. Rose, Canada
E	Weissenau	48° N.	49° N.	9° E.	Dr. A. Ehmert, Germany
F	Ottawa	45° N.	57° N.	76° W.	Dr. D. C. Rose, Canada
G	Mt. Norikura	36° N.	26° N.	137° E.	Dr. Y. Miyazaki, Japan
H	Kodaikanal	10° N.	1° N.	77° E.	Dr. V. Sarabhai, India
I	Makerere College	0°	2° S.	32° E.	Dr. D. M. Thomson, Uganda
J	Lae	6° S.	16° S.	147° E.	Dr. A. G. Fenton, Hobart
K	Huancayo	12° S.	1° S.	75° W.	Dr. J. A. Simpson, Chicago
L	Hermanus	34° S.	33° S.	19° E.	Dr. A. M. Vanwijk, Hermanus
M	Mt. Wellington	41° S.	45° S.	147° E.	Dr. A. G. Fenton, Hobart
N	Invercargill	46° S.	52° S.	168° E.	Dr. N. V. Ryder, New Zealand
O	Mawson	67° S.	73° S.	62° E.	Dr. A. G. Fenton, Hobart
1	*H*, *I*, *K*	Equator	0–2°		
2	*B*, *C*, *D* *E*, *N*, *O*	High latitude	49–73°		
3	*D*, *F*, *K*	West longitude		75–115°	
4	*C*, *E*, *I*	0-Longitude		0– 32°	
5	*J*, *M*, *N*	East longitude		147–163°	
6	*A*, *E*, *G*	Northern hemisphere	26–76° N.		
7	*L*, *M*, *O*	Southern hemisphere	33–73° S.		

was not due to the arrival of solar matter at the Earth since it occurred before the magnetic disturbances. They conclude from studies made at several stations that the preliminary depression must be attributed to a cause located at some distance from the Earth, and since it is not observed simultaneously at all stations its explanation requires some rather special form of short-lived primary anisotropy. McCracken[4] has analysed the anisotropy of a number of Forbush-type decreases which were preceded by decreases. Yoshida and Wada[5] have directed attention to increases of intensity which occur after the onset of cosmic-ray storms. They believe that the increases are mainly isotropic and have an energy-dependence nearly the same as that of the decreases.

In connexion with the Forbush-type decrease in cosmic-ray intensity which occurred on February 11, 1958, we have fortunately a large number of other solar and terrestrial observations which give us a unique set of data for following the event from the time it occurred on the Sun. These have been summarized by Trotter and Roberts[6]. During its second passage on February 9, 1958, a region 58-*B* at 15° S. heliographic latitude, then at the central meridian, suddenly underwent very rapid changes in plage brightness and sunspot growth. The region flared rapidly throughout the day; half a dozen of the flares were Class 1+ or greater. Five of these caused complete short-wave radio fade-outs of considerable duration. In addition, these events were associated with unusual solar radio noise burst activity on 2,800, 470 and 167 Mc./s. The flux density on 167 Mc./s. was very high during February 7–9. An extremely large number of high-speed dark surges were observed on the solar disk, most of them in association with small flares. The mean integrated coronal (5303 A.) intensity was low during the period. Region 58-*B*, which had very intense activity during the second passage in February, persisted with pronounced activity during the third and fourth passages in March and April respectively.

The strongest geomagnetic storm with sudden commencement (s.c.) of the present solar cycle began early on February 11, and almost simultaneously a very spectacular aurora that persisted throughout the night lit up the northern sky as far south as the 35th parallel. It was visible on the following night as well. In Table 1, the important events observed on the Sun and on the Earth are summarized in chronological order.

We have examined the effect in cosmic rays from data of the high counting-rate meson detector at the Massachusetts Institute of Technology and from a grid of neutron monitor stations distributed (1) in two belts corresponding to the equator and the middle geomagnetic latitudes, (2) in three meridional sections corresponding to 75–115° W., 0–32° E. and 147–168° E., and (3) in the northern and southern hemispheres. In Table 2 are indicated the stations which are included in the grid, particulars of their location and the name of the principal investigator at each station through whose kindness the data have been made available to us. Assuming that the variations can be dependent on the primary energy response, on local time or longitude and on the hemisphere, we have grouped stations so as to study one variable at a time with, so far as possible, an equal contribution in each group due to the other two variables. The stations from which data have been combined for the various analyses are indicated in Table 2.

Fig. 1 shows the percentage deviations in the bi-hourly counting-rates of the neutron monitors during successive bi-hourly periods in U.T. from February 9–12, the deviations in each case being taken with respect to the mean intensity on February 10, which represents a period of 24 hr. immediately preceding the onset of the Forbush decrease early on February 11. It is clear from Fig. 1*A* that the variation is strongly dependent on primary energy. It will be noticed that the meson detector at the middle latitude exhibits a variation which is intermediate between the variation of the neutron monitor intensity at the equator and at the middle latitude stations. The middle latitude stations have a much larger percentage decrease than the stations at the equator. A minimum intensity is reached at 0300 U.T., at 0500 U.T. and at 0700 U.T. at the equator, with the meson detector and at the middle latitude stations respectively. Moreover, about 12 hr. after the initial decrease, at the equator the intensity returns almost to normal before it decreases again ; on the other hand, the recovery occurs only partially at middle latitude stations.

A most interesting aspect of the present event is the increase of intensity at 2100 U.T. on February 10, observed at equatorial stations only, about 4 or 5 hr. before the arrival of the solar plasma at 0120 U.T., indicated by the storm with sudden commencement and a number of other terrestrial effects. The second increase, or the recovery of intensity at 1100 U.T. on February 11, is seen to be much more significant at the equatorial stations and in the meson detector

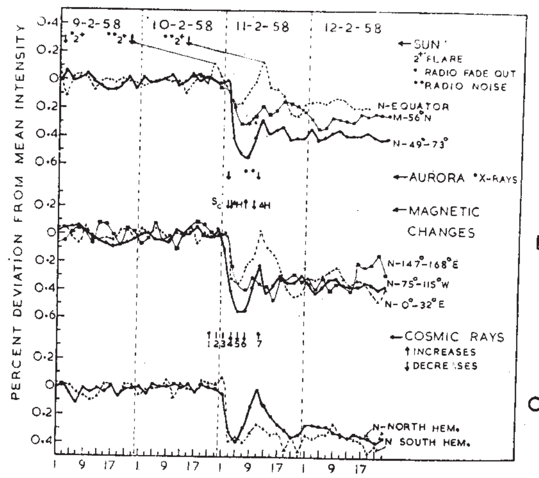

Fig. 1. Cosmic-ray intensity changes and associated solar and terrestrial effects for the cosmic-ray storm of February 11, 1958. Relationships of changes are indicated separately in *A* for low and medium latitudes and primary energy response, in *B* for meridional sections and in *C* for hemispheres

at Cambridge than at the middle latitude stations. It would thus appear that both events, which appear to be increases, are particularly characteristic of the high-energy component of the primary radiation. In contrast, the first minimum of the Forbush event is larger and occurs later for low-energy than for high-energy primaries.

In Fig. 1*B* the variations of intensity at stations in the three meridional belts are compared. It is seen that there are significant differences in the initial decrease, indicating the existence of an anisotropy. The most remarkable feature is the complete absence of the second increase at 1100 U.T. on February 11 at stations in the east meridional section (147° E. to 168° E. longitude), as also at stations in the southern hemisphere for which a comparison with the northern hemisphere is shown in Fig. 1*C*. The second increase of intensity is thus characterized by a strong anisotropy not only parallel to the ecliptic, but also perpendicular to it. This is perhaps the first evidence for an anisotropy of the latter type. In contradiction to the view of Yoshida and Wada, we believe that the second increase is mainly anisotropic and has an energy dependence different from the mainly isotropic Forbush decrease.

The main event observed early on February 11 in cosmic rays, in geomagnetism, in the aurora and in X-rays at high altitudes is undoubtedly related to the major solar outburst from region 58-*B* between 2053 and 2139 U.T. on February 9. We would like to suggest here that solar plasma reached the interaction distance of the geomagnetic field at about 0120 U.T. on February 11, but that for several hours prior to that, there was a cosmic-ray effect which involved an increase of the radiation. During the second increase of cosmic-ray intensity on February 11, we have an increase of cosmic-ray intensity occurring with a strong aurora and change of the horizontal component H of the geomagnetic field. This contrasts with the association of the aurora and the change in magnetic field with the large decrease of cosmic-ray intensity about 10 hr. earlier. From other geophysical evidence it is believed that the main plasma outburst streamed past the Earth in 10–12 hr. and it appears that the second increase of cosmic-ray intensity is related to the departure of the plasma cloud. There was a 2^+ flare with major burst of radio noise at 67° W. heliographic longitude, which occurred at 1325 U.T. on February 10. It is worth while examining whether the second increase is related to the arrival of fresh solar particles from this flare. If, in order to explain the terrestrial influence of a solar event far removed from the central meridian to the west, one postulates the presence of a guiding path of solar magnetic lines of force stretched out to the Earth by earlier streams or an outward solar wind, it would be difficult to explain the 24-hr. delay for solar particles of even a few MeV. energy. We are thus inclined not to associate the second event with the solar outburst on February 10.

We believe that in the two increases and the main decrease observed with the cosmic-ray storm of February 11, 1958, we have essentially three types of modulation process. One is directly associated with the moving plasma, probably related to the magnetic fields in the shock front and gives increases as well as decreases of intensity along with anisotropy. The second gives decreases of intensity and is related to a process which has a sharp onset but a relatively long time constant of recovery. The first is often more effective for high primary energies than low, but the second is much more effective for low than for high energies.

The large anisotropy parallel to the north–south and east–west directions in the second increase poses an important problem. The different motions of solar particles trapped by the geomagnetic field have been discussed by Gold[7], and before average conditions are established round the globe there is probably a basis for major differences in conditions over the hemisphere and at different meridional sections immediately following the arrival of a new cloud of solar particles. But the time involved is very short compared to the observed effect which shows up over periods of several hours. Moreover, even though changes in the Van Allen radiation belts could perhaps provide an adequate mechanism for the perturbation of the geomagnetic field, and through it alter cosmic-ray intensity, a quantitative evaluation of the effect has not so far been undertaken.

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The time variations of cosmic rays have been measured during the I.G.Y. with standard instruments at a large number of places distributed on the earth, and several studies have been made to understand the energy dependence of the primary variations and the anisotropy which is often associated with primary variations of intensity. From an examination of Forbush type decreases, Fenton, Fenton and Rose (1) have come to the conclusion that the cause of the transient intensity decreases is variable in its energy dependence in the range from a few Bev. to over 30 Bev. The variation in response to transient decreases observed with similar equipment at different stations suggests that a primary anisotropy is present at these times. Lockwood(2) has examined the detailed structure of several Forbush type decreases in the intensity of local neutrons during the period 1955 to 1958. He finds that in most of the decreases there was a magnetic storm at the onset. Flare activity during the preceding 30 hours was high and there was some indication of an intensity maximum during the 12-hour period preceding the start of the decrease. He comments that such an anticipatory effect might be present due to the albedo of the moving magnetic gas cloud, but that further data are needed to substantiate any anticipatory effect. McCracken and Parsons (3) have made

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* For some time guest of the Massachusetts Institute of Technology, Cambridge.

a very interesting analysis of a Forbush type event which occurred on October 21, 1957. They find that there was a preliminary depression prior to the commencement of the Forbush decrease and they comment that it was not due to the arrival of solar matter at the earth since it was prior to the magnetic disturbances. They conclude from studies made at several stations that the preliminary depression must be attributed to a cause located at some distance from the earth and since it is not observed simultaneously at all stations, its explanation requires some rather special form of short lived primary anisotropy. In his Ph.D. dissertation McCracken (4) has analysed the anisotropy of a number of Forbush type decreases which were preceded by decreases. Yoshida and Wada (5) have drawn attention to increases of intensity which occur after the onset of cosmic ray storms. They believe that the increases are mainly isotropic and have a dependence on energy nearly the same as that of the decreases.

In connection with the Forbush type decrease in cosmic ray intensity which occurred on 11th February 1958, we have fortunately a large number of other solar and terrestrial observations which give us a unique set of data to follow the event from the time it occurred on the sun. These have been summarised by Trotter and Roberts (6). During its second passage on 9th February 1958, region 58-B at 15° South heliographic latitude, then at central meridian, suddenly underwent very rapid changes in plage brightness and sunspot growth. The region flared rapidly throughout the day; half a dozen of the flares were Class 1 or greater. Five of these caused complete short wave radio fade outs of considerable duration. In addition, these events were associated with unusual solar radio noise burst activity on 2800 m.c, 470 m.c, and 167 m.c. The flux density on 167 m.c. was very high during 7th to 9th February. An extremely large number of high speed dark surges were observed on the solar disc, most of them in association with small flares. The mean integrated coronal (5303 A) intensity was low during the period. Region 58-B which had very intense activity during the second passage in February, persisted with pronounced activity during the third and fourth passages in March and April respectively.

The strongest Sc geomagnetic storm of the present solar cycle began early on 11th February and almost simultaneously a very spectacular aurora that persisted throughout the night lit up the northern sky as far south as the 35th parallel. It was visible on the following night as well. In Table I, the important events observed on the sun and on the earth are summarised in chronological order.

We have examined the effect in cosmic rays from data of the high counting rate meson detector at M.I.T. and from a grid of neutron monitor stations distributed (1) in two belts corresponding to equator and middle geomagnetic latitudes, (2) in three meridional sections corresponding to 75°W-115°W, 0-32°E and 147°E-168°E and (3) in the Northern and Southern hemispheres. We indicate in Table II, the stations which are included in the grid, particulars of their location and the name of the principal investigator at each station through whose kindness the data have been made available to us. Assuming that the variations can be dependent on the primary energy response, on local time or longitude and on the hemisphere, we have grouped stations for different analysis attempting to study one variable at a time with as far as possible an equal contribution in each group due to the other two variables. The stations from which data have been combined for the different analysis are indicated in Table II.

Fig. 1 shows the percent deviations of bihourly counting rate of the neutron monitors during successive bihourly periods in U.T. from 9th to 12th February, the deviations in each case being taken with respect to the mean intensity during 10th February which represents a period of 24 hours immediately preceding the onset of the Forbush decrease early on 11th February. It is clear from Fig. 1 A that the variation is strongly dependent on primary energy. It will be noticed that the meson detector at middle latitude exhibits a variation which is intermediate between the variation of the neutron monitor intensity at the equator and at middle latitude stations. The middle latitude stations have a much larger percent decrease than the stations at the equator. The minimum of intensity is reached at 0300 U.T., at 0500 U.T. and at 0700 U.T. at the equator, with the meson detector and at middle latitude stations respectively. Moreover, about 12 hours after the initial decrease, at the equator the intensity recovers almost to normal before it decreases again, on the other hand the recovery occurs only partially at middle latitude stations.

We believe that a most interesting aspect of the present event is the increase of intensity at 2100 U.T. on the 10th, observed at equatorial stations only, about four to five hours before the arrival of the solar plasma at

0120 U.T. indicated by the Sc storm and a number of other terrestrial effects. The second increase or the recovery of intensity at 1100 U.T. on the 11th, is seen to occur much more significantly at the equatorial stations and in the meson detector at Cambridge than at the middle latitude stations. It would thus appear that both events, which appear to be increases, are particularly characteristic of the high energy component of the primary radiation. In contrast, the first minimum of the Forbush event is larger and occurs later for low energy than for high energy primaries.

In Fig. 1 B the variations of intensity at stations in the three meridional belts can be compared. It is seen that there are significant differences in the initial decrease, indicating the existence of an anisotropy. The most remarkable feature is the complete absence of the second increase at 1100 U.T. on the 11th at stations in the East meridional section (147°E to 168°E longitude), as also at stations in the Southern hemisphere for which a comparison with the Northern hemisphere is shown in Fig. 1 C. The second increase of intensity is thus characterised by a strong anisotropy, not only parallel to the ecliptic, but perpendicular to it. This is perhaps the first evidence for an anisotropy of the latter type. In contradiction to the view of Yoshida and Wada, we believe that the second increase is mainly anisotropic and has an energy dependence different from the mainly isotropic Forbush decrease.

The main event observed early on the 11th in cosmic rays, in geomagnetism, in aurora and in X-rays at high altitudes is undoubtedly related to the major solar outburst from region 58-B between 2053 and 2139 U.T. on the 9th. We would like to suggest here that solar plasma reached the interaction distance of the geomagnetic field at about 0120 U.T. on the 11th, but that for several hours prior to that, there was a cosmic ray effect which, in fact, involved an increase of the radiation. During the second increase of cosmic ray intensity on the 11th of February, we have an increase of cosmic ray intensity occurring with strong aurora and change of the horizontal component H of the geomagnetic field. This contrasts with the association of aurora and change in magnetic field with large decrease of cosmic ray intensity about ten hours earlier. From other geophysical evidence it is believed that the main plasma outburst streamed past the earth in 10 to 12 hours and it appears that the second increase of cosmic ray intensity is related to the departure of the plasma cloud. There was a

2 flare with major burst of radio noise at 67°W heliographic longitude, which occurred at 1325 U.T. on the 10th. It is worthwhile examining whether the second increase is related to the arrival of fresh solar particles from this flare. In order to explain the terrestrial influence of a solar event far removed from central meridian to the West, if one postulates the presence of a guiding path of solar magnetic lines of force stretched out to the earth by earlier streams or an outward solar wind, it would be difficult to explain the 24 hour delay for solar particles of even a few MeV energy. We are thus inclined not to associate the second event with the solar outburst on the 10th.

We believe that in the two increases and the main decrease observed with the cosmic ray storm of February.11, 1958, we have essentially three types of modulation processes One is directly associated with the moving plasma, probably related to the magnetic fields in the shock front and gives increases as well as decreases of intensity along with anisotropy. The second gives decreases of intensity and is related to a process which has a sharp onset but a relatively long time constant of recovery. The first is often more effective for high primary energies than low, but the second is much more effective for low than for high energies.

The large anisotropy parallel to the N-S and E-W directions in the second increase poses an important problem. The different motions of solar particles trapped by the geomagnetic field have been discussed by Gold (7), and before average conditions are established round the globe there is probably a basis for major differences in conditions over the hemisphere and at different meridional sections immediately following the arrival of a new cloud of solar particles. But the time element involved is very short compared to the observed effect which shows up over periods of several hours. Moreover even though changes in the Van Allen radiation belts could perhaps provide an adequate mechanism for the perturbation of the geomagnetic field and through it alter cosmic ray intensity, a quantitative evaluation of the effect has not so far been undertaken.

We are grateful to Mr.S.R.Thakore and to the computation section at the Physical Research Laboratory as well as to Miss Britt at the M.I.T. for help in analysing data. One of us (V.S.) wishes to express gratitude for the hospitality of the Laboratory for Nuclear Science, M.I.T. and for financial assistance from the Department of Atomic Energy of India. We have had many stimulating discussions with B.Rossi and T.Gold.

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Table I

Chronology of events associated with the Forbush decrease of February 11, 1958.

Δ C and Δ H indicate change of cosmic ray intensity (CR) and horizontal component of geomagnetic field at Virginia respectively.

Date	Solar event U.T.	Solar event Event	Terrestrial effect U.T.	Terrestrial effect Effect	Cosmic ray features
9-2-58	0207	*2+Flare		Radio Fade out	
	2053) -2120)	Type III and Type I radio bursts			
	2139	*2+Flare E04.S20		Radio Fade out	
10-2-58	1325	*2+Flare with major burst radio noise W67, S12		Radio Fade out	
			2100	CR maximum + Δ C $\simeq$ +1%	(1) Anticipatory increase at equator only related to high energy

2......

Date	Solar event U.T.	Solar event Event	Terrestrial effect U.T.	Terrestrial effect Effect	Cosmic ray features
11-2-58			0120	Sc. storm	
			0126	+ ΔH, - ΔC	(2) Decrease starts at high latitudes.
			0130	Aurora	
			0154	+ ΔH, - ΔC	
			0300	CR minimum	(3) 0300 minimum at equator (4) 0500 minimum in mesons
			0622	X-ray Δ H=0	
			0635	Maximum absorption, galactic noise of 18 mc.	
					(5) 0700 minimum at high latitudes.
			0730	X-ray ends	
			0850	X-ray and Δ H	Increase commences.
			1000	Maximum aurora	
			1100	CR Maximum	(6) Seen in instruments with high and low energy response. Not observed in stations in 120^{o}E belt, nor in the Southern hemisphere.

TABLE II

Particulars of Cosmic Ray Neutron Monitor Stations considered for analysis.

Code	Station	Geog. Lat.	Geomag. Lat.	Long.	Investigator
A	Murchison Bay	80°N	76°N	18°E	Dr.A.E.Sandstrom,Sweden
B	Churchill	59°N	69°N	94°W	Dr. D.C.Rose, Canada
C	Leeds	53°N	57°N	0°	Dr.J.G.Wilson, England
D	Sulpher Mt.	51°N	58°N	115°W	Dr. D.C.Rose, Canada
E	Weissenau	48°N	49°N	9°E	Dr. A.Ehmert, Germany
F	Ottawa	45°N	57°N	76°W	Dr. D.C.Rose, Canada
G	Mt.Norikura	36°N	26°N	137°E	Dr. Y.Miyazaki, Japan
H	Kodaikanal	10°N	1°N	77°E	Dr.V.Sarabhai, India
I	Makerere College	0°	2°S	32°E	Dr.D.M.Thomson,Uganda
J	Lae	6°S	16°S	147°E	Dr.A.G.Fenton,Hobart
K	Huancayo	12°S	1°S	75°W	Dr.J.A.Simpson,Chicago
L	Hermanus	34°S	33°S	19°E	Dr.A.M. van Wijk, Harmanus.
M	Mt.Wellington	41°S	45°S	147°E	Dr.A.G.Fenton,Hobart
N	Invercargill	46°S	52°S	168°E	Dr.N.V.Ryder, New Zealand.
O	Mawson	67°S	73°S	62°E	Dr. A.G.Fenton,Hobart
1	Equator	H,I,K	0°-2°		
2	High Latitude	B,C,D E,N,O	49°-73°		
3	West Longitude	D,F,K		75°-115°	
4	O-Longitude	C,E,I		0°- 32°	
5	E-Longitude	J,M,N		147°-163°	
6	N.Hemisphere	A,E,G	26°N-76°N		
7	S.Hemisphere	L,M,O	33°S-73°S		

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ANISOTROPY AND THE ORIGIN OF THE SOLAR DAILY VARIATION OF COSMIC RAY INTENSITY

By

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I. Introduction

We wish to present here some recent experimental results concerning the time variations of cosmic rays. Even though we are not able to understand the details of the physical processes which are involved, we can now see the main characteristics of the phenomena. The results which we show are mainly derived from a series of experiments conducted over the past seven years at three stations near the geomagnetic equator along the 75°E meridian. In all cases triple coincidence telescopes with 10 cm of lead were used and apart from studies on the vertical component by Duggal (1), Razdan and Sastry (2), Rao (3) has followed at one station the intensity from east and west directions inclined at 45° to the zenith. Some interesting new results obtained with the MIT high counting rate mu-meson scintillation telescopes are also presented. These have been obtained by R.Palmeira and relate to a counting rate of about 1000 per second which enables us to follow with precision the details of variations of short period.

Without elaborating on experimental details or precedures of analysis we present results which have a bearing on the following crucial questions which we believe would help us in interpreting variations of cosmic ray intensity. We shall examine

(1) What is the nature of change of solar daily variation that one observes and how is the change related to the cycle of solar activity?

(2) What is the energy dependence of the variations of cosmic ray intensity and anisotropy?

(3) Where is the source of the daily variation located? Under what conditions can the solar daily variation be associated with an anisotropy outside the influence of the geomagnetic field?

Finally we summarise the analysis of Sarabhai & Palmeira (4) concerning the very interesting event which occurred on 10th and 11th of February 1958. For the neutron monitor data used in this analysis we are indebted to Ehmert, Fenton, Miyazaki, Rose, Ryder, Sandstrom, Simpson, Thomson, van Wijk and Wilson. The energy dependence and the east-west and north-south anisotropy associated with this large Forbush type event are studied.

II. The changes in the daily variation of meson intensity.

Fig. 1 shows the time of maximum of the semidiurnal component of the annual mean daily variation at Huancayo from 1939 to 1956. The results are derived from Carnegie Institution ion chamber data for which the authours are indebted to Forbush. The time of maximum shifts by almost 10 hours in 19 years, reflecting as we have remarked earlier (5) the very significant change of form of the daily variation at an equatorial mountain station. The change is most rapid during increasing solar activity, and appears to have a period of 22 years. We would like to emphasise again the importance of the semidiurnal component in the interpretation of the solar daily variation of cosmic ray intensity.

Fig. 2 shows the frequency distributions of the amplitudes of the diurnal and the semidiurnal components, r1 and r2 respectively, of the daily variation on individual days at the three stations Ahmedabad, Kodaikanal and Trivandrum during 1955, 1956 and 1957. During any one year, Kodaikanal which is a mountain station has a smaller amplitude than either Trivandrum or Ahmedabad which are at sea-level. Moreover with increasing solar activity from 1955 to 1957, the frequency distribution is displaced to smaller amplitudes at each station. We have reported earlier (2) the rapid decrease of amplitude of 12 month mean daily variation at Kodaikanal from 1954 to 1956 and our present results show that the same can be observed in the distribution of characteristics on individual days.

Fig. 3 shows the frequency distributions for the diurnal and the semidiurnal components of the times of maxima on the days on which the amplitude of the appropriate harmonic component on an individual day is significant at the 2 σ level. A remarkable feature is that with increasing solar activity, the time of maximum has increasing variability and this is an important reason why the annual mean daily variation exhibits a low amplitude during 1957 as compared to the amplitude in 1955.

Results of great statistical significance originating from the MIT high counting rate mu-meson detector are shown in figures 4, 5 and 6. We see firstly in Fig. 4 that the form of the monthly mean daily variation changes significantly from month to month and that in November 1958 its peak to peak amplitude is about 0.8 %. Fig. 5 shows that the most probable amplitude on an individual day is about 0.6 % but there are many days on which the amplitude is considerably greater. With this instrument it is possible to follow the daily variation through individual bihourly deviations as is seen in Fig. 6 where the histograms of the occurrence of hourly positive and negative deviations exceeding $5\sigma = 0.5$ % at different hours is shown. We conclude from this analysis that the daily variation of meson intensity has on many days an amplitude large enough to permit us to neglect the atmospheric temperature effect whose influence in the daily variation is of the order of 0.1 to 0.2 %, but with time of maximum which is somewhat uncertain at the present time. The study of the daily variation on individual days is of great interest for an understanding of modulation processes of non-meteorological origin.

III. The energy dependence of the daily variation.

Our observations made earlier by comparing the daily variations at three stations become clearer from a study with east and west pointing telescopes at Ahmedabad during 1957 and 1958. Fig. 7 shows the frequency distributions of the amplitudes of the diurnal and the semidiurnal components and the times of maxima on individual days on which the amplitude is significant. It is seen that

(1) The diurnal amplitude for east intensity is larger than for west intensity. This is not the case for the semidiurnal amplitude.

(2) The diurnal time of maximum for west has much greater variability than for east. This is not so to the same extent for the semidiurnal component.

Since the geomagnetic cut-off energies at Ahmedabad are 10.4 BeV and 20.6 BeV for west and east intensities respectively, we conclude that the amplitude of the daily variation of the component related to low mean primary energy is less than the amplitude for the component related to high mean primary energy. Also the variability of the time of maximum is greater for the former than for the latter. Fig. 8 shows that this effect is most prominent on days of low or moderate geomagnetic activity. For geomagnetically disturbed days with Cp index greater than one, the west telescope has a distribution of diurnal time of maximum which is quite similar to that of east. However the mean amplitude for west telescopes continues to be smaller than for east telescopes in all cases. There is no difference in diurnal time of maximum in the two azimuths, indicating that on geomagnetically disturbed days, the main cause of the daily variation is not located outside the influence of the geomagnetic field.

IV. The location of the source of the daily variation.

When we have the characteristic difference in the times of maxima which should be expected between the daily variations measured by east and west pointing telescopes which at the equator successively scan the same belt in space with the spinning of the earth, we relate the daily variation to a primary anisotropy. But when the daily variations in east and west telescopes have nearly the same times of maxima, we associate them with a source nearer the earth.

At equatorial latitudes where the atmospheric cut-off is smaller than the geomagnetic cut-off a change in east-west asymmetry of daily mean intensity can be associated with a change in primary energy spectrum. Fig. 9 shows the mean daily variation in east and west direction for groups of days with low, medium and high east-west asymmetry, and also through Chree analysis the relationship of low and high asymmetry with mean intensity in each direction and the index of geomagnetic disturbance, It is seen that days with high east-west asymmetry, are associated with low index of geomagnetic disturbance and a large daily variation in east as well as west telescopes with times of maxima consistent with a primary anisotropy. On the other hand, for low east-west asymmetry we have a negligible daily variation in west telescopes. We therefore conclude that on geomagnetically quiet days there is the absence of a local source of daily variation which permits us to observe the daily variation at a greater distance in interplanetary space - most probably connected with beams from the sun carrying within them frozen magnetic fields. We believe that we have atleast two principal sources, both non-meteorological in origin, of the solar daily variation of cosmic ray intensity. The local source now requires further study from a theoretical standpoint. Elliot (6) has also indicated the need for explaining a local source. The abrupt increases and decreases observed by Satyaprakash (7) in neutron monitors at the equator also point to a local non-meteorological cause for the daily variation on some days.

Finally we have new evidence relating to cosmic ray storms. The storm of February 11, 1958 has three remarkable features which are shown in Fig. 10. The first is an anticipatory increase of intensity observed only at the equatorial neutron monitor stations a few hours before the arrival of the solar plasma to a distance at which it interacts significantly with the geomagnetic field. The main Forbush decrease almost coincides with the Sc geomagnetic storm and its minimum is larger and occurs later for low energy than for high energy primaries. A second increase which is more prominent at low latitudes than at high latitudes and with strong east-west and north-south asymmetry occurs about 10 hours after the onset of the cosmic ray storm. We believe that in the two increases and the main decrease observed with the cosmic ray storm of February 11, 1958, we have essentially three types of modulation processes. One is directly associated with the moving plasma, probably related to the magnetic field in the shock front and gives increases as well as decreases of intensity along with anisotropy. The second gives decreases of intensity and is related to a process which has a sharp onset but a relatively long time constant of recovery. The first is often more effective for high primary energies than low, but the second is much more effective for low than for high energies.

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ACKNOWLEDGEMENTS

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Captions for the figures

Fig. 1 - The long term change of time of maximum of the semidiurnal component of twelve month mean daily variation of cosmic ray intensity at Huancayo from 1937 to 1956 and its relationship with the cycle of solar activity as indicated by Zurich sunspot number R. $\phi_2 = 0$ indicates the semidiurnal time of maximum at midnight or noon local time. (Sastry)

Fig. 2 - Frequency distributions of the amplitudes of diurnal and semidiurnal components of the daily variations on individual days at Kodaikanal, Ahmedabad and Trivandrum during 1954, 1955 and 1956. (Duggal, Razdan and Sastry)

Fig. 3 - Frequency distributions of times of maxima of diurnal and semidiurnal components of daily variation on days on which the variation has significant amplitude at Kodaikanal, Ahmedabad and Trivandrum during the years 1954, 1955 and 1956. (Duggal, Razdan and Sastry)

Fig. 4 - Monthly mean daily variation of cosmic ray intensity from July to November 1958 measured by the high counting rate mu-meson detector at MIT. (Palmeira)

Fig. 5 - Frequency distributions of amplitude of maximum and of minimum of daily variation of cosmic ray intensity on individual days measured by the high counting rate mu-meson detector at MIT from July to November 1958. (Palmeira)

Fig. 6 - Histograms of occurrence of positive and negative deviations of hourly intensity exceeding $5\sigma \pm 0.5\%$ at individual hours during the period July to November 1958 for the high counting rate mu-meson detector at MIT. (Palmeira)

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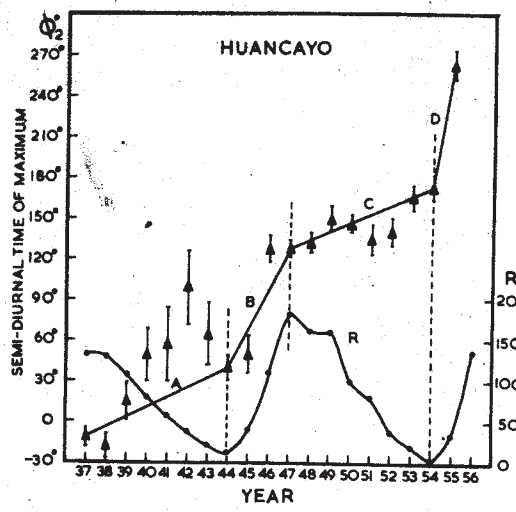


Fig 1

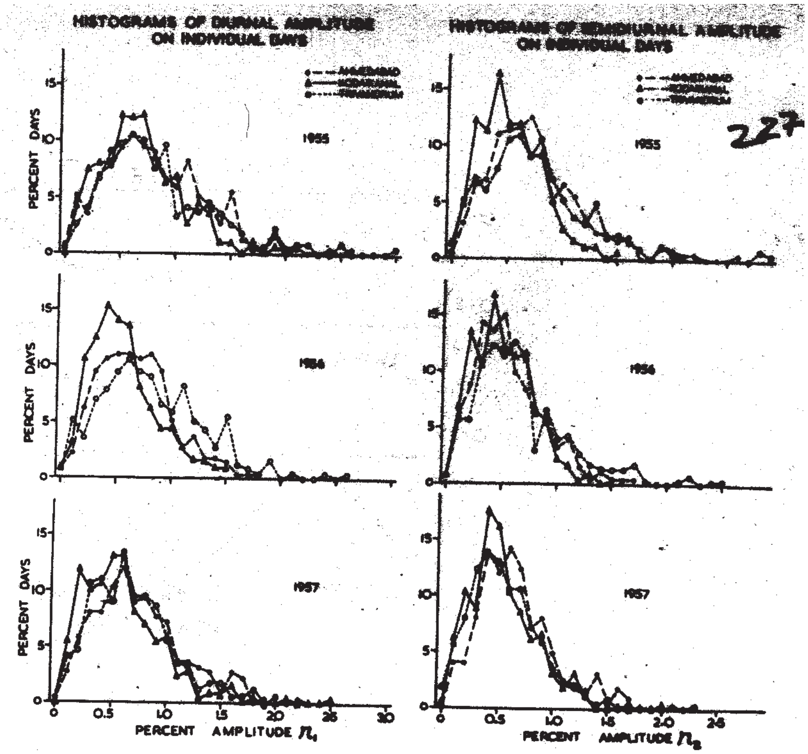


Fig 2

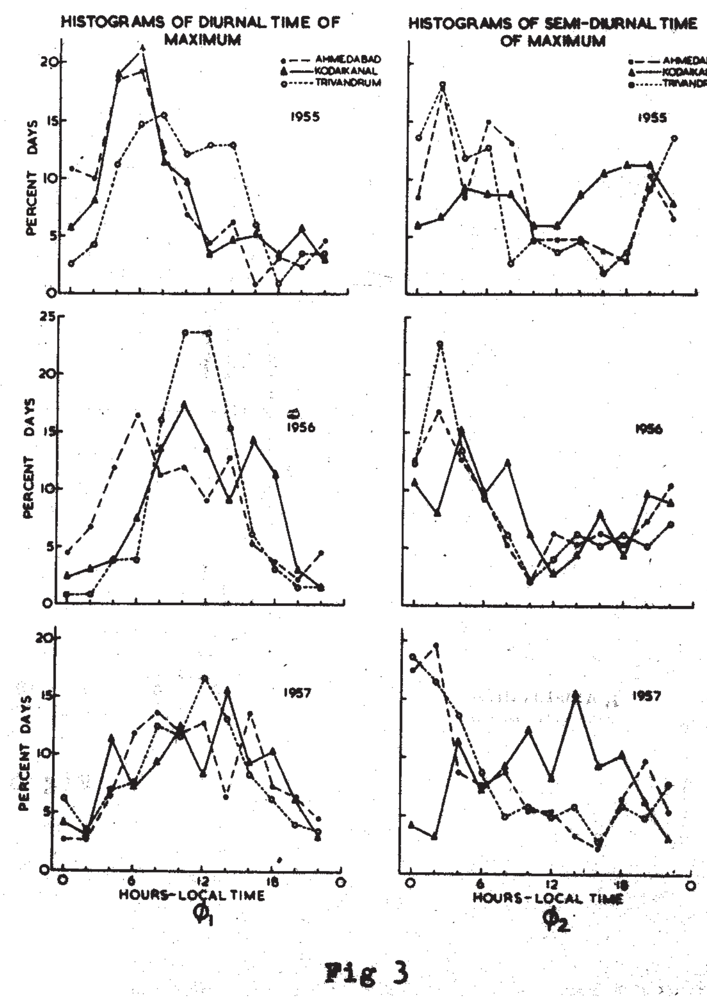


Fig 3

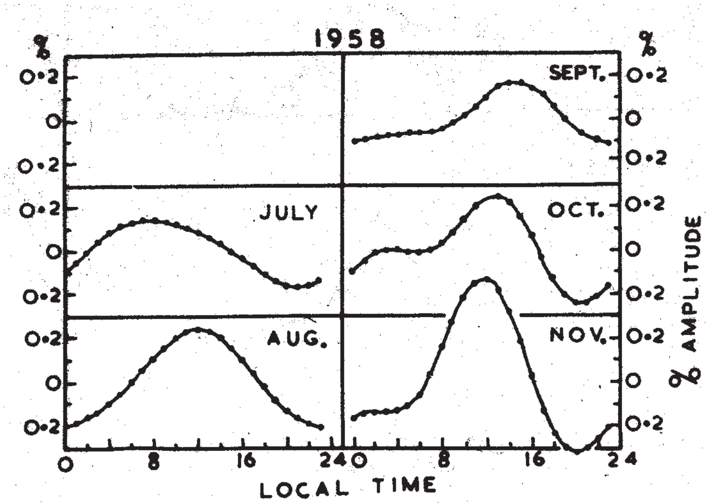


Fig 4

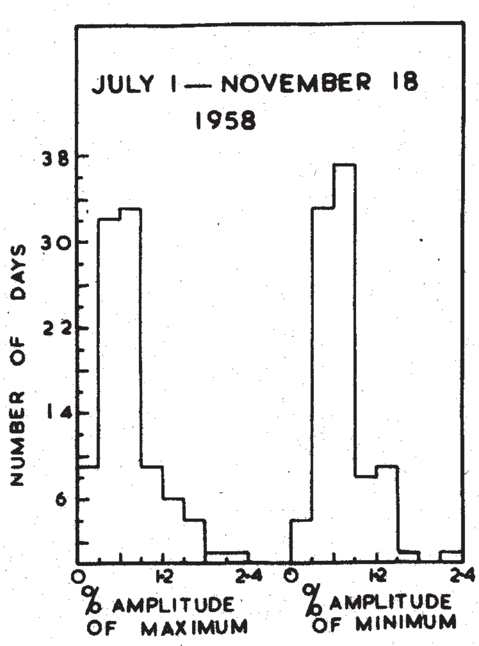


Fig 5

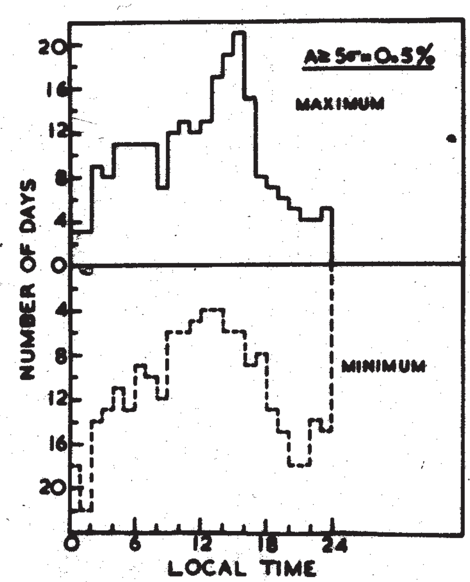


Fig 6

DAILY VARIATION IN E-W TELESCOPES IN 1967-68 AT [illegible]

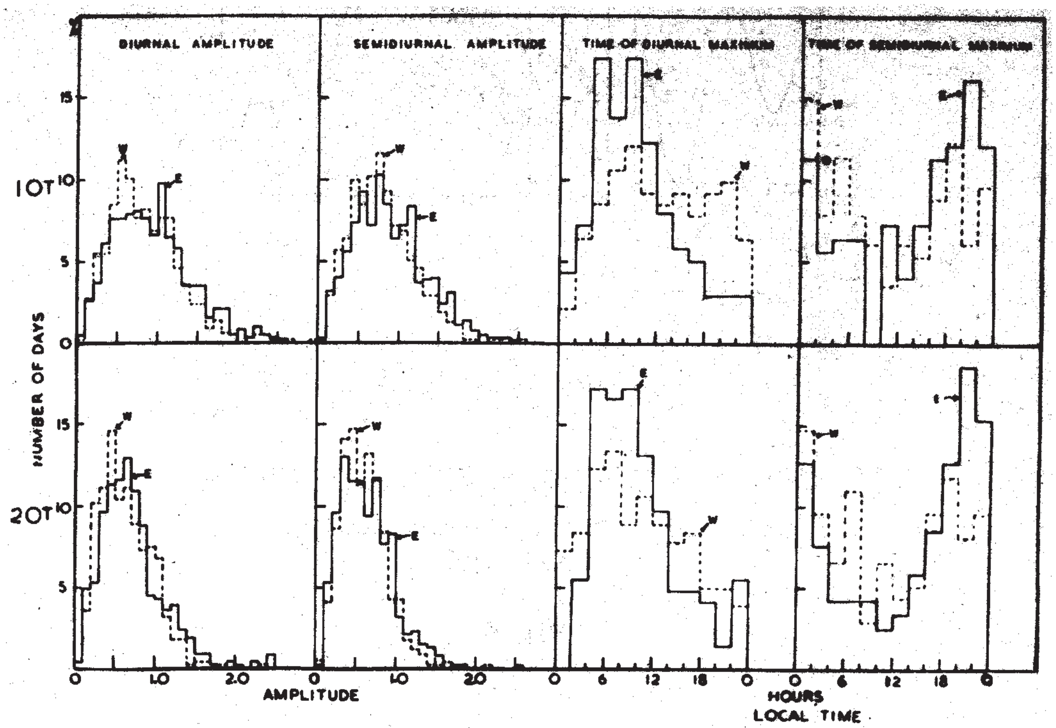


Fig 7

DAILY VARIATION IN E-W TELESCOPES RELATED TO GEOMAGNETIC ACTIVITY

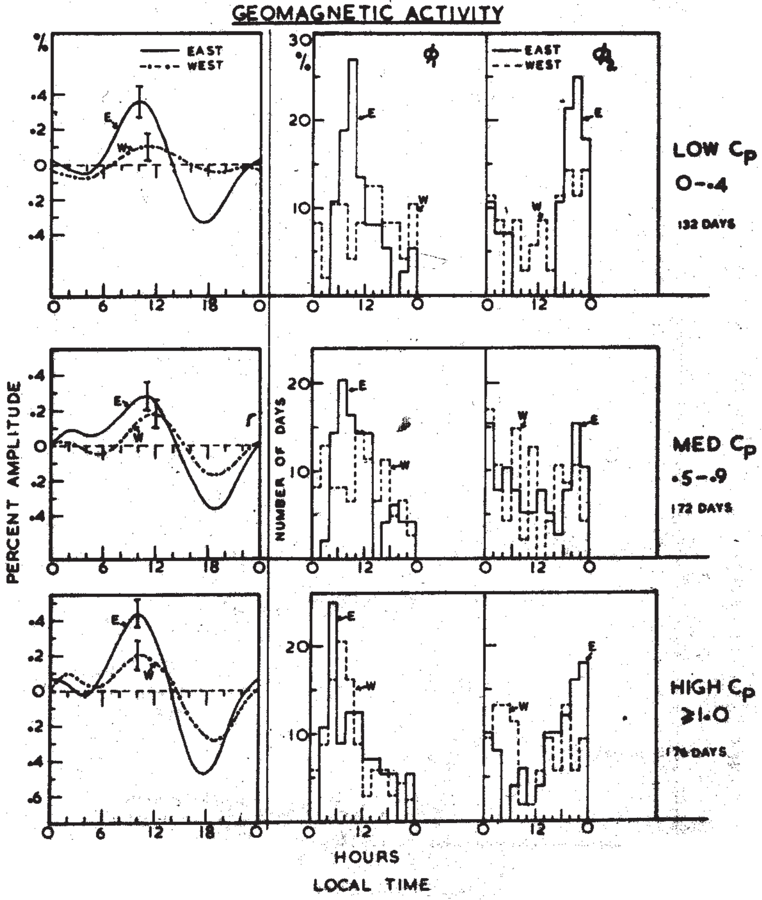
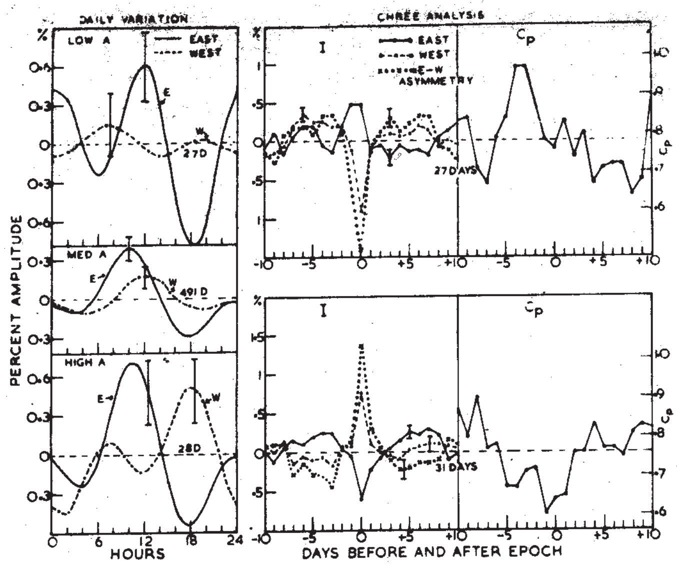


Fig 8



DAILY VARIATION IN E-W DIRECTIONS RELATED TO E-W ASYMMETRY

Fig 9

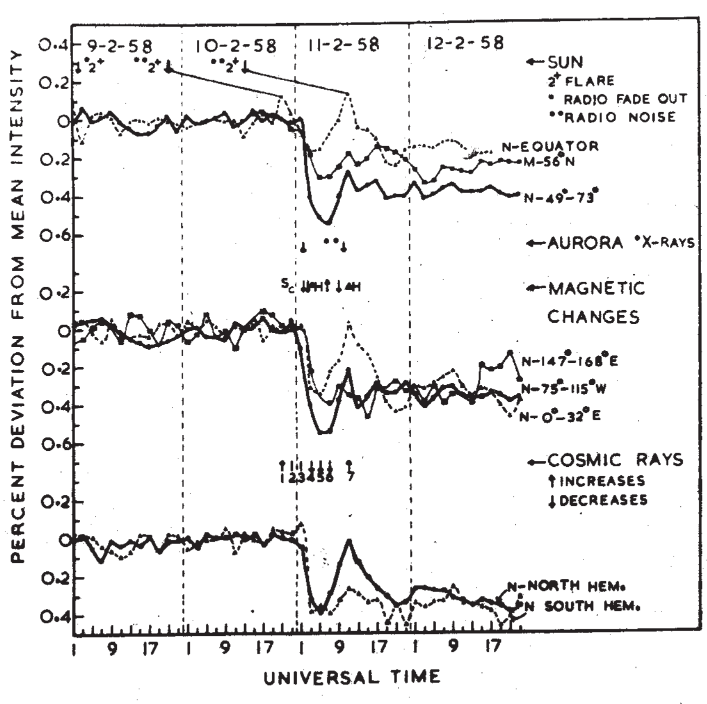


Fig 10

Role of Science in Industry

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Speaker *Vikram Sarabhai*
Physical Research Laboratory

I am happy to participate today in ATIRA's first technological conference. We have for long awaited the creation of a platform for serious discussions on textile technology and of the basic sciences related to it. The Cellulose Research Committee of the C.S.I.R. organised two symposia which served this purpose partially. But I hope that this conference will undertake this task on a more satisfactory basis. This technological conference is the natural complement to the annual management conferences organised by ATIRA. The two conferences sponsored by the same research association reflect a philosophy pioneered by ATIRA and are a recognition of the close relationship of technology and the social climate within industry.

Application of the scientific method in day-to-day working

I wish to speak this morning of the broad problems which confront us in the introduction of scientific and technological innovations in industry. It is hardly necessary to emphasise that today the very existence of industry depends on the speed and effectiveness with which this can be accomplished. We might temporarily insulate the economy of our country from the rest of the world, but so long as we are dependent on foreign trade for our basic requirements, this insulation would be precarious and sooner or later, our industry would have to stand or fall in competition with the industry of the most advanced countries. I would like to suggest that our success in keeping ourselves abreast of contemporary technology depends on three major factors. Firstly and basically, we have to adopt the scientific method as the basis of our operations. We require an approach which asks the question 'why and wherefor' at every stage. We require to understand the underlying rational basis for processes and operations rather than work on an empirical 'hit and miss' basis. We require an understanding and the cultivation of the basic sciences of physics and of chemistry, of biology and genetics, of mathematics and statistics, which form the foundation of our technology today. In the chemical or the electronic industry, this approach is built-in, but in an industry such as textiles which has past traditions extending more than ten or twenty centuries, we find quite a different climate.

Since early times, man has used the cotton fibre for spinning yarn and for weaving cloth. But today our knowledge of the relationship of fibre properties and fibre structure to yarn qualities and the properties of the fabric which is woven from the yarn, is still beset with many mysteries. We can certainly go on spinning and weaving cloth as it was done 2,000 years ago, but if we wish to stand in competition with other countries, we have to answer the most basic questions related to the mechanical processing of cotton. Later on, today, Dr. Radhakrishnan will be addressing this conference about the relationship of structural imperfections to the strength of cotton fibres. If ATIRA has now developed some insight into the significance of opening in cotton processing-a subject which would be discussed later by Mr. Bhaduri - or can see some light in the development of processes for the combing of short staples or can understand a little better the significance of fineness in cotton processing, these are all practical end results which are made possible not merely by empirical trials in the pilot mill, but by the thinking and ideas which have developed out of the more fundamental scientific investigations going on in the laboratories. Battling for many years with the problem of sizing, the chemists at ATIRA have now decided to examine the mechanical properties of starch films and the problem of the anti-crease cloth is now reduced to an understanding of the chemistry of resin finishes.

The history of science is full of examples which alternate from being extremely practical to being extremely basic in their approach and it is through this interaction between the basic and the empirical and practical problems that we find the greatest and most fruitful developments of modern science and technology. The whole field of what is now come to be known as operations research has a basis on mathematical and statistical theory, and the development of communication theory or the science of cybernetics, as it has come to be known, is finding applications not only in the design and theory of modern electronic computers, but in the working out of models of physical processes. The application then of modern science and technology to industry depends on the close collaboration and communication between the technologist and the scientist.

New administrative practices

The second factor to which I would like to invite your attention is the interdependence of administrative practices and technological innovations. It is now widely appreciated that technological innovations change the content of the task of the operator, in the mechanical loom or the automatic loom, it is the machine that weaves, not the weaver, and with greater degree of mechanisation, the task of the operator becomes one of maintenance and supervision rather than of manufacturing a particular article. Thus, while this aspect has come to be accepted, I believe there is still an insufficient appreciation of a more basic change in administrative practices which is involved in many types of technological innovations. Highly efficient and automatic machines require not only close tolerances in regard to the quality of raw material, but continued long operation with unchanged conditions. The introduction of automatic looms, therefore, is a feature which for its success depends on effective maintenanance of standard yarn quality which is, again, dependent on the effective maintenance of the quality of the initial raw material which is cotton, which is purchased and fed into the mills. Thus, the introduction of the automatic loom imposes new standards for the purchase of cotton and for the maintenance of the spinning department. If, for instance, yarn quality suffers through the imperfect training of workers or the use of many ***badli*** or temporary workers in the spinning department, the implications of the new technological innovation have to be faced in the personnel policies of the company. Moreover, the method of production planning and scheduling and of the time span for which production remains constant, require drastic modification as soon as one goes to more automated machines. The technologist knows that if he could be given conditions under which he could set machines and operate them without changes for a sufficient length of time, he could improve greatly the quality and cost of goods but the traditional administrative practices with regard to sales and distribution in the Indian textile industry are such that any long term planning of production so that the sorts remain unchanged, is unheard of in a majority of mills.

I have discussed this problem at some length merely to illustrate that a technological innovation such as the introduction of really expensive high quality looms is a feature which succeeds only when it is undertaken in the context of changed administrative practices from those which could succeed in an older level of technology.

A proper organisational structure

The third factor to which I would like to draw your attention is the question of organisational structure which will make possible the new administrative practices. The need to specialise to keep abreast of contemporary progress in science and technology has made it necessary to develop differentiated functions and a well defined organisation involving line and staff relationships. In this structure, the technologist charged with the task of production is not the know-all of all that is required to discharge his function adequately and consulting staff within the company or a group of scientists outside involves an acceptance of failure in the sense that Kenneth Rice indicated to us at the last management conference. This is possible if this does not constitute a threat to the individual concerned. These social aspects of technological innovation have been the central theme of a number of the management conferences organised by ATIRA and, in my opinion, are no less crucial than the new technology which many of our audience today have witnessed at the Milan Fair.

Having thus discussed the broader questions of the introduction of technological innovations and science in industry, I might turn to an examination of the situation of which we are most familiar. ATIRA has now been in existence for almost ten years. Through six of these years, I had the privilege of being associated closely with its day to day working and in the later years, as a member of its Council and of the Research Advisory Committee. Having thus watched it grow from small beginnings to its present position, I might be forgiven if I end this talk today with an examination of how far we have succeeded in Ahmedabad the introduction of science in industry.

Relationship of research associations with government

The objectives of ATIRA are wide and all embracing as regards the service which it can render to industry. When at the start consideration was being given to the organisational structure of the Association and its relationship to Government and to industry, it was felt that the most appropriate structure for us to follow was that of the British cooperative research associations which are admirably suited to serve the needs of a large number of small units. Research associations involve the government adopting a supportive role and the industry taking on the major responsibility for cooperative backing and participation of those who work in industry. During its first five years of existence, ATIRA's relationship with government was in conformity with this basic pattern. But in the more recent past, the relationship with Government has become nebulous with a series of encroachments on the autonomy of the research associations engendering the climate in which responsibility can hardly be shouldered effectively by the research associations. One can hardly inflict more calculated damage to the concept of research associations than by some of the perhaps well - intentioned policies of control and supervision and coordination from the top which are being mooted at the present time.

Relationship with industry

ATIRA's relationship with industry has grown through the years in maturity and in understanding. Initially, in spite of good top management support to ATIRA, there was in general a feeling of apprehension and suspicion amongst technicians, but during the last five years, there has been a very close collaboration between the technicians in industry and ATIRA, and I am perhaps right in saying that much of the suspicion has now given way to more positive feelings. However, there is insufficient participation today of top management in the functioning of ATIRA. The problem is complicated and my own feeling is that status problems in meetings and in liaison are playing an important role. In a large number of units, social and organisational factors are undoubtedly acting as a hindrance to the application of scientific and techological innovations.

Indian efforts towards industrial research still insufficient

I doubt if anyone would deny that management should base its decisions and policy on facts meaningfully obtained. However, we find that today only a third to one half of the units in Ahmedabad have regular programmes of obtaining meaningful statistics through Quality Control staff or through Quality Control functions performed by line staff. The situation with regard to chemical laboratories for the testing of raw materials is almost similar. Modern systems of cost accounting which should form the basis of contemporary management are even rarer. This is not a question of lack of know-how or lack of knowledge that the investment would pay off, for there is the significant fact that in thirteen out of the sixty Ahmedabad mills which made a profit of more than Rs. ten lakhs per annum in the year 1957, there are in 95% of the cases Quality Control departments in addition to laboratories. I hope, I am not conveying that I believe the establishment of the two facilities that I have named are themselves responsible for the profitability of the thirteen mills in question ; but it is significant that the adoption of proper and contemporary administrative procedures which are considered necessary for the application of scientific and technological innovations are associated with the most successful units in this town. As against the 95% utilisation by these units of the facilities, only 30% of the remaining have similar provision. If the so-called weaker units of the industry are to survive the challenge, it is important that before it is too late, the social and organisational climate within these organisations is modified and undergoes a change which would permit a more easy introduction of scientific and technological innovations on which the industry would stand on a firm competitive basis.

Lastly, in discussing the relationship with industry, I feel it right to emphasise that the effort that we are now devoting in cooperative research, large as it is compared to standards in this country, is nevertheless insufficient in relation to the effort which is directed by competing industry in other parts of the world.

Coming to factors within ATIRA, there is today a most impressive programme of basic research and of technological applications. There seems, however, an ever present need to emphasise the necessity of greater integration of social and operational studies with the technological studies made at ATIRA. With increasing maturity and stature of the active research worker at ATIRA, there is a growing tendency towards consultancy and this has raised a fresh problem related to salary scales within industry as compared to those in the research association. I am one who believes that a differential between the two will exist, but this has to be within certain limits and the present basis on which comparison of salary scales in ATIRA is made with other research associations, academic bodies and national laboratories rather than industry would soon be untenable.

And lastly, I would make a plea for the widening of the experimental field of ATIRA by the ever increasing use of units in industry where scientific methodology and thinking is present as one vast field laboratory. I believe we can derive satisfaction from the contribution that has been made here in the application of science to industry, but at this stage, we have new problems to face, both internal and external, within units and in the research association which we have created. Let us apply our minds to the examination of what has happened and where we should go and evolve a clear cut operational plan which will carry further and more effectively the task which we have only begun.

Chairman's Closing Remarks

Manubhai Shah

On behalf of you and myself, I congratulate Dr. Sarabhai for an excellent lecture that he gave us on "The Role of Science in Industry". As a matter of fact nobody can be considered more suitable than Dr. Sarabhai for dealing with the subject. He has in many ways pioneered scientific and technical developments in industry in our country in general and in Ahmedabad, in particular. His contributions in the deliberations of the C.S.I.R. have always been of a high order. Scientists and technologists are playing very important roles in national development in the West today, In an average factory of size 1,000 workers the ratio of technologists to lay workers is 1:3 in the Soviet Union. The number of engineers and technicians graduating through various courses has been of the order of 65,000 in Soviet Union, 43,000 in America and 22,000 in U.K The responsibility of industrial progress lies on the shoulders of scientists, technologists and engineers.

We cannot hope to advance our industries if we do not employ trained technologists with proper 'know-how' of the subject. The days are gone when a factory could be run by the boss, who kept to himself in his note book the formulae which enabled him to run the machines.

A very serious problem facing industry today is the rate at which machinery becomes obsolete. But obsolescence can be of two types: physical and mental. Physical obsolescence can be got over but mental obsolescence is very difficult to get over. It is with the help of trained scientists and technologists that mental obsolescence existing today can be got over.

Lastly I would like to make a passing mention about Group Dynamics. We particularly in underdeveloped countries, must fully utilise at the floor level whatever technical skill we have at our disposal. A small group with one technically trained leader, may be able to introduce modern ideas on production. This method has now been started in the U.S, with very rich dividends. Factories have been divided into units with a small number of workers in each unit. With small groups, there is closer cooperation between workers and efforts can be effectively pooled. Here also group dynamics works. About ten to twenty people in a group develop new production methods and are able to increase the turnover of goods. This technique of social sciences can also be of help to industry in this manner.

With that suggestion, I would end my remarks with a vote of thanks to Dr. Sarabhai for his lecture.

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VARIATIONS OF INTENSITY AND ANISOTROPY OF COSMIC RAYS MEASURED AT THE GEOMAGNETIC EQUATOR

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ABSTRACT

A study of cosmic ray intensity variations has been conducted during 1956-57 at the equatorial mountain station of Kodaikanal, using a standard neutron monitor. The data have been examined to look for the relationship between the day-to-day changes of intensity, the variance of bihourly deviations, the occurrence of large bihourly deviations at different hours of the day and the associated parameters of the daily variation. The results are related to the electromagnetic state of interplanetary space as determined by streams of solar matter in the neighbourhood of the earth, carrying with them frozen magnetic fields. Comparison is made with the model elaborated by Dorman.

The principal conclusions are as follows:

(1) Day-to-day changes of intensity involve increases as well as decreases with respect to a base intensity for the period in question.

(2) The daily variation of intensity of local neutrons at an equatorial mountain station during 1956-57, has often a large diurnal as well as a semidiurnal component.

(3) On days of high geomagnetic disturbance, the daily variation exhibits abrupt changes indicative of the source being situated at a distance shorter than the range of the geo-magnetic field. On geomagnetically quiet days, the daily

variation has a form consistent with its being related to an anisotropy in interplanetary space. On days of moderate geomagnetic disturbance, the daily variation has changeable characteristics.

(4) Correlated day-to-day changes of mean intensity and daily variation have been confirmed. For geomagnetically disturbed days, the semidiurnal component is greater than the diurnal component for increases of intensity, and conversely for decreases of intensity.

(5) An examination of the time series of Cp for high intensity and for low intensity indicates the presence of a component of the frozen magnetic field in the direction of the solar dipole field. However, during the period of observation the solar dipole field and the sunspot field were in the same direction. Therefore, the results obtained cannot be considered either to confirm or refute the possibility of beams carrying sunspot fields with them.

VARIATIONS OF INTENSITY AND ANISOTROPY OF COSMIC RAYS MEASURED AT THE GEOMAGNETIC EQUATOR*

By

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I. INTRODUCTION:

The solar daily variation of cosmic ray intensity exhibits a number of features which are clearly of non-meteorological origin. Moreover, many of these relate to radiation outside the influence of the geomagnetic field and provide information concerning the anisotropy of the primary radiation. The anisotropy is of a variable character, undergoing change from day to day, and its 12-month average characteristics also change markedly from year to year with striking relationships with the 11 and 22 year cycles of solar activity. The main features of these changes have been summarized elsewhere[1].

For a physical interpretation of the solar anisotropy of cosmic rays, in the context of its great variability, it is important to examine the distinctive forms of the daily variation that occur on individual days. It is also very useful to have knowledge of the relationship of the different forms with the level of daily mean intensity as well as with the perturbation of

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* A summary of some of the results presented here was reported at the Fifth meeting of CSAGI, Moscow - August 1958.

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the geomagnetic field by particle radiation from the sun. Often, however, the standard error of an experimental determination of the daily variation on an individual day is too large to permit valid conclusions, and data are then averaged over a number of days grouped together on some criteria. Past studies[2-6] have been mainly concerned with the change of daily variation of intensity associated with geomagnetic disturbances, sometimes in combination with decreases of daily mean cosmic ray intensity. Yoshida[7] has examined several interesting features of a stormtime anisotropy which may be considered to be superimposed over a quiet period anisotropy during geomagnetic disturbances. The changes of the stormtime anisotropy upto several days following the onset of a magnetic storm, the changes related to the solar cycle of activity, and the energy dependence of the anisotropy have been studied. Sarabhai and Nerurkar[8] have made a phenomenological classification of three types of daily variations observed in the meson intensity at low latitudes, the first designated 'd' type has a maximum near noon, the second designated 'n' type has a maximum soon after midnight, and the third designated 's' type has two maxima. Sittkus[9] as well as Remy and Sittkus[10] have similarly observed the occurrence on groups of days of distinct types of daily variations. An interesting feature about the occurrence of daily variation with large amplitude is that it is associated with about the same degree of geomagnetic disturbance as the daily variation with average or small amplitude. Sarabhai and Bhavsar[11] have found that 'd' and 'n' type days are respectively associated with increases and decreases of daily mean intensity.

It is now fairly clear that many features of the variations of intensity and of anisotropy of primary cosmic radiation are related to emission of particle radiation from the sun which alters the electromagnetic state of interplanetary space. A number of physical processes have been suggested to explain the observed effects, but their respective roles, which may be expected to differ on different occasions, have not been evaluated. We are thus quite far removed from an understanding of the phenomena which would permit us to draw conclusions concerning the electromagnetic state of interplanetary space from cosmic ray and geomagnetic indices. As a first step it is important to distinguish between states on phenomenological considerations and then relate the statestoto theoretical models which have been proposed.

We present here an account of some new results from a study of data collected with a standard neutron monitor at Kodaikanal (geomagnetic latitude = 1°N, longitude 77°E, altitude 7688 feet above sea-level) from December 1956 to September 1957. We have looked at the relationship between the day-to-day changes of intensity, the variance of bihourly deviations, the occurrence of large bihourly deviations at different hours of the day and the associated parameters of the daily variation. We have also studied the relationship of these with Cp, the daily planetary character figure for geomagnetic disturbances, which has often been considered to be an index of solar corpuscular radiation reaching the earth. In the analysis we have attempted to make a distinction between changes in the level of the cosmic ray intensity, which we can study on a day-to-day basis, and a daily variation of intensity. The former could be ideally measured by placing an omni-directional detector at a point in space unhindered by the shadow of the earth. The latter would be observed, even though all characteristics of the primary radiation are constant, by a detector scanning a region of space in which cosmic ray intensity is anisotropic. In practice we are far removed from the ideal situation since our measurements are made on the surface of the earth with a changeable atmosphere above it. The variations which we study can be due to anisotropy, meteorological factors, and those referred to as primary variations which could be due to all other causes. Nevertheless, it is possible, as we describe later, to devise procedures of analysis which permit us to gain information on the primary variations of intensity and anisotropy of cosmic rays, as well as the relationship between the two and of each of them with geomagnetic disturbances.

We show in this communication that very significant new information can be derived if the daily variation represented by 12 bi-hourly deviations is studied, instead of just the diurnal component of the variation. We present evidence which indicates that variations of primary intensity can occur independently of the creation of a strong anisotropy, and conversely, an anisotropy may exist with intensity at normal level. However, there are many instances when the changes of intensity and of anisotropy, as reflected in the form of the daily variation, are correlated in the manner observed by Sarabhai and Bhavsar. These are distinct from changes associated with geomagnetic disturbances reported earlier, and increases of intensity over a normal level of daily mean intensity, as well as decreases, are found to occur in these correlated changes. The relationship of cosmic ray changes with Cp is more complex than has hitherto been believed.

The results are discussed in relation to the electromagnetic state of interplanetary space in the neighbourhood of the earth, particularly with reference to the model developed by Nagashima[12] Nerurkar[13] and Dorman[14] on basic physical processes suggested by Alfven.

II. DATA:

The influence of meteorological changes on cosmic ray intensity can be removed with little ambiguity from the data consisting of successive bihourly intensities by applying a barometric correction to the intensity measured by a neutron monitor. The bihourly intensities were first reduced to a standard barometric pressure, using a coefficient β = -0.94% per m.m. of Hg. The primary variations of intensity can be studied in terms of averages over a period of 24 hours, so as to get an integrated effect for all directions in space which are scanned by the instrument as the Earth goes through one complete rotation about its own axis. Thus moving averages over 12 bihourly intensities provide a time series for changes of daily mean intensity. The day-to-day changes of the daily mean intensity on 306 individual days during the period of study, have been plotted in Fig. 1. The value of Cp, the daily planetary character figure of geomagnetic disturbances, is also plotted alongside.

The days involving large and rapid decreases, with a change of intensity exceeding 2.5% in 24 hours, and three days on either side have been marked in the above figure. During the period of study there were three such events, of which two were associated with large changes of Cp. As it is difficult to correct the daily variation on these days for the trend of day-to-day changes in intensity, they have been excluded from the main study of the daily variation. Days on which two or more bihourly values were missing, are also excluded. Thus the number of days available for study of the daily variation reduces to 239. Before examining the data for daily variation, the bihourly deviations were corrected for the trend of day-to-day changes of intensity, derived from the time series obtained by taking moving averages over 12 successive bihourly values.

III. DAY-TO-DAY CHANGES OF COSMIC RAY INTENSITY AND OF DAILY VARIATION:

3.1 Daily Mean Intensity:

The day-to-day changes of the daily mean intensity have been studied by considering the percent deviation ΔI of the daily mean intensity from the mean intensity of the entire period. Fig. 2 shows the histogram of days grouped according to the magnitude and sign of ΔI. The histogram drawn with solid line represents the distribution for all the 306 days while the one with dotted line represents the distribution for the 239 days used for the study of the daily variation. Neither distribution is symmetrical with respect to the mean. For an amplitude ΔI greater than 1.5%, negative deviations are more frequent than positive deviations.

For the purpose of separation of days on which we have either a positive or negative deviation or normal daily mean intensity, we consider a 3 sigma level of significance which corresponds to a deviation of 0.45%. Days having ΔI greater than + 0.45% are designated I^+ days, whereas days with ΔI less than -0.45% are designated I^- days. The group of days with average intensity, for which ΔI lies between +0.45% and -0.45%, are designated I^o days.

3.2 The Variance of Bihourly Deviations:

The variance Σ^2 is an index of the variability of the twelve successive bihourly intensities on each day. The variance of the twelve bihourly deviations from the daily mean intensity on each individual day was calculated after correcting for the trend of the day-to-day changes of daily mean intensity. For a Poisson's distribution, the variance is expected to have a value less than $2.5 \times 5 \times 10^5$ in 99.9% cases. Hence we define days of low variance as those with $\Sigma^2 < 2.5 \times 5 \times 10^5$ and designate them as Σ_L^2 days. The days with significant disturbance of the bihourly deviations have been classified into days of medium variance Σ_M^2 where $2.5 \times 5 \times 10^5 \leqslant \Sigma_M^2 \leqslant 3.5 \times 5 \times 10^5$, and days of high variance Σ_H^2, where $\Sigma_H^2 > 3.5 \times 5 \times 10^5$.

On a day on which there is a large anisotropy, there would also be a large daily variation of intensity, and this would be reflected in the variance being greater than normal. The distribution of Σ^2 for 239 days is shown in Fig. 3. Anisotropy is small or absent on about half of all days. On about 28% of the days there is a moderate anisotropy and for the remaining 23% of the days there is Σ_H^2 indicating a strong anisotropy.

3.3 Bihourly Deviations and Daily Variation:

As indicated earlier, the bihourly values were first corrected for the trend of the day-to-day changes of daily mean intensity. A bihourly deviation Δi_x from daily mean intensity of bihourly intensity centered at hour x, is considered positive or negative if its amplitude exceeds the 2 sigma level of significance which corresponds to 1.0%. A positive deviation is designated as Δi_x^+ or x^+, and a negative deviation as Δi_x^- or x^-.

The number of days on which a significant positive deviation Δi_x^+ occurs corresponding to each bi-hour is plotted in Fig. 4. The distribution of negative deviations Δi_x^- is also plotted, but with the ordinate reversed. The average number of deviations greater than 1% of each sign at each bihour that could occur in the period covered by our data, purely through chance is six. Primary variations of intensity with a time scale of change which is short compared to 24 hours, could also produce significant bihourly deviations which would not be eliminated by the process of applying correction for day-to-day changes of intensity. These as well as deviations arising through chance should occur with equal probability at all bihours. On the other hand, bihourly deviations which are connected with a daily variation of intensity, should occur preferentially at certain bihours. These deviations and the bihours at which they occur are of particular interest in our study of the anisotropy of cosmic ray primary radiation. Their identification depends on two considerations. Firstly, the number of significant deviations should greatly exceed the number expected through chance causes. We take note of only those bihours for which the number of deviations significant at the 2 sigma level is five times the expected number of six significant deviations of each sign at each bihour. Secondly, the histograms of significant positive and negative deviations, which are shown in Fig. 4, should demonstrate a pattern of regular changes in contrast to random behaviour.

At many bihours, the number of deviations exceeding ± 2 sigma is far greater than six and hence the association of the particular significant deviations with a daily variation of intensity is suggested. It would be observed that positive deviations occur most frequently at 14, 12 and 10 hours and again at 0 hours. Negative deviations occur most frequently at 20, 22 and 18 hours, and again at 6 hours. These hours are designated "important hours". At several bihours, the occurrence of significant positive, as well as negative deviations is simultaneously more than can be expected from chance, and this is strongly suggestive of the existence of more than one type of daily variation which can occur on different days.

IV. CORRELATED CHANGES OF DAILY VARIATION, DAILY MEAN INTENSITY AND GEOMAGNETIC DISTURBANCES:

4.1 Daily Mean Intensity and Cp Associated with bihourly deviations:

Using the Chree method of superposed epochs, we have studied the relationship between significant bihourly deviations occurring at "important" hours, and the changes of daily mean intensity I and of Cp. It is found that on epoch days, 10^+ and 22^- are associated with a daily intensity significantly below mean, and 6^- with an intensity significantly above mean. The mean value of Cp for epoch days is almost the same as the mean value for the whole period under consideration.

The importance of individual bihourly deviations at 6 and 22 hours is borne out by Table I where the average daily mean intensity and average Cp on days associated with positive and negative bihourly deviations of varying magnitude at these hours are shown. Days with $\sum \frac{2}{L}$ have not been considered as they represent a state when there is a non-significant anisotropy of primary radiation and it is then not meaningful to relate the form of the daily variation to the modulation of the daily mean intensity. It will be observed that increasing negative deviations at 6^- hours are associated with increasing daily mean intensity. On the other hand, increasing negative deviations at 22^- hours are associated with decreasing daily mean intensity. There is some evidence that the converse is true for positive deviations at both hours but the number of days on which such deviations are significant at the 2 sigma level is very small. In the connection seen here between negative deviations at one bihour with an increase of daily mean intensity, and a negative deviation at another bihour with a decrease of daily mean intensity, we have an indication that I^+ represents a true increase of intensity while I^- a decrease and the normal intensity for the period of the solar cycle is in or near the I^0 group. Thus, in contrast to the observations of Thambyapillai and Elliot[15] that 27-day recurrences of intensity represent exclusively decreases of intensity, the present study indicates that in general the modulation of cosmic rays on a day to day basis involves increases as well as decreases of the daily mean intensity.

4.2 Daily Mean Intensity and Daily Variation:

The 239 days which have been used for the study of the daily variation are divided into groups of days of intensity I^+, I^o and I^- classified according to the criterion described earlier. The average daily variation for each of these groups is then calculated. The results are shown in Fig.5. The parameters $\bar{r}_1$, $\bar{\phi}_1$, $\bar{r}_2$, $\bar{\phi}_2$ relating to the diurnal and the semi-diurnal components of the average daily variation are given in Table 2. For both I^+ and I^-, significant positive deviations occur at 12 and 14 hours and negative deviations at 20 hours. As we have observed earlier, I^+ is related to a daily variation having a large negative deviation at 6 hours, and I^- is related to one with large negative deviation at 22 hours. It is interesting to note that the negative deviations at 20 hours are part of a sharp minimum for I^+ days but are part of a broad minimum for I^- days. The daily variation for I^+ days is thus characterized by two sharp minima, one on either side of a predominent broad maximum near noon. On the other hand, the daily variation on I^- days is characterized by a broad maximum near noon, a broad minimum in the evening, and a subsidiary maximum at midnight. The diurnal component for I^+ has a time of maximum at 13 hours and for I^- a maximum at 10 hours. This is consistent with the observation of Sarabhai and Bhavsar with a narrow angle meson telescope that a daily variation with a maximum near noon is related to increases of mean intensity, while a daily variation with an earlier time of maximum is related to decreases of mean intensity.

4.3 Geomagnetic Disturbances and Daily Variation:

Many authors have examined the changes in the diurnal component of the daily variation associated with geomagnetic disturbances. A further criterion that has often been applied relates to the occurrence of sharp decreases of daily mean intensity associated with geomagnetic storms. In the present data, days involving

~~decrease of cosmic ray~~

large sudden decreases of cosmic ray intensity have been removed. The remaining 239 days were divided into three groups of Cp designated as Cp^L, Cp^M, Cp^H corresponding to $Cp^L \leqslant 0.5$, $0.6 \leqslant Cp^M \leqslant 0.9$ and $Cp^H \geqslant 1.0$ respectively. The mean daily variation for these three groups of days is plotted in Fig. 6. The characteristics of the harmonic components of the mean daily variation and the mean Σ^2 for each group are given in Table 3. The daily variation for all three groups of days has a predominent maximum near noon with minima on either side of it. The subsidiary maximum near midnight is much smaller than the principal maximum near noon. The noticeable alteration in daily variation for Cp^L and Cp^H groups relates to the form of the principal maximum and the minima on either side of it. These are sharp for the Cp^H group but are quite broad for the Cp^L group. The time of maximum of the diurnal component for the two groups remains almost unchanged while the amplitude of the diurnal component is smaller for Cp^H than for Cp^L group. This is contrary to the observations of Sandstrom[2] from a study of the meson component at a high latitude station during 1947-1950. Sandstrom found an increase of r_1, and a shift of ϕ_1 to earlier hours with increasing Cp. On the other hand, Sarabhai and Sastry[19], at Kodaikanal with a meson telescope have observed during 1956, a behaviour exactly similar to that reported here for the daily variation of local neutrons at the same station. The difference between the results relating to 1947-50 and 1956-57 is understandable on the observations of Yoshida[7] that the disturbance vector, which displaces the vector representing the quiet period diurnal variation, has itself an eleven year period of change in amplitude as well as time of maximum. Thus the net change that is observed with Cp^H should be dependent on the period of observation relative to the phase of the solar cycle of activity. Our observations are qualitatively in agreement with Sandstrom's if account is taken of this fact.

If the criterion for storm days relates to the occurrence of geomagnetic disturbances associated with decrease of daily mean intensity I, as has been considered by some authors[2,3], we should compare the form of the daily variation for the sub-group $Cp^H\ I^-$ with the rest of the days for which we have Cp^M or Cp^L. In a later section the daily variations of all the sub-groups corresponding to the three classes of Cp and I are given. For the group corresponding to storm days ($Cp^H\ I^-$), the diurnal component of the daily variation has $r_1 = 0.30 \pm 0.02\%$, $\phi_1 = 159^\circ$ as compared to $r_1 = 0.22 \pm 0.04\%$, $\phi_1 = \pi + 7^\circ$ for the diurnal variation on non-storm days. The increase of the diurnal amplitude and its shift to earlier hours during storm days is in conformity with the observations of other workers. The Cp^M group with intermediate value of Cp corresponds to a much smaller average daily variation than the average daily variation for Cp^H group (disturbed days) and Cp^L group (quiet days). On the other hand the mean Σ^2 for Cp^M is approximately the same as for Cp^H and Cp^L groups. This indicates that the small amplitude of the average diurnal variation on Cp^M days is due to the great variability of the form of the daily variation rathern than to an intrinsically small anisotropy on individual days.

4.4 Characteristics of the Daily Variation on Individual Days:

The conclusions derived from an examination of the characteristics of the average daily variation for groups of days sorted according to I and Cp, may be confirmed by studying separately for each group the histogram of the time of maximum ϕ_1 of the diurnal component of the daily variation on days on which its amplitude r_1 is significant at the 2 sigma level. The histograms of ϕ_1 and ϕ_2 for the groups I^+, I^o and I^- as well as for the groups Cp^H, Cp^M and Cp^L are shown in Fig. 7. It will be observed that the ϕ_1 histograms for I^+ and I^- groups are significantly different and reveal a shift of time of maximum as observed previously in the average daily variation curves for the I^+ and I^- days. The histogram for the I^o group is intermediate between the histograms for I^+ and I^- groups. The shift to earlier hours in the time of maximum of the diurnal component of the average daily variation for the I^- group compared to the I^+ group is therefore also a feature of the daily variation on individual days in the respective groups. The histograms of time of maximum ϕ_2 of the semidiurnal component remain unaltered for all three groups of I.

The histograms of ϕ_1 for the Cp^M group corresponding to days with intermediate values of Cp, when compared with the histograms for Cp^H and Cp^L groups reveal that the daily variation on individual days of the Cp^M groups is of a more variable character than the variation on days of the Cp^H and Cp^L groups. As we have remarked earlier, the small amplitude of the average daily variation of the Cp^M group is due to a large scatter of the time of maximum for both the diurnal and semidiurnal components of the daily variation rather than to a small amplitude of the daily variation on individual days of the group.

5.0 The Electromagnetic State of Interplanetary Space:

5.1 Specification of State from Modulation of Cosmic Ray Intensity and Geomagnetic Disturbances:

Experimental evidence indicates that the modulation of cosmic ray intensity, the anisotropy of the primary radiation, and geomagnetic disturbances are phenomena which are related in some ways, but the relationship of any two of them is not constant at all times. All three have marked solar relationships and an interesting possibility exists of being able to interpret them in terms of streams of ionized solar matter emitted from the sun. On this basis, the cosmic ray effects may be related to the influence of the streams on the electromagnetic state of interplanetary space in the environment of the earth, and the geomagnetic effects to the interaction of the streams with the geomagnetic field. Dorman has considered in detail the type of effects which may be observed. In attempting to verify this approach, we can start with a phenomenological identification of the state of the environment of the earth in terms of observable effects produced in cosmic rays and in geomagnetic changes.

We can, to begin with, examine the anisotropy or daily variation associated with the nine states characterised simultaneously by values of I and of Cp. For this purpose, the 239 days were first divided into three groups, I^+, I^o, I^- and these three were each further subdivided into groups Cp^H, Cp^M, Cp^L. The mean daily variation for each of the nine states is plotted in Fig. 8. The characteristics of the diurnal and the semidiurnal components corresponding to the mean daily variations are given in Table 4. The following are the noteworthy features:

(a) The variance Σ^2 for all the nine states is comparable. However, the amplitude of the average daily variation for all Cp^M states has a magnitude much smaller than for Cp^H and Cp^L states. Thus the large variability of the daily variation on individual days of the Cp^M state is present for each of the states corresponding to I^+, I^o, I^- respectively.

(b) Leaving aside states involving Cp^M, we see more clearly than before the characteristic features associated with I^+, I^o, I^- for Cp^H and Cp^L. The largest positive bihourly deviation occurs at 14 hours for I^o, with Cp^H as well as with Cp^L. The sharp negative deviation at 6 hours associated with I^+ is also seen for I^o Cp^H, but not for I^o Cp^L.

A sharp positive deviation at midnight is observed for $I^o\ Cp^H$ and for $I^-\ Cp^L$ states.

(c) $\bar{r}_1$ and $\bar{r}_2$ are significant in all states except those involving Cp^M. $\bar{r}_1$ and $\bar{\phi}_1$ are dependent on I as well as Cp states; but ϕ_2, the time of maximum of the semidiurnal component is the same for all states.

(d) At Kodaikanal, during the period of experimentation, differentiation of days, in respect of I^+ and I^- states, using the characteristics of the harmonic components of the daily variation on individual days is possible only for Cp^H days. We then have $r_1/r_2 \gg 1$ for I^- days and $r_1/r_2 < 1$ for I^+ days. This is because while in the latter state the semidiurnal component predominates over the diurnal component, the reverse is the case in the former state. Differentiation in this manner is not possible in general because for $Cp^L\ I^-$ state, $r_1/r_2 < 1$ as is the case for the $Cp^H\ I^+$ state.

5.2 Specification of State in Terms of Modulation of Daily Mean Intensity and Anisotropy of Cosmic Rays:

In the preceeding section it has been pointed out that there is no significant difference in the mean variance Σ^2 for the nine states characterised by values of I and Cp. In order to study the nature of the daily variation associated with low, medium and high variance the I^+, I^o, I^- states were subdivided into groups with Σ^2_H, Σ^2_M and Σ^2_L. The mean daily variation for each of these nine groups is shown in Fig. 9 . The characteristics of the harmonic components are indicated in Table 5.

As is to be expected, the daily variation is largest for Σ^2_H and is least for Σ^2_L. The characteristic differences in the nature of the daily variation for I^+, I^o and I^- states are shown well for $\sum_{H}^{2}$ and $\sum_{M}^{2}$ states; but for $\sum_{L}^{2}$ state the differentiation is not clear as the state includes all days on which the amplitude of the daily variation is comparable with the magnitude of bihourly deviations which can occur through chance causes. Other interesting points are as follows:

(a) On about half of all days belonging to each of the states I^{+}, I^{o} and I^{-}, there is no anisotropy large enough to be significant under the conditions obtaining in our experiment.

(b) The states $\sum_{H}^{2} I^{-}$ and $\sum_{M}^{2} I^{-}$ have the greatest mean Cp, indicating that geomagnetic disturbances are associated with decreases of the daily mean intensity occurring simultaneously with the creation of a strong anisotropy. The decreases are of greater amplitude than the increases.

(c) The $\sum_{L}^{2}$ states are in general associated with moderate to low mean Cp

5.3 Sequential Changes of Intensity I and of Cp Connected with States:

Using the Chree method of superposed epochs, we have examined the time series of the daily mean cosmic ray intensity and of Cp on days preceeding and following epoch days, defined by the occurrence of a particular state. If the modulation of cosmic ray intensity is produced by an electric field associated with a frozen magnetic field in a beam of ionized solar matter in the neighbourhood of the earth, it has been suggested by Alfven[16] that the magnitude of the quantity $\frac{-1}{I} \frac{dI}{dt}$, representing the rate of change of intensity from day-to-day, would be proportional to the magnitude of the electric field in the beam. A modulation of intensity by the electric field is then inferred by Venkatesan[17] when there is high correlation between the time series of $\frac{-1}{I}\frac{dI}{dt}$ and of Cp derived through Chree analysis.

Figure 10 shows the time series for Cp^L and for Cp^H epochs. The Cp^L state at epoch is related to a gradual increase of daily mean cosmic ray intensity commencing about six days before epoch. The maximum is reached one day after epoch and is followed by a decrease which extends for several days beyond the day (+4) when average intensity is reached. The time series for Cp has a very interesting form. Cp is low only for -2 to +1 days and rapidly regains average value after epoch. It is not suggestive of Cp^L epochs representing a state when solar beams are absent in the neighbourhood of the earth. There is apparently no relationship between the time series of Cp and of $\frac{-1}{I} \frac{dI}{dt}$. If we are to infer from this that the electric field in the beam plays an insignificant role, we would be required to explain what we consider to be the increase of cosmic ray intensity through an alternative acceleration process of a type which involves preferentially the low energy primaries, the radius of curvature of whose orbits are less than the width of the stream. However, we might question the correctness of a basic assumption which is made in looking upon the time series for Cp as indicating the relative position of the solar beam with respect to the earth. It does not appear likely that we can follow this reasoning for geomagnetic quiet days for which we have the Cp^L state. It would then be not appropriate to conclude that we have here an increase of intensity not related to the electric field in the beam. Without knowledge of the energy dependence of the radiation involved in the increase, it is difficult to resolve this major ambiguity in interpretation.

For the time series in Fig. 10 relating to the Cp^H state at epoch, there is an abrupt decrease of intensity starting one day before epoch. The intensity reaches a minimum one day after epoch and then gradually recovers to normal value in about five days. There is close association between the time series of $\frac{-1}{I} \frac{dI}{dt}$ and of Cp, with the former having a maximum value on epoch days. On the interpretation outlined earlier, this indicates the influence of the electric field in the beam in producing decreases of intensity. Moreover, there is a marked anti-correlation between the time series of I and of Cp which suggests that the decreases are also produced through processes not connected with the electric field. The additive effects of the processes for the Cp^H state result in the decreases of intensity being much larger than the increases of intensity for the Cp^L state.

We have been earlier that both I^+ and I^- states can occur in conjunction with either Cp^H or Cp^L states. In Fig. 11 we show the time series from −10 to +30 days of I and Cp for the occurrence at epoch of the states $I^+ Cp^H$, $I^+ Cp^L$, $I^- Cp^H$ and $I^- Cp^L$. It will be observed that for $I^+ Cp^L$ state, the intensity remains high for several days after epoch and then decreases sharply to a negative level.

The time series of I and of Cp for $I^- Cp^H$ and for $I^- Cp^L$ states are similar except for a relative shift corresponding to a change from the Cp^H state to Cp^L state. The detailed features of both time series appear to be preserved for at least ten days on either side of epoch during the shift that is associated with change from Cp^H to Cp^L. If $I^- Cp^H$ state is associated with a condition in which a solar beam envelopes the earth, the $I^- Cp^L$ state appears to correspond to conditions a few days later as the beam moves away from the earth.

The time series in Fig. 11 are suggestive of a 27-day recurrence tendency in I only for $I^- Cp^L$ state at epoch. The time series of Cp are devoid of any notable features such as a 27-day recurrence tendency, and bring out rather well that during the period of investigation, solar activity had already risen to a level where there were at almost all times a large number of active regions on the sun.

We can study the time series for epochs corresponding to states specified by I^+ or I^- which are associated with the presence of large anisotropy signified by Σ^2_H or the relative absence of a significant anisotropy indicated by Σ^2_L. The time series of I, of Cp and of $\frac{-1}{I}\frac{dI}{dt}$ for the states $I^+\Sigma^2_H$, $I^+\Sigma^2_L$, $I^-\Sigma^2_H$ and $I^-\Sigma^2_L$ at epoch are indicated in Fig. 12A, B, C and D respectively. For I^+ state, the correlations of the time series of I^+ and of $\frac{-1}{I}\frac{dI}{dt}$ are both rather low. For I^- state there is good correlation of Cp with $\frac{-1}{I}\frac{dI}{dt}$ only for the Σ^2_H state. There is anti-correlation between Cp and I for both I^- states, though this is higher for Σ^2_H than for Σ^2_L. On the basis of the model which we have discussed earlier, this would imply that when decreases of intensity are related to Cp as well as to an electric field in the beam, there is also present a strong anisotropy. Decreases can also occur without a strong anisotropy but then they are not associated with an electric field in the beam.

VI. INTERPRETATION OF EXPERIMENTAL RESULTS:

6.1 The Solar Daily Variation and the Anisotropy of Primary Cosmic Radiation:

The daily variation of cosmic ray intensity is generally described in terms of its diurnal and semidiurnal components or, sometimes, by the difference between the mean intensities during daylight and night hours. With either method, the analysis is capable of revealing only those changes in intensity within 24 hours which are gradual and represent deviations of intensity, positive or negative, which persist for several hours. While sudden changes of intensity lasting for one to two hours, which recur at the same solar time on different days, should properly be considered features of a solar daily variation of intensity, it has been widely believed that the occurrence of such changes is improbable. Therefore, the adoption of techniques of analysis which would be incapable of revealing them has not been considered a handicap. Moreover, unless the apparatus which measures cosmic ray intensity has a high counting rate and an adequate angular resolution for directions of incidence, it would be impossible to establish with appropriate statistical significance single bihourly deviations which are associated with a daily variation. A neutron monitor at a mountain elevation, with its high counting rate and a directional sensitivity towards the vertical due to the rapid attenuation of the nucleonic component in inclined directions, provides a convenient instrument to test the existence or otherwise of such changes. The unambiguity in applying to the local neutron intensity, a correction for atmospheric changes is an added advantage when studying the primary variations of cosmic rays.

We have earlier examined the mean daily variation associated with states specified by deviations of daily mean intensity I and magnitude of Cp, the index of geomagnetic disturbance. Amongst the hours at which significant bihourly deviations occur on a large number of days, designated 'important hours', positive deviations at 0 hour and negative deviations at 6 hours represent sharp changes of intensity. Positive deviations near noon and negative deviations in the late evening correspond to a broad maximum and a broad minimum respectively. Moreover, the maxima and minima of the daily variation for Cp^H state are sharp while for the Cp^L state they are broad. Thus in studies which have been made by considering the diurnal and the semidiurnal components rather than the individual bihourly deviations, the influence of the sharp maximum at midnight and the sharp minimum at 6 hours is underestimated in relation to the broad features near noon and in the late evening.

The study made at Kodaikanal during 1956-57 reveals that sharp changes of bihourly intensity are not only present as features of a daily variation on some days, but they are of considerable significance. It is, therefore, meaningful to refine existing techniques of experimentation to be able to deal with single bihourly deviations in addition to the diurnal and the semi-diurnal components of the daily variation. The abrupt increases and decreases of bihourly intensity at certain periods of the day, which occur particularly in association with geomagnetically disturbed days, would be indicative of the source of the changes being nearer the earth than the anisotropy produced in streams of solar matter outside of the main influence of the geomagnetic field. This conclusion is reached from the zenith angle response of a neutron monitor and the large scatter in asymptotic longitude of primaries, with orbits parallel to the plane of the ecliptic, which influence the intensity measured at the geomagnetic equator.

On a number of days during the period of observation, the daily variation of local neutrons at Kodaikanal has significant diurnal and semidiurnal components. Taking this result in relation to observations made by Sarabhai et al[18] concerning the form of the daily variation of meson intensity at Kodaikanal and at Huancayo at different periods of the solar cycle, it is clear that the form of the daily variation is dependent on latitude and elevation of station, of the geometry of instrument, the secondary component which is measured and the period of observation in relation to the cycle of solar activity. Certain conclusions which have been drawn in the past are related to particular conditions obtaining in the experiment. For instance the distinction observed, by Sarabhai and Bhavsar with narrow angle telescopes in 1955 at Ahmedabad, between two types of daily variations differing in the time of maximum of the diurnal component, is seen only during Cp^H state at mountain stations at the equator in 1956-57 where the semidiurnal component is present on a large number of days along with a diurnal component. $\emptyset_2$ at Kodaikanal during 1956-57 remains remarkably constant on a day-to-day basis in contrast to ϕ_1. When we relate this with the observation of Sarabhai and Sastry[19] that ϕ_2 for the annual mean daily variation at Huancayo goes through a 22 year cycle, it is clear that we have a situation where there are two types of changes, one with a long period related to gross changes in the condition of interplanetary space in the plane of the ecliptic. There is superposed on it a day-to-day effect related to localised conditions associated with individual beams in the neighbourhood of the earth.

Because of the foregoing, there are many features of the daily variation and changes in it which are not similar on a global basis. Nevertheless they respond to physical conditions in interplanetary space; the differences in the daily variations being due to the region of the anisotropy which is scanned by the instrument and the primary energy response of the instrument.

6.2 Cosmic Ray Effects Produced by Solar Streams with Trapped Magnetic Fields:

Dorman has considered the detailed implications of the cosmic ray effects that can be produced by streams of ionised solar matter in the neighbourhood of the earth. Day-to-day changes in the electromagnetic state of interplanetary space are expected to be produced by streams in which ionised matter travels outwards from the sun with a velocity of about 10^8 cms/sec. A stream carries with it a frozen magnetic field which may be derived from the local field at the place of ejection of the stream, or from the dipole field of the sun. With increasing radial distance from the sun, the radial and transverse components of the trapped field get progressively weaker, the radial component more so than the transverse components. Moreover, turbulence can set in at a certain stage and this would further weaken the trapped field. Thus the magnitude and orientation of the trapped field within a beam in the neighbourhood of the earth, and in consequence the electromagnetic state can have a great degree of variability from beam to beam and at different periods of the cycle of solar activity.

Amongst the most important effects of beams which can be observed on the earth are the changes of intensity and of isotropy of the primary cosmic radiation and the disturbances of the geomagnetic field. The effects are as follows: ~~se ... a e~~

(a) Changes of cosmic ray intensity can be produced firstly, by the electric polarization of the beam through what is often referred to as the electric effect which is proportional to $(\bar{u} \times \bar{H})\, b$. Here $\bar{u}$ is the radial velocity of the particles of the beam while $\bar{H}$ and b are the frozen magnetic field in the beam and the width of the beam, both at $R_{\odot}$ respectively. The electric field can produce a modulation of intensity not only while the earth is within a beam but also when it is outside of it during the few days when the beam is approaching or receding from the earth. The second process which is often referred to as the magnetic effect produces a modulation of cosmic ray intensity through the reflection by the beam of low energy primaries. This effect can be expected mainly when the earth is within the beam.

When the earth is not within the beam, the electric effect is operative only on particles above a certain minimum energy determined by $\bar{H}$ and b of the beam. The modulation is not present in cosmic ray primaries below a critical energy Ec (from 5 to 20 BeV, and sometimes according to Dorman as high as 100 BeV), but for primaries above Ec, the percent modulation decreases with increasing primary energy. When the earth is within a beam both the electric and the magnetic effects should be operative. An effect which can be observed only in low energy primaries when the earth is outside the beam, is related to the drift imposed by the outward gradient of the trapped field in the beam. The modulation of intensity by the magnetic effect would be observed preferentially in low energy primaries, in the region 2 to 20 BeV (sometimes upto 100 BeV) as compared to primaries of higher energy.

(b) All the processes discussed above in connection with the modulation of cosmic ray intensity would also disturb the isotropy of the primary radiation which could be observed through study of the daily variation. In addition, the form of the daily variation is related to the orientation of the trapped magnetic field of the beam and to the distance from the sun at which the magnetic field gets weakened through turbulence. The energy dependence of the anisotropy is closely related to the energy dependence of the process of modulation of the mean intensity discussed above.

(c) At the present moment there is no clear understanding of the physical processes through which the characteristics of the beam can be related in a quantitative way to the magnitude of Cp, the daily planetary character figure of geomagnetic disturbance. According to current thinking, geomagnetic disturbances are related to the interaction of the solar beams with the geomagnetic field and it is expected that the important properties of the beam would be the energy in the beam, its density ρ and its velocity u. Thus a beam which has its trapped magnetic field largely randomised through turbulence would have negligible effect on cosmic rays but could still produce geomagnetic disturbances. While over a long period it may perhaps be legitimate to associate high Cp with the presence of a beam, we have little basis, at the present moment, to make specific inferences concerning ρ or u from the magnitude of Cp. The occurrence of high Cp in a time series of Cp, nevertheless appears to be of value in indicating the relative position of the beam with respect to the earth.

From the foregoing considerations we can relate the electromagnetic state of the environment of the earth to the modulation of daily mean intensity I (I^+, I^o, I^-), to the absence (Σ_L^2) or the presence of anisotropy (Σ_M^2 or Σ_H^2), and to Cp. The orientation of the trapped magnetic field in a beam is of critical significance to the nature of modulation and anisotropy (daily variation) produced. The particular effects of the component perpendicular to the ecliptic (↑ or ↓), the radial component (⊙) and the transverse component in the plane of the ecliptic (⇄) of the frozen field are summarised in Table 6. The latitude and longitude of the anisotropy are indicated by the angles ϕ and χ respectively at the earth produced by a virtual source. χ is measured with respect to the sun-earth line. $\chi = 0$ indicates a time of maximum of the diurnal component at noon. At an equatorial station, the measured time of maximum would then be at about 6 hours due to the geomagnetic deflection of particles.

Dorman has attempted to test the validity of the model by comparing characteristics of the average diurnal variation measured under a variety of experimental conditions and relating them to predictions from theory. As regards the stream characteristics, he makes distinction principally between streams of the first kind with $H \approx 10^{-5}$ gauss which he relates to the quiet period diural variation and those of the second kind with $H \approx 10^{-4}$ which he relates to stormtime daily variation.

Dorman's comparison with experimental results is inadequate to test rigorously the validity of the model mainly because he relies on time averages over long periods and he considers only the diurnal component to describe the daily variation. Thus he neglects important aspects of the form of the daily variation and significant changes that take place in the form. The inadequacy is worst at an equatorial station such as Huancayo during 1948 to 1953 where the form deviates significantly from a simple diurnal variation. Moreover, it is evident from our results that phenomenological distinction requires to be made between states defined not only in terms of a quiet period and a stormtime daily variation, but also by other factors. While we are unable at present to study detailed characteristics on individual days, the average daily variation requires to be examined separately at least for states distinguished phenomenologically on considerations of modulation of intensity and geomagnetic disturbances.

The effect of streams on cosmic ray intensity and anisotropy is summarised in Table 7. The important states which can be identified in terms of the observable features indicated here are as follows:

(1) Condition $I^{o}\sum^{2}_{L}$ may be associated with two unique states. The first is related to the absence of a beam, when we should expect low Cp, and the second is related to earth in a beam with no H at $R_{\odot}$. There would then be high Cp but no effect would be observable in cosmic rays.

(2) If we have I^{o} and simultaneously $\sum^{2}_{M}$ or $\sum^{2}_{H}$, then the earth should be within a beam or situated symmetrically between two beams. This could be checked by looking at the time series of Cp for $I^{o}\sum^{2}_{H}Cp^{L}$ and $I^{o}\sum^{2}_{M}Cp^{L}$ epochs and varifying whether we have one beam or two beams symmetrically situated to the right and to the left of the earth. The daily variation should show a maximum, outside the geomagnetic field, between 12 and 18 hours for ↑ H and between 12 and 6 hours for ↓ H which would approximately correspond

to a diurnal maximum at an equatorial station between 8 to 14 (nearer to 8 hours for the low energy particles) and 2 to 8 hours (nearer to 2 for low energy particles) respectively.

(3) If we have I^+ and I^- with Σ^2_M or Σ^2_H we could have one of the three following conditions.

(a) The beam is in the plane of the ecliptic but outside the earth to the left or to the right of it.

(b) The beam is in the plane of the ecliptic and the earth is in the beam.

(c) The beam is above or below the plane of the ecliptic and the beam does not strike the earth at any stage.

The first two conditions can be identified by an increase of Cp and the third by the absence of change of Cp. Whether, in the first case, the earth is to the right or to the left of a beam can be determined by looking at the time series of Cp. There is then a precise relationship between I and the nature of the daily variation as indicated in tables 4 and 5.

It will be observed from this discussion that a correlated study of the daily variation of cosmic rays on individual days, the modulation of the daily mean intensity and the time series of Cp can enable a verification of the proposed model for the interpretation of the variations. Moreover, if the model is substantially correct, we have a tool to determine the electromagnetic state of beams in the neighbourhood of the earth. From the limited data collected so far and the analysis already undertaken, the authors have been able to make a beginning along these lines. The preliminary results can be summarised as follows:

(1) Out of the total number of days of observation during the period 1956-57, on 21% of the days we had the condition $I^o \sum_L^2$, which is indicative of the absence of beams or the absence of a frozen magnetic field at $R_{\frac{1}{0}}$. Of these, 5 % are high Cp days indicating the earth in beams without H. Medium Cp days have been neglected as they represent a transitionary state and cannot identify the presence or absence of beams.

(2) On 18.% of all days, we have $I^o \sum_H^2$ or $I^o \sum_M^2$ and this represents the earth within the beam or symmetrically situated between two beams. The first state (earth in the beam) is identified by high Cp and occurs on 6% of the days. While the second state (earth symmetrically situated between two beams) is identified by low Cp and occurs on 8 % of days.

(3) The relationship of the time series of Cp with those of I and $\frac{-1}{I} \cdot \frac{dI}{dt}$ for I^+ and I^- epochs for conditions which relate to the presence or the relative absence of a strong anisotropy of the primary radiation have been studied in Sec.5.5 (Fig.13). It has been observed that for decreases of intensity, there is high correlation between the time series of I and Cp on days with high anisotropy as well as on days with low anisotropy. On the other hand the correlation of the time series for Cp and $\frac{-1}{I} \frac{dI}{dt}$ is good only for $\sum_H^2$ days when there is a strong anisotropy. Decreases of intensity can, therefore, be produced by the electric effect as well as the magnetic effect. When there is strong anisotropy present the electric effect is also observed. This implies that there are processes whereby a decrease of intensity can occur without the creation of a significant anisotropy.

(4) An examination in Fig.12 of the time series for I and Cp for both increases as well as decreases of I indicates that for I^+ epoch days, Cp is high on and after the epoch while, for I^- days, it is high on or before the epoch. Also when I^+ epochs are divided into groups characterised by high and low anisotropy it is seen that only epochs with high anisotropy are preceeded by disturbance. This shows that for the I^+ days the beams approach from the left and produce a strong anisotropy while for the I^- days, they recede to the right. This implies that the component of electric field in the ecliptic plane as seen from the earth is in the direction left to right. This indicates the presence of a component of the frozen magnetic field in the same direction as the earth's magnetic field. The direction of the magnetic field is in conformity both with the expected direction of the sunspot field during this period and the direction of the magnetic field of the sun.

(5) While decreases can be due to both electric and magnetic effects of the beam, the increases can be due mainly to the electric effect and hence the decreases due to the two processes are additive while increases would represent the net result of their opposing effects on I. As has been shown in section 3.7 this corresponds to the observations at Kodaikanal where the decreases of cosmic ray intensity are larger in amplitude than increases.

VII. CONCLUSIONS:

We summarise here some of the principle conclusions that emerge from the present study.

(1) Day-to-day changes of intensity involve increases as well as decreases with respect to a base intensity for the period in question. Decreases are much larger in amplitude

than increases. Decreases are generally related to the so called "magnetic effect" of beams, but if the "electric effect" is also present, there is high anisotropy.

(2) The daily variation of intensity of local neutrons at an equatorial mountain station during 1956-57, has often a large diurnal as well as a semidiurnal component. The prominent features of the variation are a maximum near noon and a minimum at 2000 hours. There is often a second maximum near midnight and a minimum at 0600 hours.

(3) On days of high geomagnetic disturbance, the daily variation exhibits abrupt changes indicative of the source being situated at a distance shorter than the range of the geomagnetic field. On geomagnetically quiet days, the daily variation has a form consistent with its being related to an anisotropy in interplanetary space. On days of moderate geomagnetic disturbance, the daily variation has changeable characteristics.

(4) Correlated day-to-day changes of mean intensity and daily variation have been confirmed. For geomagnetically disturbed days, the semidiurnal component is greater than the diurnal component for increases of intensity, and conversely for decreases of intensity. Low anisotropy is on the average associated with days of moderate and low Cp.

(5) An examination of the time series of Cp for high intensity and for low intensity indicates the presence of a component of the frozen magnetic field in the direction of the solar dipole field. However, during the period of observation the solar dipole field and the component of the sunspot field perpendicular to the ecliptic were in the same direction. Therefore, the results obtained cannot be considered either to confirm or refute the possibility of beams carrying sunspot fields with them.

(6) For a rigorous test of various interpretations that are proposed there is need to refine measuring techniques to enable study of the daily variation on individual days. It is also necessary to examine single bihourly deviations in addition to the diurnal and semidiurnal component of the daily variation.

(7) Cosmic ray evidence concerning anisotropy and modulation of intensity appears to be very promising in supplementing geomagnetic data for the specification of the electromagnetic state of interplanetary space, in the neighbourhood of the earth. The orientation of the trapped magnetic field in a beam is of crucial significance to the nature of modulation and anisotropy or daily variation that is produced. At the present moment no detailed verification of the modulation theories involving beams could be considered to have been achieved. It appears that beams certainly play an important role, but it is more than likely that we have other processes as well.

VIII. ACKNOWLEDGEMENTS:

The authors are grateful to K.R. Ramanathan, N.W. Nerurkar and to R.P. Kane for many valuable suggestions. One of us (V. Sarabhai) has had the opportunity of valuable discussions with B. Rossi and received hospitality at the Laboratory for Nuclear Science at the M.I.T. Cambridge, which are gratefully acknowledged. The apparatus at Kodaikanal was for some time under the supervision of T.S.G. Sastry and of B.A. Holla. To them, and to S.R. Thakore and the computation section we are greatly indebted. We are also grateful to U.D. Desai and S.P. Duggal for their kind assistance. We have received generous assistance from the Atomic Energy Commission of India.

TABLE 1

RELATIONSHIPFOF BIHOURLY DEVIATIONS AT 0600 AND 2200 HOURS WITH Cp AND AVERAGEDMEAN I FOR Σ_M^2 AND Σ_H^2 DAYS

0600 hours				2200 hours			
Groups of deviation	No.of days	Averaged Mean I x 32	Mean Cp	Groups of deviation	No.of days	Averaged Mean I x 32	Mean Cp
$\geqslant +2\sigma$	6	1269.2	0.40	$\geqslant +2\sigma$	5	1276.8	0.84
$+\sigma$ to $+2\sigma$	15	1268.1	0.71	$+\sigma$ to $+2\sigma$	11	1277.1	0.88
0 to $+\sigma$	25	1269.0	0.73	0 to $+\sigma$	22	1270.2	0.70
0 to $-\sigma$	18	1270.8	0.97	0 to $-\sigma$	20	1274.7	0.69
$-\sigma$ to -2σ	26	1271.2	0.73	$-\sigma$ to -2σ	27	1268.7	0.76
$\leqslant -2\sigma$	25	1276.1	30.87	$\leqslant -2\sigma$	30	1268.5	0.86

TABLE 2

THE CHARACTERISTICS OF THE MEAN DAILY VARIATION FOR GROUPS OF I

Group	No. of days	$r_1 \pm \sigma$ * %	ϕ_1	$r_2 \pm \sigma$ %	ϕ_2	Mean $\Sigma^2 X$ 5.10^5
I^+	82	0.17 ± 0.02	$\pi + 15^\circ$	0.24 ± 0.02	25°	2.75
I^o	84	0.26 ± 0.02	$\pi + 6^\circ$	0.26 ± 0.02	49°	2.61
I^-	63	0.22 ± 0.03	153°	0.24 ± 0.03	51°	2.67

* σ = Standard Error

TABLE 3

THE CHARACTERISTICS OF THE MEAN DAILY VARIATION FOR GROUPS OF Cp

Group	No. of days	$r_1 \pm \sigma$ * %	ϕ_1	$r_2 \pm \sigma$ %	ϕ_2	Mean $\Sigma^2 X$ 5.10^5
Cp^H	67	0.19 ± 0.03	$\pi + 7^\circ$	0.31 ± 0.03	45°	2.77
Cp^M	66	0.15 ± 0.03	144°	0.16 ± 0.03	38°	2.57
Cp^L	96	0.27 ± 0.02	$\pi + 7^\circ$	0.26 ± 0.02	33°	2.69

* σ = Standard Error

TABLE 4

THE CHARACTERISTICS OF MEAN DAILY VARIATION AND MEAN Σ^2 FOR STATES OF Cp AND I

Cp \ I		I^+	I^o	I^-
Cp^H	No. of days	22	23	22
	$r_1 \pm \sigma$* %	0.10 ± 0.04	0.27 ± 0.04	0.30 ± 0.04
	ϕ_1 degrees	$\pi + 28$	$\pi + 20$	159
	$r_2 \pm \sigma$ %	0.32 ± 0.04	0.35 ± 0.04	0.24 ± 0.04
	ϕ_2 degrees	38	55	58
	Mean $\Sigma^2 \times 5.10^5$	2.7	2.9	2.7
Cp^M	No. of days	25	21	20
	$r_1 \pm \sigma$ %	0.07 ± 0.04	0.22 ± 0.04	0.21 ± 0.04
	ϕ_1 degrees	170	150	120
	$r_2 \pm \sigma$ %	0.15 ± 0.04	0.26 ± 0.04	0.11 ± 0.04
	ϕ_2 degrees	30	46	30
	Mean $\Sigma^2 \times 5.10^5$	2.6	2.5	2.6
Cp^L	No. of days	35	40	21
	$r_1 \pm \sigma$ %	0.26 ± 0.03	0.32 ± 0.03	0.20 ± 0.04
	ϕ_1 degrees	$\pi + 19$	$\pi + 5$	162
	$r_2 \pm \sigma$ %	0.27 ± 0.03	0.25 ± 0.03	0.33 ± 0.04
	ϕ_2 degrees	20	44	25
	Mean $\Sigma^2 \times 5.10^5$	2.9	2.5	2.7

* σ = Standard Error

TABLE 5

THE CHARACTERISTICS OF THE MEAN DAILY VARIATION,
MEAN I AND MEAN Cp FOR STATES OF I AND Σ^2

Σ^2 \ I		I^+	I^o	I^-
Σ_H^2	No. of days	20	20	13
	$r_1 \pm \sigma$ * %	0.37 ± 0.04	0.39 ± 0.04	0.38 ± 0.06
	ϕ_1 degrees	$\pi + 27$	173	163
	$r_2 \pm \sigma$ %	0.41 ± 0.04	0.36 ± 0.04	0.42 ± 0.06
	ϕ_2 degrees	34	58	37
	Mean Cp	0.84	0.71	0.94
	Mean I	1282 x 32	1272 x 32	1259 x 32
Σ_M^2	No. of days	25	21	19
	$r_1 \pm \sigma$ %	0.19 ± 0.04	0.30 ± 0.04	0.36 ± 0.05
	ϕ_1 degrees	$\pi + 32$	$\pi + 20$	143
	$r_2 \pm \sigma$ %	0.19 ± 0.04	0.26 ± 0.04	0.39 ± 0.05
	ϕ_2 degrees	15	60	46
	Mean Cp	0.66	0.68	0.95
	Mean I	1282 x 32	1273 x 32	1258 x 32
Σ_L^2	No. of days	36	43	30
	$r_1 \pm \sigma$ %	0.19 ± 0.03	0.20 ± 0.03	0.07 ± 0.04
	ϕ_1 degrees	139	180	163
	$r_2 \pm \sigma$ %	0.19 ± 0.03	0.23 ± 0.03	0.17 ± 0.04
	ϕ_2 degrees	15	35	45
	Mean Cp	0.68	0.63	0.78
	Mean I	1281 x 32	1275 x 32	1259 x 32

* σ = Standard Error

TABLE 6

CHARACTERISTICS OF THE SOURCE OF DIURNAL VARIATION RELATED TO ORIENTATION OF MAGNETIC FIELD IN THE BEAM

Direction of magnetic field	Effect observed	Beam to the left of earth		Beam to the right of earth		Beam surrounding the earth	
		Position positive source	Position negative source	Position positive source	Position negative source	Position positive source	Position negative source
↑	On isotropy	$0 < \chi < \frac{\pi}{2}$ $\phi = 0$	-	-	$\chi \leq \frac{3}{2}$	$0^* < \chi < \frac{\pi}{2}$	$\pi^* < \chi < \frac{3\pi}{2}$
↓	On isotropy	-	$\chi \leq \frac{\pi}{2}$	$\chi \leq \frac{3\pi}{2}$	-	$\pi^* < \chi < \frac{3\pi}{2}$	$0^* < \chi < \frac{\pi}{2}$
→	On isotropy	$\phi \leq \frac{\pi}{2}$	-	$\phi \leq \frac{\pi}{2}$	-	$0^* < \phi < \frac{\pi}{2}$ $\chi = 0$	$-\frac{\pi}{2} < \phi < 0^*$
←	On isotropy	-	$\phi \leq \frac{\pi}{2}$	-	$\phi \leq \frac{\pi}{2}$	$-\frac{\pi}{2} < \phi < 0^*$	$0^* < \phi < \frac{\pi}{2}$
⊙	No effect on isotropy	-	-	-	-	-	-

Note: For low energy particles the position of the source will be nearer the limit marked with a star and would shift towards the other limit with increased primary particle energy.

TABLE 7

GEOMAGNETIC DISTURBANCES, COSMIC RAY INTENSITY VARIATION

AND ANISOTROPY PRODUCED BY SOLAR BEAMS

	Earth in beam	Earth outside beam but near it
	(a) No trapped magnetic field in beam at $R_\oplus$	
1. Effect on Cp	Relative increase of Cp on earth entering beam and relative decrease when it crosses the earth.	No change in Cp
2. Effect on daily mean intensity I.	No effect, occurrence of I^o	No effect , occurrence of I^o
3. Effect on isotropy	No effect, occurrence of $\sum_L^2$	No effect, occurrence of $\sum_L^2$
	(b) Beams having frozen magnetic field 10^{-4} - 10^{-5} gauss at $R_\oplus$	
1. Effect on Cp	Relative increase of Cp on earth entering beam and relative decrease after it crosses the beam	No effect
2. Effect on daily mean intensity I.	Electric and magnetic effect on I, occurrence of I^+, I^o, I^-	Only electric effect is present, occurrence of I^+ and I^-
3. Effect on isotropy	Both the electric and magentic effects are present and the observed effect depends on the orientation and magnitude of H, occurrence of $\sum_M^2$ and $\sum_H^2$.	Electric effect is more important but the effect of the magnetic field is also present to a small extent. Occurrence of $\sum_M^2$ and $\sum_H^2$.

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CAPTIONS FOR THE FIGURES

Fig. 1 : The percent deviation Δ I of daily mean cosmic ray intensity at Kodaikanal and the daily planetary character figure Cp of geomagnetic disturbance, during the period December 1956- to September 1957.

Fig. 2 : Histogram of occurrence of positive and negative percent deviations Δ I of daily mean cosmic ray intensity. The histogram in full line corresponds to a sample of all days during the period of study, while the diagram in dotted line corresponds to the sample of days used for study of daily variation.

Fig. 3 : Histogram of variance Σ^2 on individual day of deviations of bihourly cosmic ray intensity from daily mean intensity.

Fig. 4 : Diagrams showing frequency of occurrence at different hours of positive and negative bihourly deviations Δ x of significant amplitude.

Fig. 5 : Average daily variation of cosmic ray intensity for days of high (I^+), normal (I^o) and low (I^-) daily mean intensity.

Fig. 6 : Average daily variation of cosmic ray intensity for days of high (Cp^H), medium (Cp^M) and low (Cp^L) index of daily planetary character figure for geomagnetic disturbance.

Fig. 7 : Histograms of occurrence of time of maximum ϕ_1 of diurnal component and ϕ_2 of semidiurnal component on days on which the amplitude of the respective components have significant amplitude during groups of days in the I^+, I^o, I^- and Cp^H, Cp^M and Cp^L characteristics.

Fig. 8 : Average daily variation of cosmic ray intensity for the nine states formed by paired characteristics of I (columns) and of Cp (rows).

Fig. 9 : Average daily variation of cosmic ray intensity for the nine states formed by paired characteristics of I (columns) and of Σ^2 (rows).

Fig. 10 : Chree analysis of I and of Cp for Cp^L and Cp^H epochs corresponding to low and high degree of geomagnetic disturbance respectively. The time series for $\frac{-1}{I}\frac{dI}{dt}$, derived from the time series of I is also shown.

Fig. 11 : Chree analysis of I and of Cp for epochs corresponding to the four states $I^+ Cp^H$, $I^+ Cp^L$, $I^- Cp^H$ and $I^- Cp^L$.

Fig. 12 : Chree analysis of I and of Cp for epochs corresponding to the states $I^+ \Sigma^2_H$ (Fig. 12A), $I^+ \Sigma^2_L$ (Fig. 12B), $I^- \Sigma^2_H$ (Fig. 12C) and $I^- \Sigma^2_L$ (Fig. 12D). The time series for $\frac{-1}{I}\frac{dI}{dt}$ derived from the time series of I is also shown in each figure.

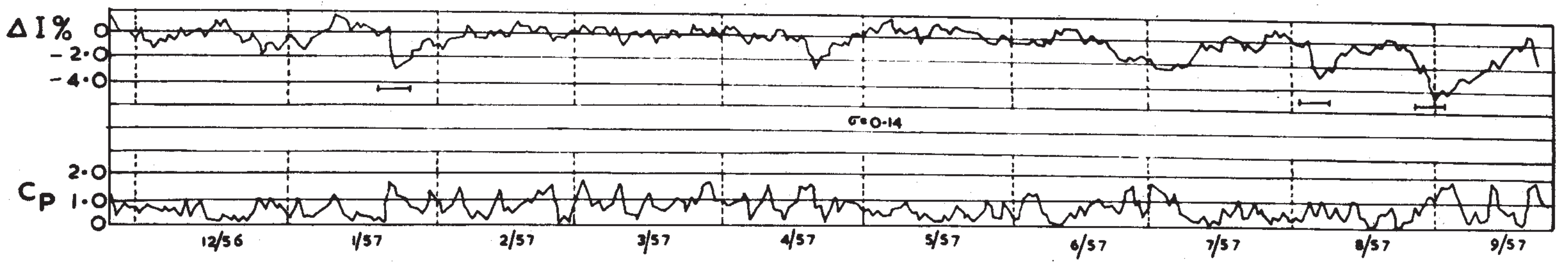
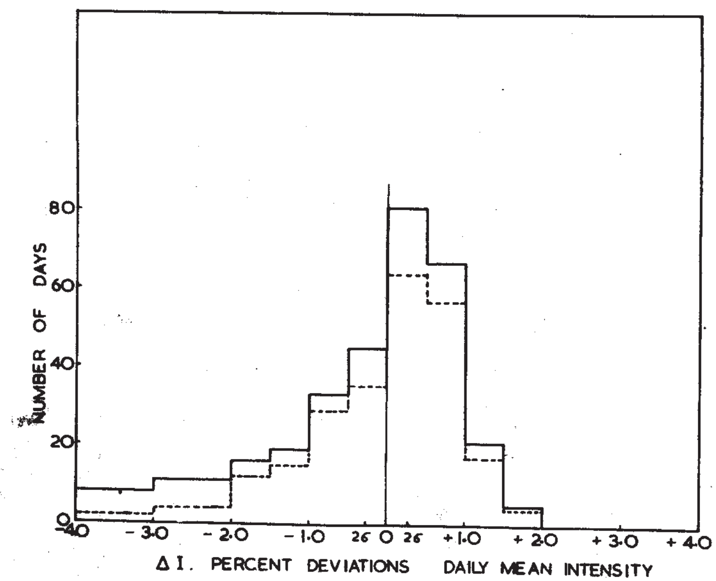

ΔI%
0
-2·0
-4·0
σ=0·14
2·0
CP
1·0
0
12/56
1/57
2/57
3/57
4/57
5/57
6/57
7/57
8/57
9/57

Fig 1


NUMBER OF DAYS
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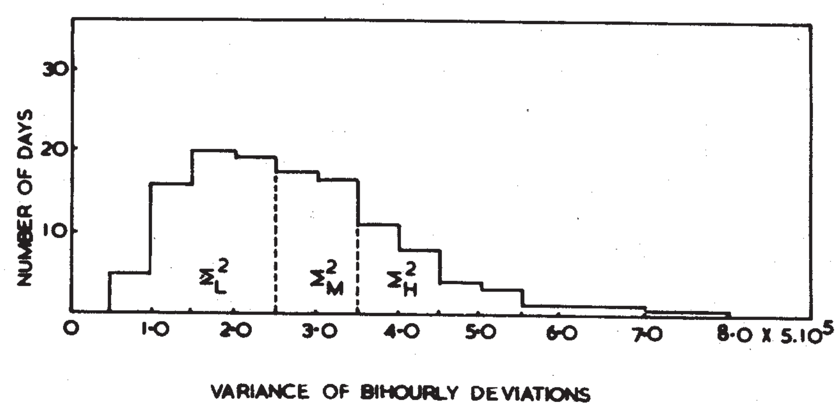
60
40
20
0
-4·0
-3·0
-2·0
-1·0
2σ
0
2σ
+1·0
+2·0
+3·0
+4·0
ΔI. PERCENT DEVIATIONS DAILY MEAN INTENSITY


NUMBER OF DAYS
30
20
10
Σ_L^2
Σ_M^2
Σ_H^2
0
1·0
2·0
3·0
4·0
5·0
6·0
7·0
8·0 X 5.10⁵
VARIANCE OF BIHOURLY DEVIATIONS

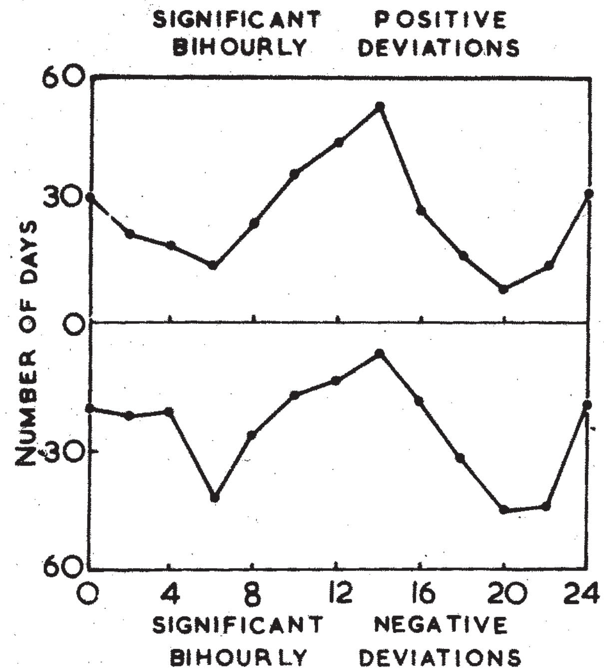


Fig 4

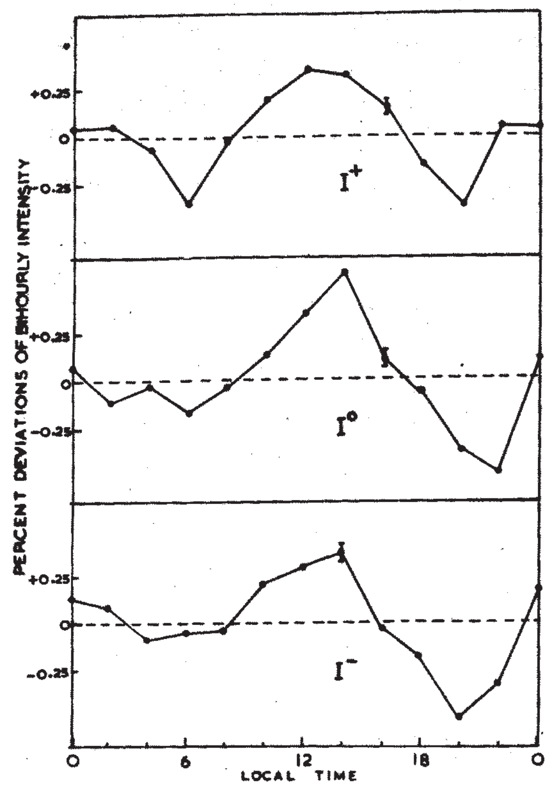


Fig 5

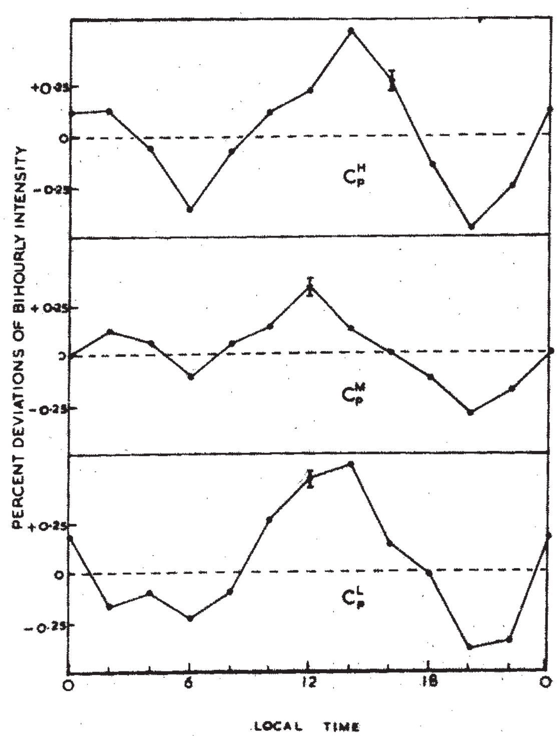


Fig 6

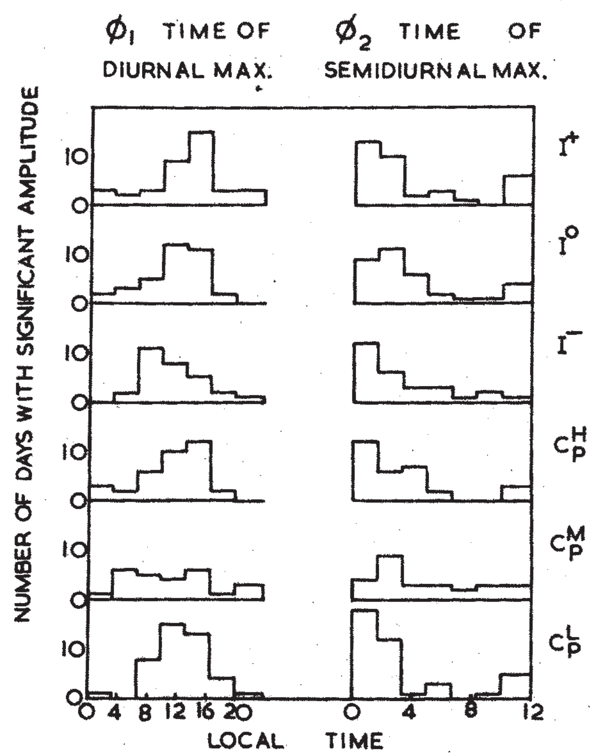


Fig 7

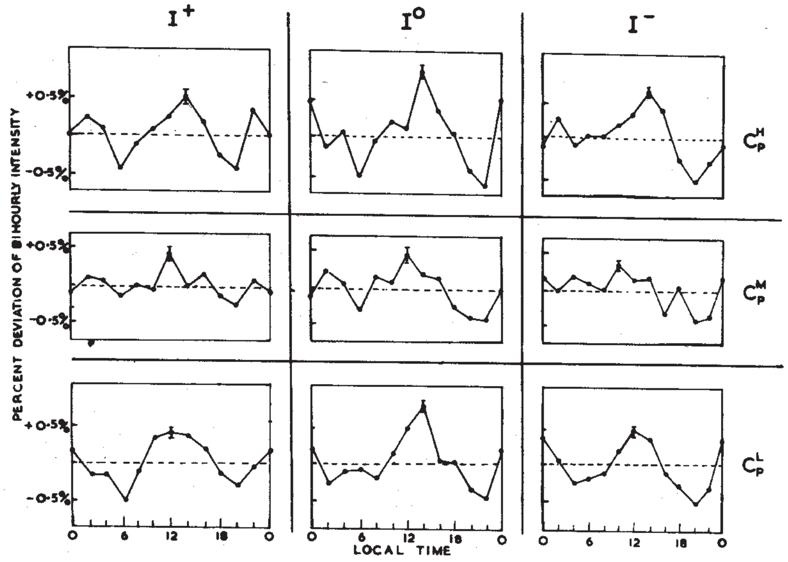


Fig 8

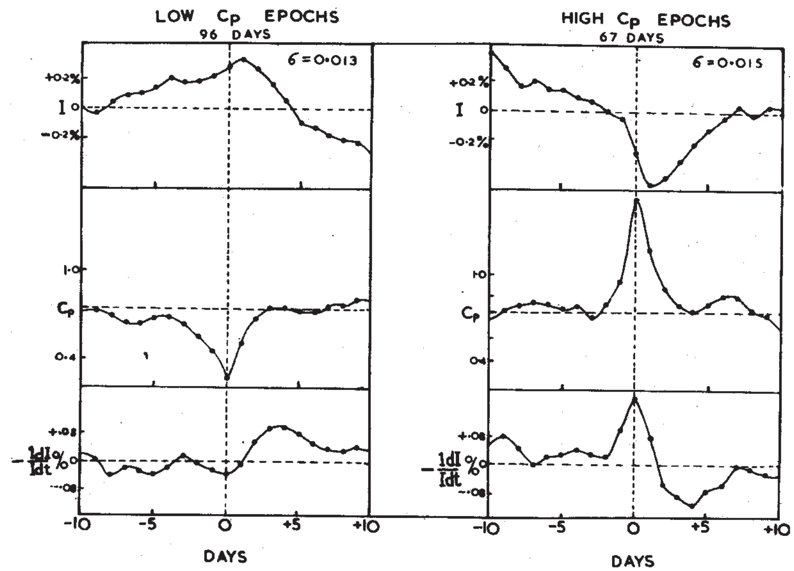


Fig 10

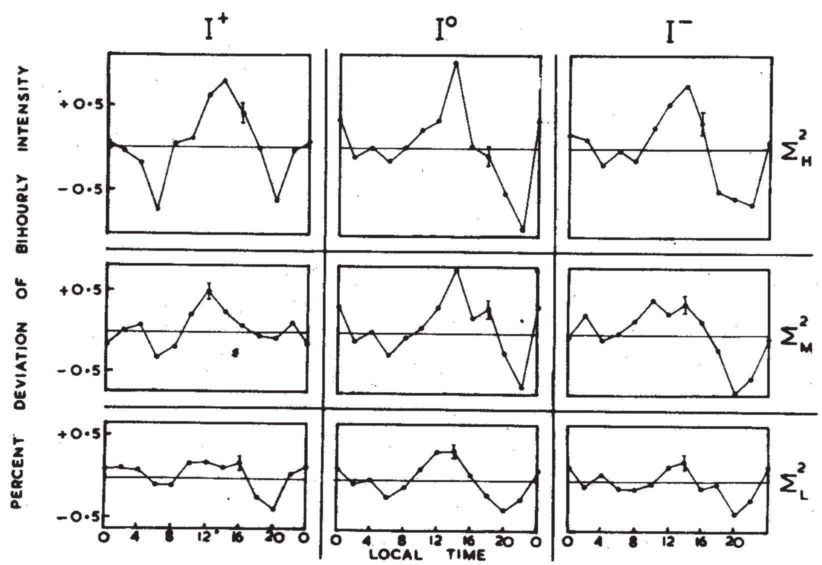


Fig 9

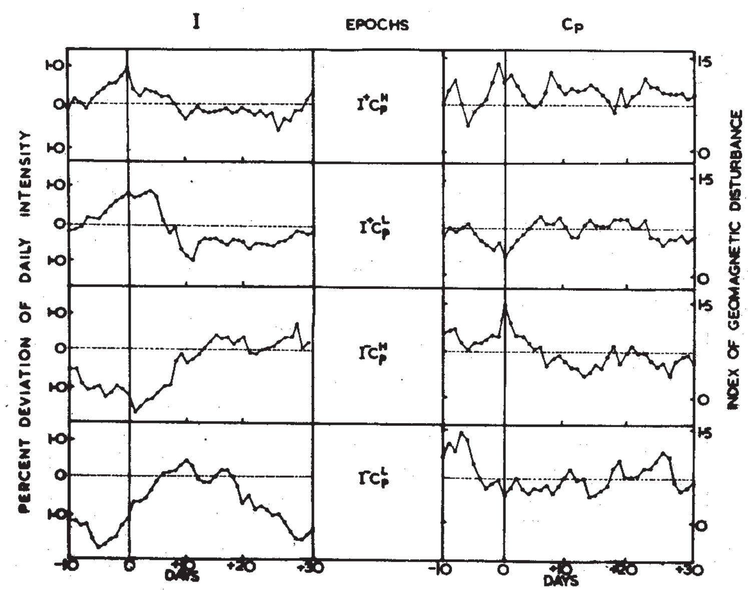


Fig 11

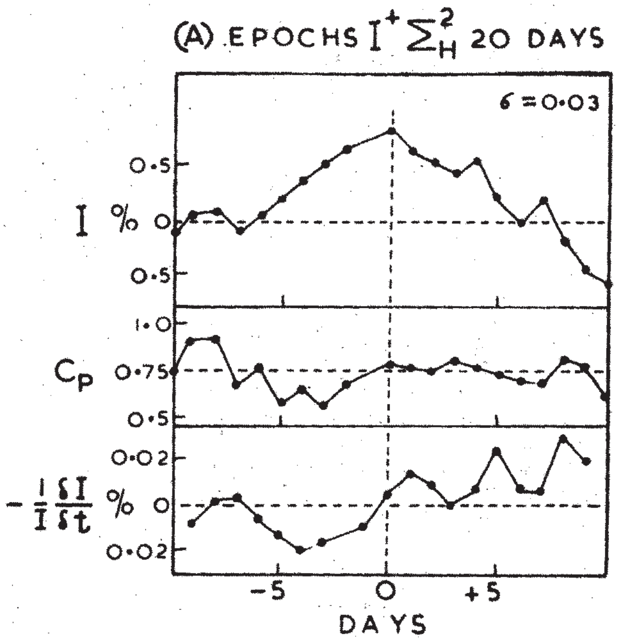


Fig 12 a

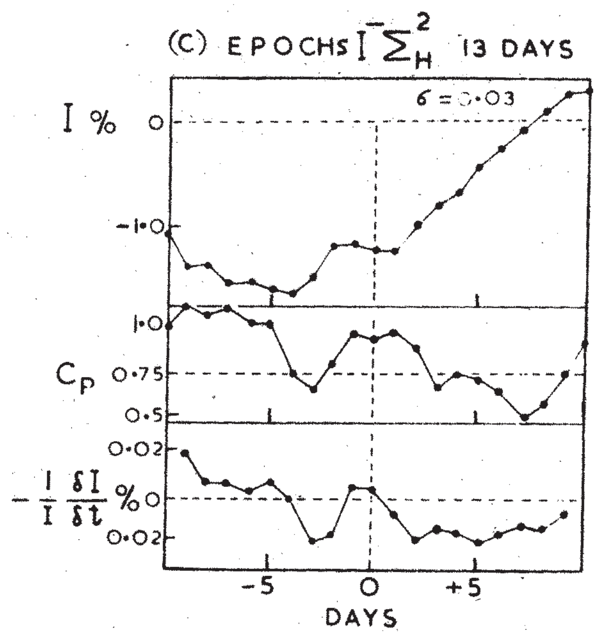


Fig 12 c

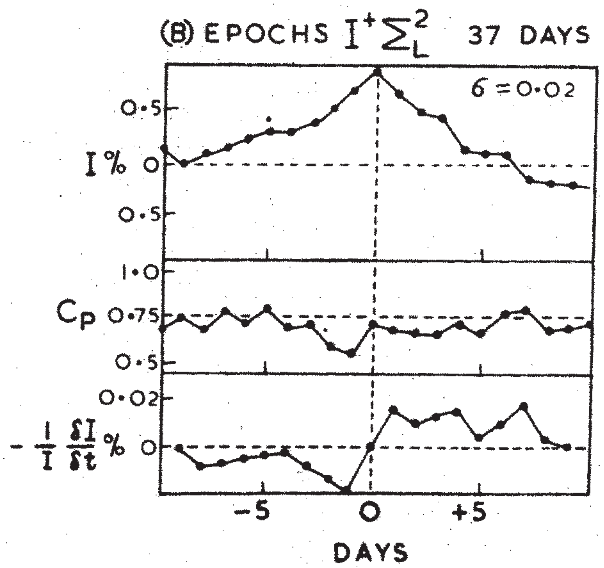


Fig 12 b

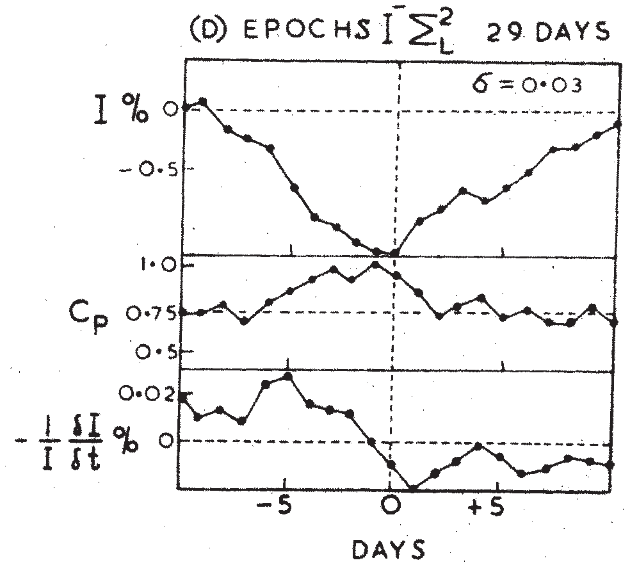


Fig 12 d

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Arrival Directions of Cosmic-Ray Air Showers from the Equatorial Sky*

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(Received March 21, 1960)

The celestial arrival directions of over 100 000 showers with sizes greater than 10^5 particles have been determined by fast timing in observations at an altitude of 2034 m. The observations covered a band of declinations from −30° to +50° with an angular resolution of 4°, and they extended a survey begun in an earlier experiment that covered the northern sky. As in the earlier experiment no significant deviation from isotropy was found. The atmospheric attenuation of the shower intensity was determined from the zenith angle distribution, and also from a comparison of the absolute shower intensity at 2034 m and at sea level. Within an experimental uncertainty of about 5%, both methods yield an exponential attenuation length consistent with the value of 107 g cm^{-2} previously found at sea level. The absolute intensity of showers with more than 10^5 particles at 2034 m was found to be $(1.11\pm0.30)\times10^{-9}$ cm^{-2} sec^{-1} sr^{-1}.

I. INTRODUCTION

A PREVIOUS survey of the arrival directions of 2660 extensive cosmic-ray air showers from the northern sky (from declination +20° to +70°) has been reported in an earlier paper.[1] In that survey the arrival direction of each detected shower was determined from measurements of the differences in arrival times of the shower particles at four scintillation detectors located at the corners of a square. Showers in the size range from 10^5 to 10^6 particles at sea level were recorded. The observed distribution of the arrival directions was found to be consistent with the assumption that the flux of primary particles which generate showers in this size range is isotropic within the uncertainty due to the statistical fluctuations in the data. Similar conclusions have been drawn from the results of other surveys,[2] carried out by different experimental methods.

The detection of a deviation from isotropy of the flux of high-energy primaries would give important clues to the origin and propagation of cosmic rays in the galaxy. Alternatively, a reduction in the observed upper limit to anisotropy serves the useful purpose of restricting the choice of models for the explanation of the origin of cosmic rays. The earlier survey was, therefore, extended to the equatorial sky (from declination −30° to +50°) using the same experimental method that is described in detail in I, but with a large increase in the number of events recorded. This region of the sky is of particular interest because it contains the galactic center. As a byproduct, the new data make possible a comparison of the zenith angle distribution of arrival directions and the absolute shower intensity at different altitudes, and this comparison gives information on the development of extensive air showers in the atmosphere.

Since the present experiment is largely an extension of the earlier one, the results will be presented in essentially the same form as in I, but abbreviated to avoid repetition and with detailed descriptions of only those features of the analysis which are significantly different. Reference will be made to the earlier paper for details of the abbreviated descriptions.

II. DESCRIPTION OF THE METHOD

For each shower event we determined the relative arrival times (t_1, t_2, t_3, t_4) of the first shower particles to traverse each of four detectors at the corners of a square. From these data, together with the time and date of occurrence, we computed the zenith angle, azimuth, declination, and right ascension of the shower axis, and the quantity $\Delta=c(t_1+t_4-t_2-t_3)$ which indicates the goodness of the least squares fit of the data to the calculated arrival directions. The formulas for these computations are given in I.

III. EXPERIMENTAL ARRANGEMENT

For the present survey a new and improved fast timing apparatus was constructed which is described in detail elsewhere.[3] In this apparatus we used four plastic scintillation detectors with high-gain RCA 6810 photomultipliers connected to a fast oscilloscope. The detectors were located at the corners of a square 35.5 m

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[1] G. Clark, Phys. Rev. 108, 450 (1957), referred to as I.

[2] F. J. M. Farley and J. R. Storey, Proc. Phys. Soc. (London) A67, 996 (1954); T. E. Cranshaw and W. Galbraith, Phil. Mag. 45, 1109 (1954); J. K. Cranshaw and H. Elliot, Proc. Phys. Soc. (London) A69, 102 (1956); P. Rothwell, B. Wade, and A. Goodings, Proc. Phys. Soc. (London) A69, 902 (1956); J. Daudin, P. Auger, A. Cachon, and A. Daudin, Nuovo cimento 3, 1017 (1956); T. E. Cranshaw and W. Galbraith, Phil. Mag. 2, 804 (1957).

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on a side, at an altitude of 2034 m in Kodaikanal, South India, which is located at 10° N geographic latitude and 78° E longitude. Approximately 40 000 showers were recorded during a "fast run" with scintillators that were cylindrical slabs 16 in. in diameter and $2\frac{1}{2}$ in. thick with a total surface area of 1300 cm^2. About 70 000 more showers of four times larger average size were recorded during a "slow run" with smaller scintillators made by cutting a 16-in. scintillator into four equal segments.

The photographic record of the timing pulses on the fast oscilloscope was projected and measured, and the data were transferred to IBM cards. The remainder of the data processing was carried out on the IBM 704 computer in the MIT Computation Laboratory. Data were processed at the rate of about 5000 events per hour of computer time.

IV. RESPONSE OF THE DETECTOR ARRAY

In I we calculated the response of the detector array to showers of various sizes on the assumption that the lateral distribution can be represented by the function

$$f(r)=(N/2\pi)\frac{e^{-r/r_0}}{rr_0},$$

and that the integral size spectrum has the form

$$K(N,\theta)=K(10^6,\theta)(N/10^6)^{-\Gamma(N)}.$$

We repeated this calculation for the present experiment using for r_0 the value 101 m which is the Molière unit at Kodaikanal. According to the results obtained by Greisen[4] from an analysis of the density spectrum at mountain altitudes, the value of $\Gamma(N)$ changes only slightly over the range of sizes of most of the showers detected in this experiment. We therefore used for $\Gamma(N)$ the constant value 1.50. The results are presented in Fig. 1, which shows the distributions in sizes of showers detected in the fast and slow runs.

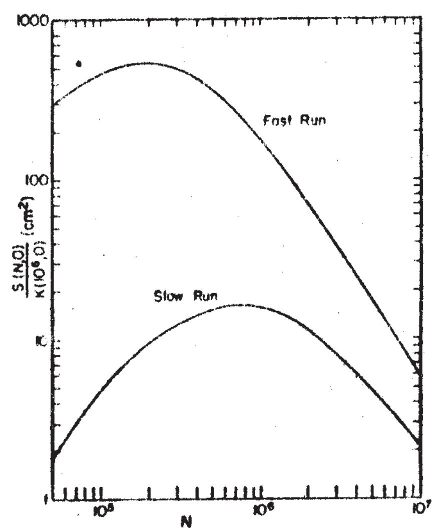

FIG. 1. Distributions in size of showers recorded during the fast and slow runs.

[4] K. Greisen, *Progress in Cosmic-Ray Physics*, edited by J. G. Wilson (North Holland Publishing Company, Amsterdam, 1956), Vol. III, Chap. 1.

V. EXPERIMENTAL RESULTS

A. Angular Resolution

The angular resolution of the timing method for determining the arrival directions of extensive air showers is limited primarily by the lack of perfect coplanarity of the shower particles. The quantity Δ, defined above, differs from zero by an amount that depends on the degree of noncoplanarity of the shower particles which first traverse the four detectors. Following a procedure described in I, we can determine the uncertainty in a measurement of the arrival direction of a shower from the observed distribution of Δ. The distributions of Δ for large samples of events recorded during the fast and the slow runs are essentially identical to the distribution observed at sea level. As in the previous experiment, the contribution of purely instrumental and reading errors to the breadth of the distribution is negligible, and essentially the entire breadth of the distributions is due to a lack of coplanarity of the shower particles. The standard deviations of the two distributions are not significantly different from one another or from the value observed at sea level, and they indicate that the error in an arrival direction determination corresponds to a circle of confusion with a radius of 5°. As in the sea-level experiment, we increase the effective resolution of the instrument by rejecting events in which Δ exceeds 6.4 m so that the angular resolution for showers selected according to this criterion is about 4°.

B. Zenith Angle Distribution

The slant thickness x of atmosphere traversed by a shower whose axis is inclined at a zenith angle θ is given by the relation

$$x=x_0(\sec\theta-1),$$

where x_0 is the vertical thickness from the top of the atmosphere to the point of observation. Thus the relative intensity of showers arriving from various zenith angles is related to the growth and absorption of showers in the atmosphere.

Figure 2 shows semilogarithmic plots of the observed rates of selected showers per unit solid angle $\Delta R/\Delta\Omega$ versus the atmospheric thickness x. The slopes of these two plots are constant for $x-x_0\leq 170$ g cm^{-2} corresponding to $\theta\leq 35°$. It was shown in I that at sea level the effective sensitive area of the detector array projected onto a plane perpendicular to the arrival direction is approximately constant and independent of the arrival direction out to zenith angles near 45°. Consequently, the dependence of the observed counting rate on x is determined essentially only by the zenith angle dependence of the shower intensity K. The same conclusion is valid in the present experiment. Therefore, the constant slopes of the two plots for values of x corresponding to zenith angles less than 35° indicate that K can be approximately represented by the formula

$$K(N,\theta)=K(N,0)\exp[-(x-x_0)/\Lambda(N)],$$

where $\Lambda(N)$ may change slowly with N.

For Λ we find the values 100 ± 6 g cm^{-2} and 106 ± 5 g cm^{-2}, respectively, for the fast and slow runs. These values are the reciprocal slopes reduced by 5% to take into account the broadening effect of timing errors on the observed zenith angle distribution. Within the limits of the experimental errors, both values are the same as the value found at sea level, namely 107 ± 11 g cm^{-2}.

C. The Absolute Intensity

If the lateral distribution is independent of size and the size spectrum is a power law, then the counting rate of our apparatus for vertical showers is related to the area of the detectors by a power law with the same exponent as the size spectrum. This conclusion follows from a simple calculation well known in the analysis of measurements of the density spectrum. Thus the ratio

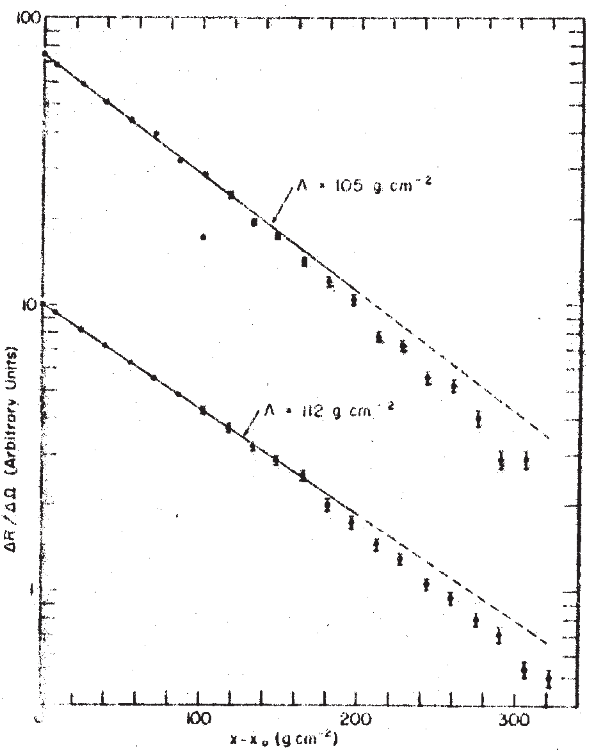

FIG. 2. Semilogarithmic plots of shower intensity versus atmospheric thickness as derived from the observed distributions in zenith angle for the fast (upper plot) and slow (lower plot) runs.

of the counting rates for vertical showers in the fast and slow runs should be the ratio of the areas of the detectors raised to the exponent of the size spectrum, namely $4^{1.5}=8$. The experimentally determined ratio of counting rates for vertical showers is 8.4 ± 0.5. The indicated error arises in part from the uncertainties in the zenith angle distributions on which the evaluation of the vertical rates depends, and in part from the magnitudes of the fluctuations in rates observed during the best selected periods of observation. These fluctuations are due primarily to small variations in the efficiencies of the detectors. The agreement between the expected and observed ratios indicates a satisfactory degree of internal consistency in the data analysis.

According to Greisen's analysis, $\Gamma(N)$ changes only slightly between sea-level and mountain altitudes. Therefore, to a good approximation, we can attribute the change in the value of $K(N,0)$ between sea level and Kodaikanal entirely to atmospheric absorption. At Kodaikanal we find $K(10^6,0)=(3.5\pm1.0)\times10^{-11}$ cm^{-2} sec^{-1} sr^{-1}. At sea level we found $K(10^6,0)=(3.0\pm1.0)\times10^{-12}$ cm^{-2} sec^{-1} sr^{-1}. In both cases the errors are intended to indicate the possible systematic errors in the calculations of the responses of the detector arrays. Since the calculations are essentially identical in the two cases, their fractional systematic errors should be nearly identical. Thus, if we assume that K is an exponential function of the vertical depth in the atmosphere, we can find a value for the absorption length Λ' whose uncertainty will not be seriously affected by these systematic errors. We find for Λ' the value

$$\Lambda'=103\pm5 \text{ g cm}^{-2},$$

which agrees with the value found from the zenith angle distributions.

Assuming the above value of $K(10^6,0)$ and $\Gamma=1.5$, we find the vertical intensity of showers with more than 10^5 particles at an altitude of 2034 m to be $(1.11\pm0.30)\times10^{-9}$ cm^{-2} sec^{-1} sr^{-1}.

D. Distribution of Celestial Arrival Directions

The principle problem in the analysis of the distribution of the celestial arrival directions is to make proper allowance for the fact that the experiment was interrupted occasionally for maintenance and by power failures. As a result of these interruptions, some regions of the sky were under observation longer than others. Thus the number of showers observed to come from those regions would be expected to be greater even if the primary flux were isotropic. In order to keep track of the time during which various regions of the sky were under observation, we kept a running record of ON-TIME $Q(\gamma)$ which we define to be the number of days on which the apparatus was functioning at the sidereal time γ. We then prepared a plot of Q versus γ for a given group of events to be analyzed, and determined the average $\bar{Q}_i$ of $Q(\gamma)$ for each of m equal intervals of sidereal time for that group (for most of the analysis $m=36$, and for the rest $m=24$). Finally, for each interval of sidereal time we calculated a weight factor w_i according to the formula

$$w_i = \frac{1}{m}\left(\sum_{j=1}^{m} \bar{Q}_j\right) \Big/ \bar{Q}_i,$$

and assigned this weight to each event in the group which was recorded during the ith sidereal time interval. In practice, the groups into which we divided the data were large enough and covered enough days of observation so that the values of w_i were always in the range from 0.85 to 1.15. Thus the effect of this procedure is to even out the effective exposure time for all portions of the sky without significantly changing the statistical significance of each event from what it would have been if it were given unit weight. The weights determined in the above manner are called weights based on logged ON-TIME. We combined the data from the steadiest periods of operation during the fast and slow runs and tabulated the total weights of events in 10°×10° areas of a Mercator projection of the celestial sphere. The results of this tabulation are shown in Fig 3.

In view of the difficulty of maintaining very uniform triggering efficiencies which is inherent in a detector system utilizing scintillation detectors, and also in view of the difficulty of maintaining an exact record of the operation of the apparatus, it seemed advisable to use, in addition to the weighting procedure outlined above, another one which would remove nearly all trace of anisotropy due to systematic errors in the evaluation of ON-TIME. This other procedure is a conservative one which removes the suspicion of instrumental cause from any observed anisotropy. It is made possibly by the fact that at any given moment the apparatus views a circular region of the sky which is limited by atmospheric absorption to a solid angle of approximately 30° in radius. As the earth turns during a day this broad circular region sweeps out a band on the celestial sphere extending approximately 30° in declination on either side of the zenith. If, in the tabulation of the celestial arrival directions, the same number of events are included from each of M($M \gg 360°/60°$ equal sidereal time intervals, then the observed intensity from any part of the sky will be approximately normalized to the average intensity within the large field of view. Consequently, if the primary flux is isotropic, and if M is sufficiently large, this procedure should give an observed distribution with statistical fluctuations less than those expected in an analysis with weights based on an accurate ON-TIME calculation. On the other hand, if the primary flux is anisotropic with a broad first harmonic variation in right ascension, this procedure would give an observed distribution with nearly isotropic characteristics, since the broad variation would not produce a large variation in intensity within any given field of view. Suppose, however, that an anisotropy of the primary flux existed in the form of a concentrated source, or of a ridge of high or low intensity. Such an anisotropy, highly localized in celestial coordinates, would affect the observed distribution of arrival directions in a small por

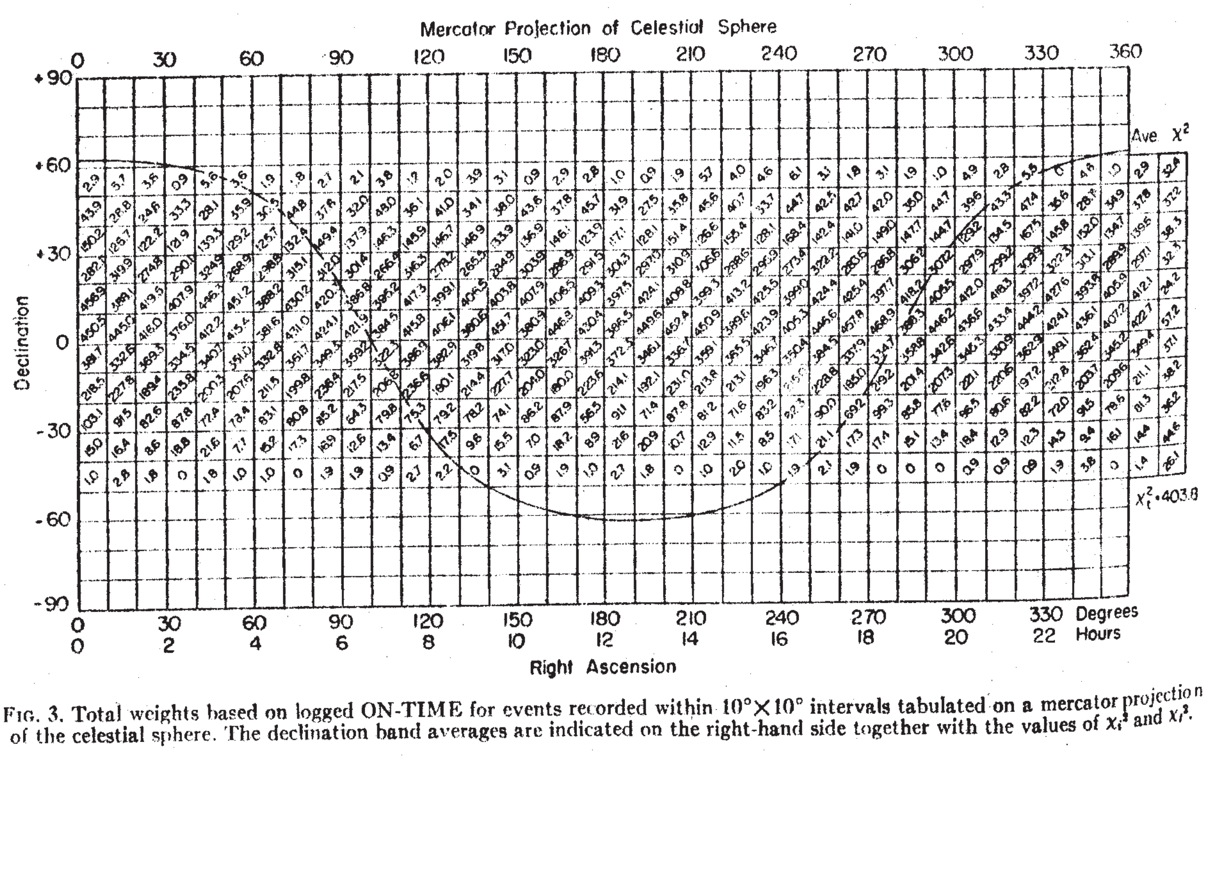

FIG. 3. Total weights based on logged ON-TIME for events recorded within 10°×10° intervals tabulated on a mercator projection of the celestial sphere. The declination band averages are indicated on the right-hand side together with the values of χ_i^2 and χ_t^2.

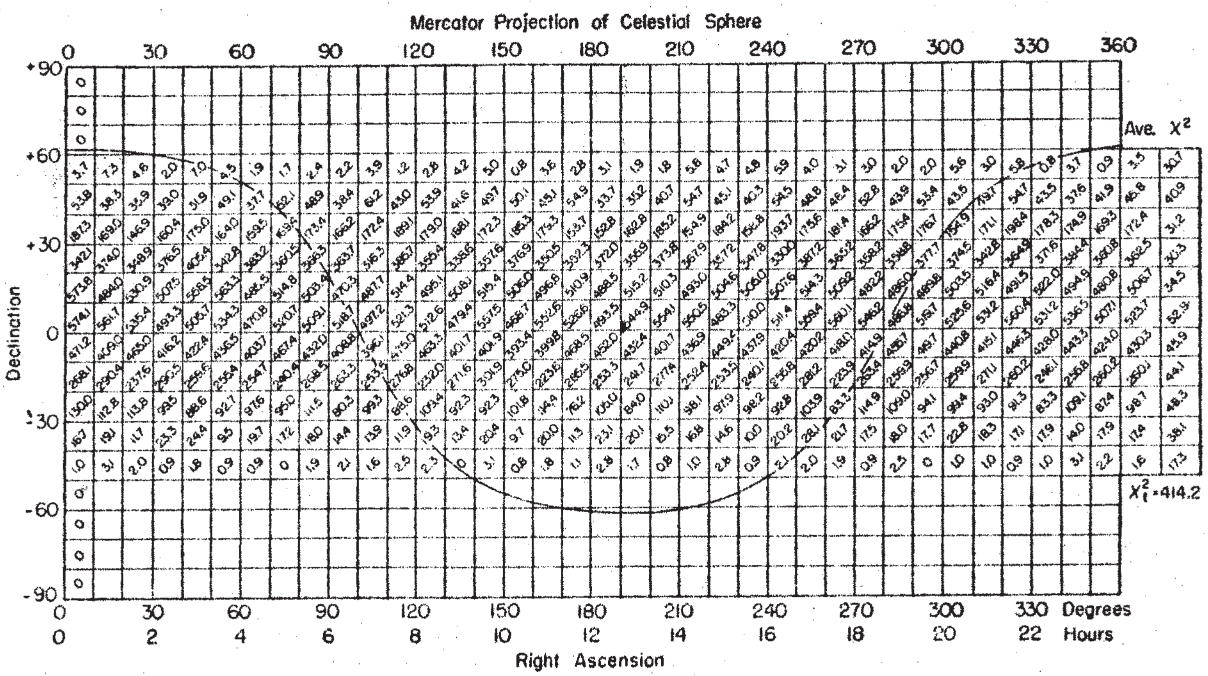

FIG. 4. Total weights based on numbers of events recorded during equal intervals of sidereal time.

tion of the field of view during three or four sidereal hours. This weighting procedure would therefore only slightly reduce the magnitude of the observed anisotropy. It is clear, consequently, that this procedure is a conservative one which eliminates false effects due to nonuniform ON-TIME and which tends to suppress real anisotropies. However, if the observed distribution obtained in this way reveals evidence of anisotropy, then this evidence is specially significant.

In practice, we carried out this procedure by first counting the numbers N_i of accepted events in each of M equal intervals of sidereal time in each of several large (~6000) groups of events (for most of the analysis $M=36$, and for the rest $M=24$). For each sidereal time interval we then calculated a weighting factor W_i according to the formula

$$W_i=\frac{1}{M}\left(\sum_{j=1}^{M} N_j\right)\Big/ N_i.$$

We then assigned the weight W_i to each accepted event which occurred during the ith sidereal time interval, and tabulated the total weight of the events in $10°\times10°$ areas of a mercator projection of the celestial sphere. The results of this tabulation are shown in Fig. 4. More events are included in this tabulation than in the previous one (Fig. 3) because this more conservative procedure for the calculation of the weights removes the requirement that only events recorded during steady periods of equipment operation be accepted.

Once the distributions of total weights were tabulated on Mercator projections of the celestial sphere, a series of statistical tests were applied in order to determine whether the observed distributions were consistent with the hypothesis that the flux of primary particles is isotropic. These tests are all based on the observation that if the primary flux were, indeed, isotropic, then the observed intensity of events should be independent of right ascension. This conclusion follows from the fact that, as the earth revolves, all points on the celestial sphere with a given declination pass through the field of view in exactly the same way Thus one can determine for a given band of declinations on a Mercator tabulation an average weight of events for a series of equal intervals of right ascension. One can then compare the fluctuations of the observed weights of events in the intervals with that to be expected on the hypothesis of isotropy. In addition, one can compare the total weight of events observed to lie in a certain pre-selected region, (e.g., near the plane of the galaxy) with the total weight expected on the basis of the averages calculated for each declination band.

The fluctuations from the declination band averages are summarized in Fig. 5 where the sizes of the fluctuations are indicated by characteristic markings in each $10°\times10°$ interval. We recognize no significant pattern in these fluctuations.

The following specific tests for isotropy were applied to the Mercator tabulations:

(a) Chi-squared tests: We call C_{ij} the total weight of events which arrived from directions in the ith ($i=1,\cdots 18$) declination and jth ($j=1,\cdots 36$)

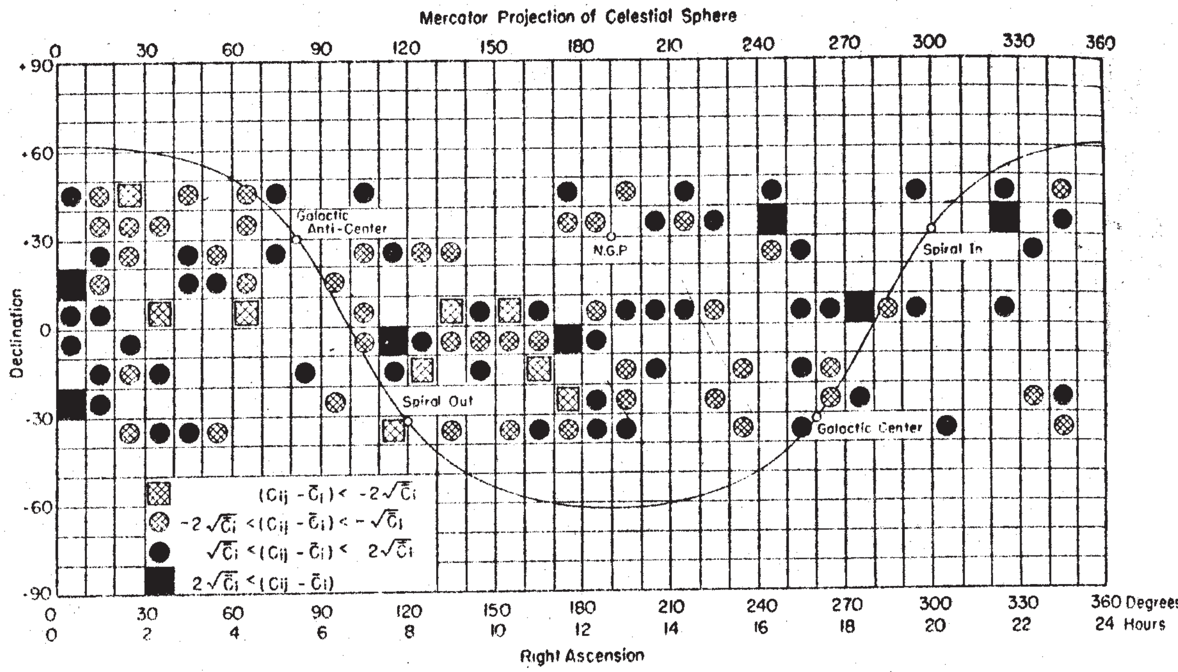

FIG. 5. Fluctuations from declination band averages of the tabulation (Fig. 3) based on logged ON-TIME.

right ascension intervals. We call $\bar{C}_i$ the declination band average and define it by the equation

$$\bar{C}_i = \frac{1}{36}\sum_{j=1}^{36} C_{ij}.$$

Then the value of chi-squared for each declination band is

$$\chi_i^2 = \frac{1}{\bar{C}_i}\sum_{j=1}^{36} (C_{ij}-\bar{C}_i)^2,$$

and for an entire tabulation is

$$\chi_t^2 = \sum_{i=a}^{b} \chi_i^2,$$

where a and b are chosen so that only declination bands with a significant weight of events are included. If n intervals are included in an evaluation of χ^2, then the value of $(2\chi^2)^{\frac{1}{2}}-(2n-3)^{\frac{1}{2}}$ should have an approximately normal distribution, provided the primary flux is isotropic.

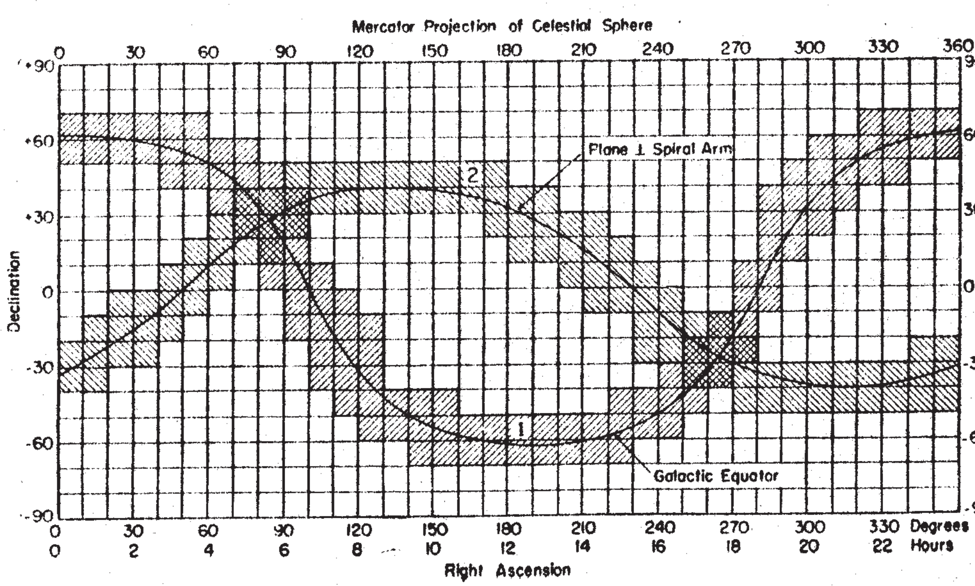

FIG. 6. Diagram showing special regions (1) near the galactic plane, and (2) near the plane normal to the spiral arm.

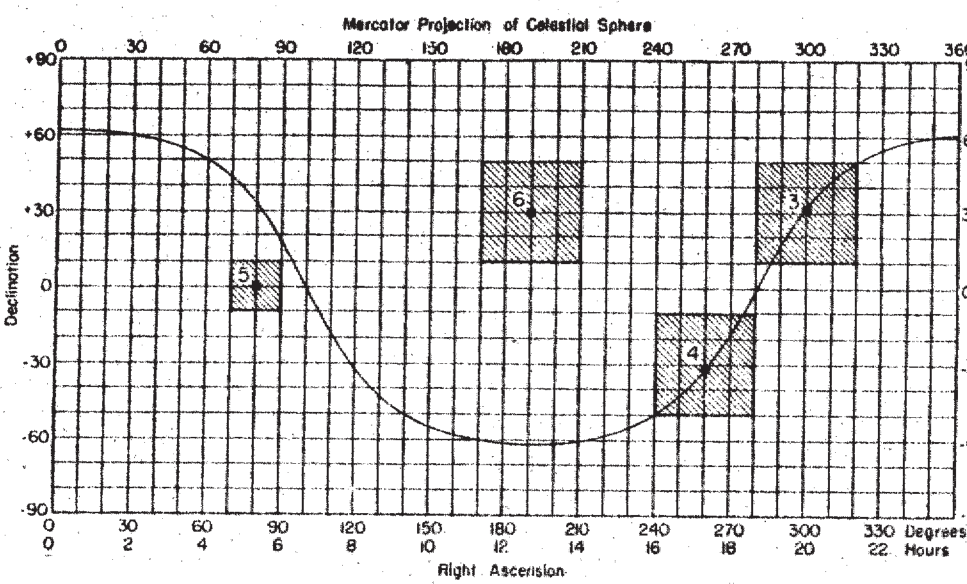

FIG. 7. Diagram showing special regions (3) near the direction along the spiral arm, (4) near the galactic center, (5) near the location where Sekido found evidence of a point source, and (6) near the north galactic pole.

The values of χ_i^2 and χ_i^2 for the two tabulations are listed in Figs. 3 and 4. The largest value of χ_i^2 for either tabulation is 57.2, and the probability that χ_i^2 should have exceeded this value for one or more of eleven independent bands is 0.09. The probability that χ_i^2 exceed the largest of the two values quoted is 0.54. Thus the chi-squared tests show no evidence of a "lumpy" anisotropy in the tabulated distributions.

(b) We compared the expected and observed total weights within special regions including the $10°\times10°$ areas whose centers (on a Mercator projection) lie:

1. Within 10° of the galactic plane (Fig. 6).
2. Within 10° of the plane normal to the spiral arm (Fig. 6).
3. Within 20° of the direction in along the local spiral arm of the galaxy ($\alpha=20^h$, $\delta=35°$ N; Fig. 7).
4. Within 20° of the galactic center ($\alpha=17^h\ 20^m$, $\delta=42°$ S; Fig. 7).
5. Within 10° of the location where Sekido[6] has found evidence of a point source of high-energy particles ($\alpha=5^h\ 30^m$, $\delta=0.5°$ N; Fig. 7).
6. Within 20° of the north galactic pole ($\alpha=12^h\ 40^m$, $\delta=30°$ N; Fig. 7).

TABLE I. Expected and observed weights of showers from several special regions of the sky.

	Expected	Observed
1. Galactic equator	13 528.6	13 555.3
2. Perpendicular to spical arm	17 880.6	17 949.9
3. Along the spiral arm ($\alpha=20^h$, $\delta=35°$)	3546.4	3583.2
4. Galactic center ($\alpha=17^h\ 20^m$, $\delta=42°$ S)	1232.8	1267.3
5. Sekido's point source ($\alpha=5^h\ 30^m$, $\delta=0.5°$ N)	1544.2	1566.1
6. North galactic pole ($\alpha=12^h\ 40^m$, $\delta=30°$ N)	3546.4	3501.8

The results of these tests are summarized in Table I. They show no significant evidence of anisotropy. It should be emphasized in connection with region 5 that the results of this experiment are not directly comparable to those of Sekido since the average energy of the primaries we observed is at least 100 times the average energy of those observed by Sekido.

All of the above tests yield no evidence of anisotropy in the celestial arrival directions of over 100 000 showers with an average size of about 3×10^5 at 2034 m as observed from a station at 10° N latitude.

ACKNOWLEDGMENTS

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Symp. on Geophysical Aspects of Cosmic Rays at the IUGG conf., Helsinski (1960)

Les différents phénomènes se classent donc chronologiquement et statistiquement de la façon suivante:

1. Prébaisse cosmique.
2. Eruption importante associée à un sursaut type IV suivi du début des évènements à protons et des black-out polaires.
3. Phase principale de l'orage cosmique et orage magnétique.

Ainsi le phénomène de prébaisse apporte un élément important aux prévisions géophysiques car il permet de déceler la présence de centre très actif arrivant sur le bord Est du soleil et de nous renseigner sur l'évolution de l'activité solaire.

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ANISOTROPY AND NON-METEOROLOGICAL LOCAL SOURCE RESPONSIBLE FOR SOLAR DAILY VARIATION OF COSMIC RAY INTENSITY

by

V. Sarabhai and U.R. Rao

1. Introduction. Inclined cosmic ray telescopes operated near the equator to measure simultaneously muon intensities incident from different azimuths, particularly east and west, are a powerful tool for understanding the time variations of cosmic rays and the electromagnetic conditions in interplanetary space in the neighbourhood of the earth. As the earth spins on its axis, an anisotropy of primary radiation shows up as a daily variation with a characteristic shift of 6 hours between east and west telescopes inclined at 45° to the zenith. On the other hand, a local source of daily variation situated within the influence of the geomagnetic field shows up as a daily variation with the same pattern for east and west directions. Moreover since the geomagnetic cut-off energies for east and west are different, we also have information regarding the energy dependence of the variations. Thus from an examination of the data for east and west directions at a low latitude station we can study: (1) the location and energy dependence of the anisotropy of primary radiation; (2) the occurrence of a local source of modulation related to solar time and the energy spectrum of the daily variation produced by it; and (3) the isotropic changes of intensity, of east-west asymmetry and the changes of primary energy spectrum associated with them.

We can also study the solar and terrestrial relationships of all three types of cosmic ray variations.

We present here results of an investigation, conducted during 1957-1958, with directional telescopes pointing 45° east and 45° west at Ahmedabad (geomagnetic coordinates: 13°9 N, 143°8 E; sea level). The geomagnetic cut off energies for 45° east, vertical and 45° west are 23.1 Bev, 14.6 Bev and 11.2 Bev respectively. The daily variation of meson intensity has been corrected for the daily variation of atmospheric temperature and pressure and in the calculation of the daily mean east-west asymmetry, correction for barometric pressure has been applied. Some preliminary results of our study were presented at Moscow (1).

2. Identification of source of daily variation. We have examined the relative difference in the times of maximum of the diurnal component of the daily variation of meson intensity for east and west directions on days when the amplitude of the diurnal variation in both the directions was significant at the 2 σ level. Figure 1 shows, on a harmonic dial, the histogram of occurrence of the diurnal component for west relative to that for east, assuming the latter to be along 0000 hour local time. The figure shows that there is a marked preference for days on which the diurnal time of

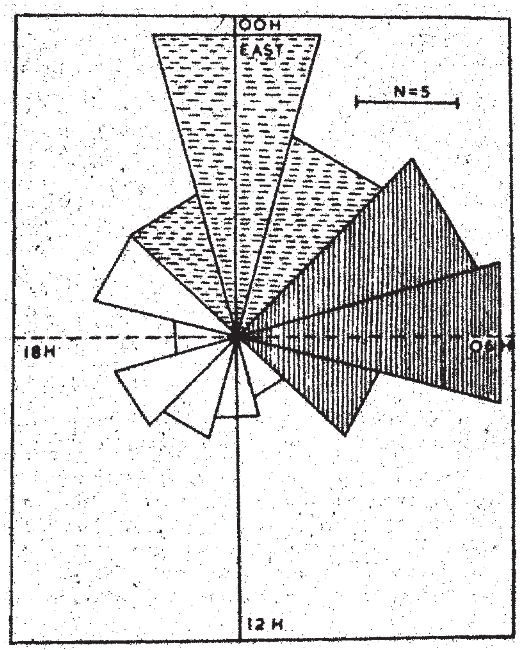

Fig. 1 - Harmonic dial representation of the histogram of occurrence of the diurnal maximum for west relative to that for east, assumed to be along 0000 hour direction, on individual days when both east and west amplitudes are significant at the 2 σ level. Days on which the daily variation is caused by an anisotropy are shaded with vertical lines and days on which the daily variation is caused by a local source are shaded with dashed lines.

maximum for west is later than that for east telescopes by 3 to 9 hours ($+45 < (\varphi_W - \varphi_E) < +135°$), showing that on such days the daily variation is related to an anisotropy of primary radiation. There is also a significant number of days on which there is no difference ($-45° < (\varphi_W - \varphi_E) < 45°$), within the limits of experimental error, in time of maximum for east and west directions. On these days the daily variation is related to a local source situated within the influence of the geomagnetic field rather than to an anisotropy of primary radiation.

Figure 2 shows the average daily variation of cosmic ray intensity for east, vertical and west during the periods 1954-1955 and 1957-1958. The data for east and west for the period 1954-1955 have been taken from Nerurkar (2) and the data for vertical telescopes from Razdan (3). We observe that the diurnal time of maximum for

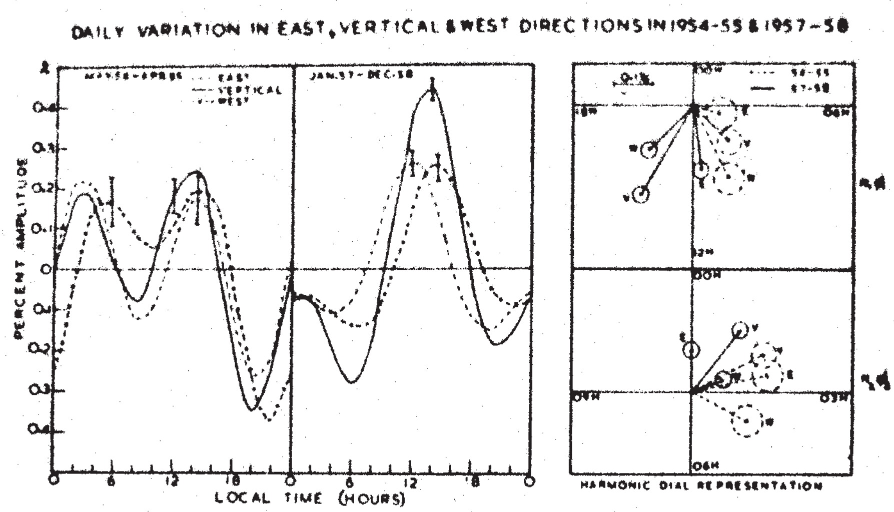

Fig. 2 - The average daily variation of meson intensities for east, vertical and west directions during the periods May 1954 - April 1955 and January 1957 - December 1958. The mean diurnal and semidiurnal components during the two periods for each direction are separately shown on a harmonic dial.

vertical lies intermediate between that for east and west and occurs 2 to 3 hours later than for east during both the periods. This indicates that the average solar daily variation can be ascribed to an anisotropy of primary radiation. The study of daily variation on individual days, however, shows conclusively that there are many days on which a local source is mainly responsible for the daily variation. Thus we conclude that besides the meteorological source, there exist at least two sources of daily variation of cosmic ray intensity.

Table 1

The parameters describing the average daily variation of meson intensity for East and West directions on groups of days having high C_p ($C_p \geq 1.0$). The parameters for 10 T and 20 T telescopes are separately shown.

Telescope	No. of days	EAST				WEST			
		$\bar{r}_1$	$\bar{\varphi}_1$	$\bar{r}_2$	$\bar{\varphi}_2$	$\bar{r}_1$	$\bar{\varphi}_1$	$\bar{r}_2$	$\bar{\varphi}_2$
10T	218	0.22±0.04	177°	0.13±0.04	-28°	0.14±0.04	π +15°	0.13±0.04	61°
20T	176	0.18±0.03	150°	0.14±0.03	-12°	0.12±0.03	π + 8°	0.10±0.03	73°

We have examined the daily variation for east and west on days when C_p, the planetary index of geomagnetic disturbance, is equal to or greater than 1. Table 1 gives the parameters of the average daily variation for east and west on days of high C_p. On such days both east and west show a diurnal maximum at local noon. We have also examined the histograms (Fig. 3) of the diurnal and the semi-diurnal times of maxima for east and west on days of high C_p when the appropriate component is significant at the 2 σ level. The figure shows that the histograms for east and west are alike, in conformity with the conclusion derived earlier. Thus on geomagnetically disturbed days, the difference in the time of diurnal maximum of the daily variation of meson intensity for east and west vanishes, indicating that the daily variation on such days is mainly produced by a local source, in agreement with the conclusions of Sarabhai and Satyaprakash (4).

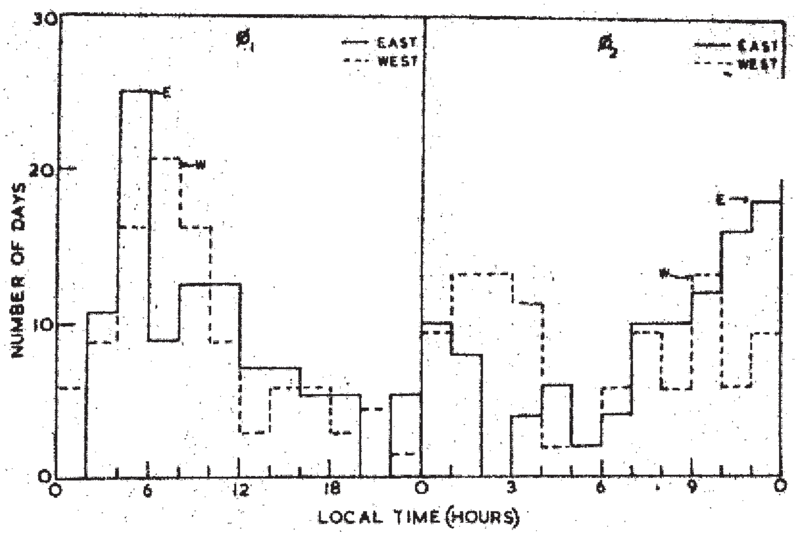

Fig. 3. The frequency distributions of the occurrence, at each bihour, of the maximum of the diurnal (0_1) and the semidiurnal (0_2) components for days of high geomagnetic disturbance.

3. Correlated changes of east-west asymmetry and daily variation. East-west asymmetry which is defined as $[2(W-E)/(W+E)]100$, where W and E are daily mean intensities for west and east, has a mean value of $14.97 \pm 0.55\%$ at Ahmedabad. Days on which the east-west asymmetry has a value on above 16.1 % or below 13.9% are called days of high and low asymmetry respectively. During the period of observation there are 491 days with normal, 28 days with high and 26 days with low east-west asymmetry.

Figure 4 shows the changes associated with epochs of low and high east-west asymmetry through Chree analysis of (a) daily mean neutron intensity in middle and equatorial latitude belts, (b) C_p and (c) H, the daily mean intensity of the horizontal component of the geomagnetic field at Kodaikanal, for ten days prior to and following the two types of epochs. Particulars of the stations representing the middle latitude belt covering the range 55° to 75° geomagnetic latitudes and equatorial latitude belt covering the range 15°N to 15°S are given in Table 2. Days of low asymmetry are associated with a depressed mean intensity of neutrons at all the stations and days of high asymmetry are associated with an enhanced mean intensity, the change in both cases having a lower amplitude at equatorial stations compared to that at middle latitude stations.

From the Chree analysis of C_p and of H, the horizontal component of the earth's magnetic field at the equator, we can draw the following principal conclusions:

(a) The horizontal component of the earth's magnetic field has a high value six days prior to low asymmetry epochs. It reaches a minimum with an associated enhanced C_p three days prior to such epochs. This is characteristic of intense magnetic storms, particularly of the SC type. The related changes of daily mean cosmic ray intensity make it clear that low asymmetry epochs occur 3 to 5 days after the onset of cosmic ray storms, generally occurring with SC magnetic storms.

(b) High asymmetry epochs occur with relatively undisturbed geomagnetic conditions and high value of the horizontal component of the geomagnetic field. However, during the four days following high asymmetry epochs, C_p continuously rises and H, the horizontal component of the earth's magnetic field decreases, indicating that high asymmetry occurs 3 to 5 days prior to the arrival of solar corpuscular beams which envelop the earth.

Changes in east-west asymmetry can be caused due to the change in geomagnetic cut-off energy and due to the change of primary energy spectrum. If the former is responsible, then an increase in asymmetry would be caused by a decrease in geomagnetic cut off energy in all directions, the decrease being smaller for west than for east. However, as can be seen from Figure 4, high asymmetry is associated with a world-wide increase of neutron intensity and low asymmetry is associated with a decrease of

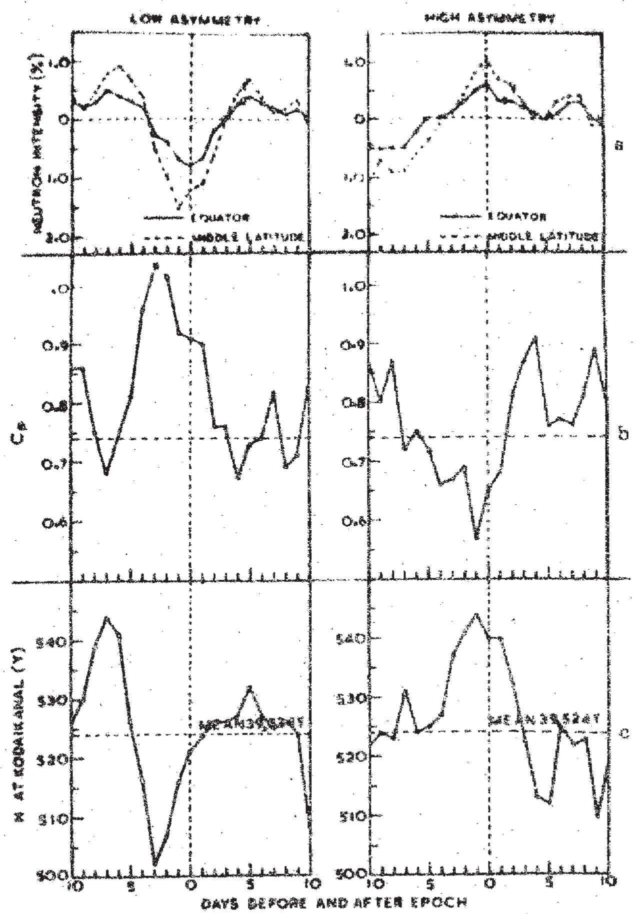

Fig. 4. The Chree analysis for epochs corresponding to days of low and high east-west asymmetry of (a) daily mean neutron intensity at stations situated in equatorial and middle latitude belts (b) C_p and (c) H, the daily mean intensity of the horizontal component of the geomagnetic field at Kodaikanal.

neutron intensity. Thus the observed changes of asymmetry cannot be explained through changes in geomagnetic cut off. We examine, in the next section, the effect of the change of primary energy spectrum on the changes of east-west asymmetry and the daily variation associated with them.

Figure 5 shows the daily variation of meson intensity for east and west and of neutron intensity at stations situated in middle and equatorial latitude belts on days of high asymmetry. The parameters describing the diurnal and the semidiurnal components for these are given in Table 3. On days of high asymmetry the average daily variation for east and west has large amplitude. Moreover there is a difference of about 6 hours in the time of maximum for east and west for the diurnal as well as for the semi-diurnal components which have significant amplitudes. Thus the daily variation on days of high asymmetry is consistent with its being produced by an anisotropy located outside the influence of the geomagnetic field. The similarity of form and amplitude of the daily variation observed by the six middle latitude and five equatorial stations on days of high asymmetry and the earlier time of maximum of the daily variation at the equatorial stations are consistent with the above conclusion.

While the amplitude of the diurnal component is comparable at middle and equatorial latitudes the semi-diurnal component is significant only at equatorial latitudes. Thus the primary anisotropy observed at equatorial stations, with neutron monitors or meson telescopes, has an inherent semi-diurnal component associated with it.

Table 2

Particulars of Cosmic Ray Neutron Monitor Stations Used in the Analysis

Stations	Altitude (Meters)	Geographic Coord.		Geomagn. Coord.		Investigator
		Lat.	Long.	Lat.	Long.	
Equatorial Stations						
Ahmedabad	S. L.	N23°01'	E72°36'	13°.9	143°.9	Dr. V. Sarabhai India.
Huancayo	3400	S12° 02'	W75°20'	-0°.6	353°.8	Dr. J. A. Simpson Chicago.
Kodaikanal	2343	N10° 14'	E77°28'	0°.6	147°.1	Dr. V. Sarabhai India.
Lae	S. L.	S 6° 44'	E147°0'	-16°.0	217°.4	Dr. A. G. Fenton Hobart
Makerere College	1196	N 0°20'	E32°34'	-2°.0	101°.4	Dr.D.M.Thomson Uganda.
Middle Latitude Stations						
Churchill	39	N58° 45'	W94°05'	68°.7	322°.9	Dr. D. C. Rose Canada
Ottawa	101	N45° 24'	W75°54'	56°.8	351°.1	Dr. D. C. Rose Canada
Murchinson Bay	S. L.	N80° 03'	E 18°15'	72°.2	137°.2	Dr.A.E.Sandstrom Sweden
Resolute	17	N74° 41'	W94°54'	82°.9	289°.3	Dr. D. C. Rose Canada
Mawson	S. L.	S67° 36'	E62°53'	-73°.1	103°.8	Dr. A. G. Fenton Hobart
Mt. Wellington	725	S42° 55'	E147°14'	-51°.5	224°.5	Dr. A. G. Fenton Hobart

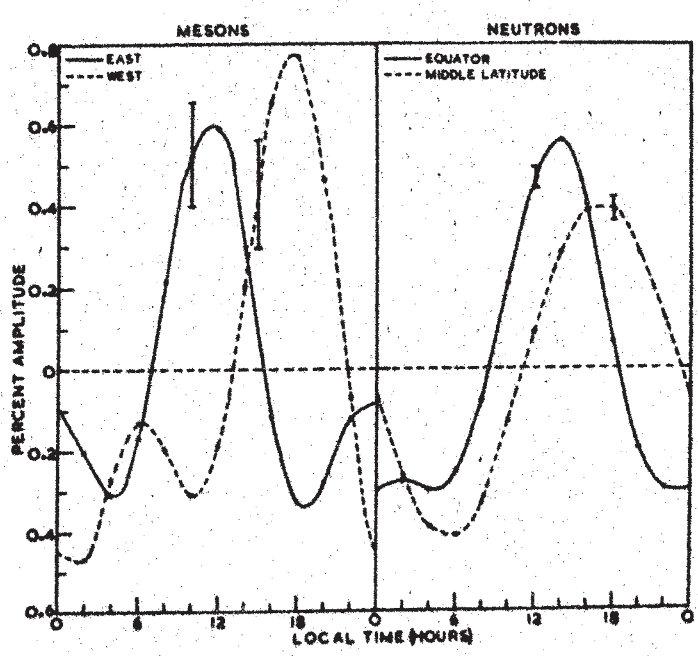

Fig. 5. The average daily variation of meson intensity for east and west at Ahmedabad and of neutron intensity at stations situated in equatorial and middle latitude belts on days of high east-west asymmetry.

Table 3

The characteristics of the average daily variation of meson intensity for east and west at Ahmedabad and of neutron intensity at stations situated in equatorial and middle latitude belts on days having high east-west asymmetry.

Station	$\bar{r}_1$	$\bar{\varphi}_1$	$\bar{r}_2$	$\bar{\varphi}_2$
East (Meson)	0.35 ± 0.12	π 167°	0.26 ± 0.12	-20°
West (Meson)	0.46 ± 0.11	π +76°	0.32 ± 0.11	175°
Equatorial stations (Neutron)	0.42 ± 0.02	π +17°	0.14 ± 0.02	48°
Middle latitude stations (Neutron)	0.41 ± 0.02	π +79°	0.02 ± 0.02	63°

(a) High asymmetry. With a knowledge of the cut off energy E^{min} for east and west directions derived by using Quenby and Webber's (5) method, and from the coupling coefficients derived for the two directions, the energy spectrum $\delta D(E)/D(E)$ of daily variation can be estimated by using the formula

$$\frac{\delta N^i}{N^i} = \int_{E^{min}}^{\infty} \frac{\delta D(E)}{D(E)} \cdot W \, dE$$

where $\frac{\delta N^i}{N^i}$ is the percent change of intensity and W is the coupling coefficient in the appropriate direction. The coupling coefficients for east and west have been calculated by utilising the experimental curves of Johnson et al (6) showing the latitude effect of cosmic rays incident from these directions and the method of extrapolation suggested by Dorman (7).

On days of high asymmetry when the ratio of the diurnal amplitude for west to the amplitude for east is 1.4 ± 0.3, the daily variation has an energy spectrum of the type $aE^{-0.8 \pm 0.3}$ where $a = 0.10$ and is consistent with an external source situated at an angle of $112° \pm 10°$ to the left of the earth-sun line. Assuming the daily variation to be caused by the acceleration of cosmic ray particles crossing beams of solar plasma with frozen in magnetic field and for telescopes looking at the beam for 12 hours, we find that the energy increment required to explain the observed increase in asymmetry of 1.29 % is 3.4 Mev. For a beam of width 3×10^{12} cms and an intensity of the trapped magnetic field of 10^{-6} gauss, the radial velocity would be about 10^8 cm/sec. The width of the beam would be sufficient for the earth to remain in it for about 1 day as the beam overtakes the earth, due to the spinning of the sun. The radial velocity of the beam corresponds to a transit time of 36 hours from the sun to the earth. The magnitude of the trapped magnetic field is of the order obtained from astrophysical evidence.

The near quantitative explanation of the increase in asymmetry and the associated daily variation by a common mechanism involving the acceleration of cosmic ray particles crossing beams of solar plasma supports some of the basic concepts underlying the theory. Of particular significance is the evidence for such streams with trapped magnetic fields and presenting an electric polarisation as viewed from the earth, even during a period of maximum solar activity. The process is possible only if the ejection of beams takes place in rarefied regions of interplanetary space which extend radially over active solar regions.

(b) Low asymmetry. We have shown that low east-west asymmetry which occurs in conjunction with decreases of daily mean cosmic ray intensity about 3 to 5 days after the onset of SC type magnetic storms cannot be explained through changes in geomagnetic cut off energy. Moreover the daily variation on geomagnetically disturbed days has the same exponent as the background cosmic ray intensity. Qualitatively it appears plausible that a screening or scattering of low energy particles due to magnetic fields in plasma clouds could be responsible for the decrease of east-west asymmetry.

(c) Local Source. The daily variation when the local source of modulation is operative has an energy spectrum of variation of the type aE° and is consistent with a source situated along the earth-sun line and within the influence of the geomagnetic field. Moreover, the local source of modulation causing daily variation becomes prominent only during geomagnetically disturbed days.

The mechanism of the local source of daily variation is not clear at present. It is, however, well recognised that on geomagnetically disturbed days the earth's magnetic field will be substantially altered at a distance of perhaps 4 to 6 earth radii or less (8) depending upon the velocity and density of the beam. We believe that the distortion of the geomagnetic field and changes in the allowed and forbidden cones during such days may cause a daily variation of geocentric origin. A proper evaluation of this process for comparison with experimental results is needed.

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ON RELATION OF COSMIC RAY INTENSITY TO MAGNETIC ACTIVITY AND SOLAR RADIO NOISE

by

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Many authors have stated that radio noise sun spots crossing the Sun's central meridian (Denisse (4) calls them type R spots), are followed by increasing geomagnetic activity, and sunspots without radiation (type Q) are connected with decreasing geomagnetic activity while crossing the central meridian. It seems likely, that radio noise shows the presence of the emission from the sun of geoactive corpuscular streams.

According to L. I. Dorman (1), the variations of cosmic ray intensity are caused by the magnetic fields of the sun's corpuscular streams which influence the primary cosmic radiation. These charged primary cosmic ray particles crossing the sun's corpuscular stream with the "frozen in" magnetic field will change its energy or reflect from the stream. This causes the change of cosmic ray intensity, observed on the earth's surface. As intensive radio noise shows the ejection of the sun's corpuscular streams we can suppose that there is a certain connection between solar radio noise and the cosmic ray intensity observed on the earth.

Some studies, dealing with relation of radio noise and cosmic ray intensity, have been published (5, 6) but the conclusions are not quite certain.

We obtained the Sun's radio noise data from Quarterly Bulletin on Solar Activity (VIII-XII-1951, VII-1952-, IX-1955) and from "Sun's Data Bulletin (III-IX-1958) for 14

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Time variations of directional cosmic ray intensity at low latitudes

III. Interpretation of solar daily variation and changes of east-west asymmetry

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The daily variation of cosmic ray intensity at low latitudes can under certain conditions be associated with an anisotropy of primary radiation. During 1957–8, this anisotropy had an energy spectrum of variation of the form $a\epsilon^{-0.8\pm0.3}$ and corresponded to a source situated at an angle of $112\pm10°$ to the left of the earth-sun line. The daily variation which can be associated with a local source situated along the earth-sun line has an energy spectrum of variation of the form $a\epsilon^{0}$.

Increases in east-west asymmetry and the associated daily variation for east and west directions can be explained by the acceleration of cosmic ray particles crossing beams of solar plasma in the neighbourhood of the earth. For beams of width 5×10^{12} cm with a frozen magnetic field of the order of 10^{-4} G, a radial velocity of about 1.5×10^{8} cm/s is required. The process is possible only if the ejection of beams takes place in rarefied regions of interplanetary space which extend radially over active solar regions. An explanation of Forbush type decreases observed at great distances from the earth requires similar limitation on the plasma density and conductivity of regions of interplanetary space.

The decrease of east-west asymmetry associated with world-wide decreases of intensity and with *SC* magnetic storms is consistent with a screening of the low-energy cosmic ray particles due to magnetic fields in plasma clouds.

1. Introduction

Many different interpretations (Alfvén 1954; Brunberg & Dattner 1954; Nagashima 1955; Nerurkar 1957; Dorman 1957) have been proposed for the solar daily variation of cosmic ray intensity, but none of them has been tested with any rigour against experiment. In interpreting experiments, it is helpful to distinguish between daily variations which may be caused by different physical causes. The location of the source of variation with respect to the earth and the sun, the energy spectrum of the variation and the associated solar and terrestrial phenomena have all to be considered.

In part I (Rao & Sarabhai 1961 *a*), which will henceforth be referred to as I, we have shown that though, on the average, the daily variation can be ascribed to an anisotropy of primary radiation, there exist a number of days on which the maximum of the daily variation in telescopes pointing to 45° E and 45° W occurs at about the same time and this variation is therefore caused by a local source. In part II (Rao & Sarabhai 1961 *b*), which we henceforth refer to as II, we have shown that there are many days with enhanced east-west asymmetry and on these days

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the daily variation of intensity could be ascribed to an anisotropy of primary cosmic radiation. In this communication, we study the energy spectra of the local and external sources of the daily variation.

Dorman has calculated the effects on the daily variation of intensity of an anisotropy of primary radiation that could be caused by the presence near the earth of beams of solar plasma carrying within them frozen magnetic fields. Beams with a radial velocity V, width b and frozen magnetic field H perpendicular to the direction of motion of the beam and the plane of the ecliptic, would have an electric field across them of $-(1/c)(V \times H)$ as viewed from the stationary earth. Because of the magnetic field in the beam, cosmic rays with energy less than $\epsilon^{\text{min.}} \approx 300$ Hb would be scattered back and would not cross the beam. Particles of higher energy can cross the beam and would arrive at the earth with an energy increment or decrement of about 0·5 GeV, dependent on the direction of the field. Thus, according to this model, the beams would not disturb the isotropy of primary cosmic rays of $\epsilon < \epsilon^{\text{min.}}$, but for particles above this energy, an anisotropy with a variational spectrum of the form $a\epsilon^{-1}$ may be expected.

Examining the data from 1937 to 1951 of a number of stations scattered all over the world, Dorman concluded that the spectrum was of the type expected on the proposed model with $\epsilon^{\text{min.}}$ equal to 6·6 GeV. He also found that the mean position of the source of the daily variation was at an angle of $82 \pm 8°$ to the left of the earth-sun line.

We examine here whether during 1957–8 the anisotropy of primary radiation as distinct from a local source of the daily variation has the characteristic variational spectrum and direction predicted by the model. We also examine whether the same model can explain the enhanced east-west asymmetry which is associated with the anisotropy of primary radiation.

2. Energy spectrum of the daily variation

2·1. *Procedure*

Following Dorman, we can represent the intensity of the component of type i (muons, neutrons, etc.) observed at latitude λ, at a level h_0 and incident at a zenith angle ζ and azimuth angle ϕ by

$$N^i(h_0, \zeta, \phi) = \int_{\epsilon_{\text{min.}(\lambda, \zeta, \phi)}}^{\infty} D(\epsilon)\, m^i(\epsilon, h_0, \zeta)\, \mathrm{d}\epsilon, \tag{1}$$

where $D(\epsilon)$ is the differential energy spectrum of the primary cosmic rays, $m^i(\epsilon, h_0, \zeta)$ is the multiplicity function or the number of particles of type i at h_0, ζ formed by a single primary particle of energy ϵ and $\epsilon_{\text{min.}(\lambda,\zeta,\phi)}$ is the geomagnetic cut-off energy in that direction. Neglecting the variation due to change in $\epsilon_{\text{min.}(\lambda,\zeta,\phi)}$ (which is determined by the earth's magnetic field) and $m^i(\epsilon, h_0, \zeta)$, we can show that

$$\frac{\delta N^i}{N^i} = \int_{\epsilon_{\text{min.}(\lambda, \zeta, \phi,)}}^{\infty} \frac{\delta D(\epsilon)}{D(\epsilon)}\, \omega\, \mathrm{d}\epsilon, \tag{2}$$

where ω the coupling coefficient is given by $\{D(\epsilon)\, m^i(\epsilon, h_0, \zeta)\}/N^i$ and $\delta D(\epsilon)/D(\epsilon)$ is the fractional change in the energy spectrum of primary intensity.

In calculating the daily variation, we have to take into account the varying geomagnetic deflexion of particles of different energies. We assume that for the daily variation, the energy spectrum $\delta D(\epsilon)/D(\epsilon)$ is of the form $a\epsilon^{-n}$. Since the daily variation of meson intensity can be adequately represented by a diurnal and a semi-diurnal component, we can consider the total variation as being due to a diurnal source of strength a_1 and a semi-diurnal source of strength a_2. The diurnal variation due to primaries having energies between ϵ and $\epsilon + d\epsilon$ is given by

$$a_1 \epsilon^{-n} \sin(\psi_\epsilon + 90)\, \omega\, d\epsilon,$$

where $\psi\epsilon$ is the geomagnetic deflexion of particles of energy ϵ. The total diurnal variation

$$\sum_{\epsilon=\epsilon_{\text{min.}}(\lambda,\zeta,\phi)}^{\infty} a_1 \epsilon^{-n} \sin(\psi_\epsilon + 90)\, \omega\, \Delta\epsilon \tag{3}$$

can be calculated by vectorial addition of the contributions of all groups of primaries taking into account their appropriate deflexions.

TABLE 1. TABLE SHOWING THE RATIO OF AMPLITUDE OF DAILY VARIATION FOR WEST INTENSITY TO THE AMPLITUDE FOR EAST AND THE DIFFERENCE IN THE TIME OF DIURNAL MAXIMUM BETWEEN THE TWO FOR DIFFERENT EXPONENTS OF THE ENERGY SPECTRUM OF VARIATION ASSUMING (*a*) $\epsilon^{\text{min.}}$ TO BE LESS THAN 10 GeV, (*b*) $\epsilon^{\text{min.}}$ TO BE 30 GeV

energy spectrum of variation	(*a*) $\epsilon^{\text{min.}} < 10$ GeV		(*b*) $\epsilon^{\text{min.}} = 30$ GeV	
	$(\phi_W - \phi_E)$	r_W/r_E	$(\phi_W - \phi_E)$	r_W/r_E
$a\epsilon^0$	79°	1·0	97°	0·7
$a\epsilon^{-1}$	73°	1·7	100°	0·7
$a\epsilon^{-2}$	70°	3·0	102°	0·6
$a\epsilon^{-4}$	68°	10·2	113°	0·5
$a\epsilon^{-6}$	68°	39·3	116°	0·4

For simplifying the calculation, the primary spectrum is assumed to be made up of 12 discrete energy bands and the angle of deflexion ψ_ϵ of these 12 bands to vary in steps of 30° from 0 to 360°. Taking Brunberg's (1956) values of ψ_ϵ for Ahmedabad (geomagnetic co-ordinates 13·9° N, 143·9° E; altitude—sea level) for particles of different energy and the cut-off energies and coupling coefficients of mesons for incidence from 45° E and 45° W at Ahmedabad (as given in part I), we have calculated the ratio of amplitude of daily variation for west to the amplitude for east and the difference in the time of diurnal maximum between the two for different exponents of the energy spectrum of variation of an external source. The results are given in table 1. Starting with a spectrum $a\epsilon^0$ characteristic of the normal primary radiation at one end, we have considered at the other end the spectrum $a\epsilon^{-6}$ characteristic of the very marked energy dependence observed during solar flare type events. The ratio of the amplitude and the difference in the times of maxima for east and west for the semi-diurnal component are similar to those for the diurnal component given in table 1.

Table 1 (*a*) can be applied where the geomagnetic cut-off energy applicable to the measured radiation is more than $\epsilon^{\text{min.}}$. At the equator, the geomagnetic cut-off for west is 11·2 GeV, while with the usual values of the velocity v, width b and frozen magnetic field H of the beam, $\epsilon^{\text{min.}}$ is about 7 GeV. Thus table 1 (*a*) is normally applicable to directional studies in equatorial regions. On geomagnetically disturbed days, if the characteristics of solar streams are such that the value of $\epsilon^{\text{min.}}$ is $\approx$ 30 to 40 GeV as suggested by Dorman, the expected results would be as indicated in table 1 (*b*).

It can be seen from table 1 that when $\epsilon^{\text{min.}} < 10$ GeV, the time of diurnal maximum for east occurs 4 to 6 h earlier than west. When on the other hand $\epsilon^{\text{min.}} = 30$ GeV, the difference in the time of diurnal maximum between east and west is 6 to 8 h. The situation with regard to the semi-diurnal component of the daily variation is similar.

For $\epsilon^{\text{min.}} < 10$ GeV, the ratio of diurnal amplitude for west to the amplitude for east is very sensitive to the exponent of the energy spectrum. The ratio increases rapidly with the steepness of the energy spectrum of variation. On the other hand, for $\epsilon^{\text{min.}} = 30$ GeV, table 1 (*b*) indicates that the ratio is less than 1, and decreases with increasing steepness of the assumed spectrum of variation.

If the source of the daily variation is located at an angular distance x^i_λ with respect to the earth-sun line, *outside the influence of the geomagnetic field*, the angle x^i_λ can be calculated by using the formula

$$x^i_\lambda = \psi^i_\lambda + 15^\circ(t^i_{\text{max.},\lambda} - 12), \tag{4}$$

where $t^i_{\text{max.},\lambda}$ is the measured diurnal time of maximum in hours and ψ^i_λ is the geomagnetic angle of drift (angle of deviation due to the geomagnetic field) in the equatorial plane.

2·2. *Comparison with experimental results*

(*a*) *Daily variation due to external source*

An anisotropy of primary radiation which can be attributed to an external source has been observed in papers I and II under two separate conditions: (1) when the amplitudes for both east and west directions are significant at the 2σ level and the difference between the time of diurnal maximum is 6 h, or (2) when the east-west asymmetry is high. The ratios of the mean diurnal amplitude for west to the amplitude for east derived experimentally under these conditions are $1·6 \pm 0·3$ (see table 4 of I) and $1·4 \pm 0·3$ (see table 2 of II), respectively. Using a mean ratio of $1·5 \pm 0·3$ we find that the corresponding energy spectrum of daily variation is $a\epsilon^{-0·8\pm0·3}$, where $a = 0·10$ when ϵ is expressed in GeV. This may be compared with the value of $a = 0·14$ obtained by Dorman from the data of 1937–51. The ratio of the *semi-diurnal component* for west to that for east on days of high asymmetry is found to be $1·2 \pm 0·4$ and is consistent with the spectrum of variation derived from the diurnal component. These facts imply an external source of daily variation located at an angle of $112 \pm 10^\circ$ to the left of the earth-sun line.

(b) Daily variation due to local source

It has been shown in I that on days when the planetary index of geomagnetic disturbance C_p is greater than or equal to 1·0, the daily variation of cosmic ray intensity is principally attributable to a local source of modulation. The ratio of amplitude for west to the amplitude for east on such days can be calculated by neglecting in expression (3) the deflexion of secondaries in the earth's magnetic field. The observed ratio $0{\cdot}8 \pm 0{\cdot}1$ is consistent with an energy spectrum of variation of the form $a\epsilon^0$, where $a = 0{\cdot}0025$. The local source is situated along the earth-sun line and within the influence of the geomagnetic field since the daily variations for east and west have a maximum near noon.

3. Interpretation of changes in east-west asymmetry

The change in east-west asymmetry can be related either to change in geomagnetic cut-off energy or to change in primary energy spectrum. We consider these two possibilities to explain the observed changes of east-west asymmetry associated with the changes of daily mean intensity and the horizontal component of the geomagnetic field as described in II.

3·1. *Effect of changes of geomagnetic cut-off energy*

Rothwell (1959), Parker (1958) and others have suggested that ionized clouds emitted from the sun can modify the geomagnetic cut-off energy $\epsilon_{\text{min.}}$. When $\epsilon_{\text{min.}}$ changes to $\epsilon'_{\text{min.}}$, the percentage change in intensity can be calculated if we know the coupling coefficients.

Following Alpher (1950), we can write the expression for cut-off energy as

$$\epsilon_{\text{min.}} = Q \cos^4 \lambda \{1 + (1 - \sin\zeta \cos\phi \cos^3\lambda)^{\frac{1}{2}}\}^{-2}, \tag{5}$$

where ζ = zenith angle,

ϕ = azimuth angle measured clockwise from east,

and $Q = ZeM/cR^2$, M being the magnetic moment and R the radius of the earth.

If the geomagnetic field varies such that the cut-off is changed in all directions, then at Ahmedabad

$$\delta\epsilon^{W}_{\text{min.}} = \frac{2{\cdot}52}{5{\cdot}23} \quad \delta\epsilon^{E}_{\text{min.}}. \tag{6}$$

Thus a small change in cut-off for west is associated with nearly twice as large a change in cut-off for east. If the observed increase in asymmetry of 1·29 % were to be explained solely by assuming a change in cut-off energy, we require an increase of $\epsilon^{W}_{\text{min.}}$ by 0·58 GeV. This will produce a *decrease* of 1·16 % in west intensity and of 2·59 % in east intensity. On the other hand, it has been shown in figure 4 of paper II that associated with high east-west asymmetry there is a world-wide *increase* by about 1 % of neutron intensity at middle latitude stations. On similar considerations it can be shown that low asymmetry, like high asymmetry, cannot be caused by a change of the geomagnetic cut-off energy.

3·2. Effect of change of the primary energy spectrum

On days of high asymmetry the spectrum of daily variation is $a\epsilon^{-0.8\pm0.3}$ which is consistent with an anisotropy being produced by cosmic ray primaries traversing beams of solar plasma with magnetic fields frozen in them. For a frozen magnetic field of a stream which is parallel to the earth's field, the positively charged primary cosmic ray particles passing through the beam would undergo an acceleration or deceleration depending on whether the stream is to the left or to the right of the earth with respect to an observer facing the sun. When the stream is to the left of the earth, particles of energy $(\epsilon - e)$ passing through it will get accelerated to energy ϵ. The modified differential energy spectrum will be

$$D'(\epsilon) = K(\epsilon - e)^{-\gamma} \approx K\epsilon^{-\gamma}(1 + e\gamma/\epsilon). \tag{7}$$

Let us suppose that as the earth spins on its axis, the telescopes look at the normal spectrum for X h and at the beam for $(24 - X)$ h. The increase in the intensity for east is given by

$$\Delta N_E = N_E - \overline{N}_E \approx \frac{\overline{N}_E}{100} \int_{\epsilon^E_{\text{min.}}}^{\infty} \left(1 - \frac{X}{24}\right) \frac{e\gamma}{\epsilon} \omega_E \, d\epsilon, \tag{8}$$

where $\overline{N}_E$ is the normal intensity and ω_E is the coupling coefficient for east. The expression for ΔN_W is similar. Equation (8) can be solved by numerical integration

TABLE 2. TABLE SHOWING THE ENERGY INCREMENT SUFFERED BY COSMIC RAY PARTICLES CROSSING A BEAM PRODUCING THE OBSERVED 1·29 % INCREASE IN EAST-WEST ASYMMETRY FOR DIFFERENT DURATIONS DURING WHICH THE TELESCOPES LOOK AT THE BEAM

time for which telescopes look at the beam (h)	energy increment, e (GeV)
12	0·58
9	0·78
6	1·16
3	2·32

with the use of the values of coupling coefficients for east and west derived in I. The energy increment e required to explain the observed increase in asymmetry of 1·29 % is given in table 2, for different durations during which the telescopes look at the beam. The duration is related to the angular width of the external source viewed from the earth.

Brunberg (1958) has estimated the influence of the spread of the secondaries in the atmosphere as well as the bending of the primaries in the geomagnetic field on the amplitude of the daily variation. Even a narrow angle telescope looks at a point source for about 3 or 4 h. To produce a given increase of asymmetry, the energy increment of cosmic rays in the beam should be larger as the duration for which the telescopes look at the beam is reduced from 12 to 3 h. The limiting value of 12 h requires an energy increment $e = 0{\cdot}58$ GeV to explain an increase of asymmetry by $1{\cdot}29$ %. Assuming the beam to have a width of 5×10^{12} cm and an intensity of the trapped magnetic field of 10^{-4} G, the radial velocity of the beam would be about $1{\cdot}5 \times 10^8$ cm/s. The width of the beam would be sufficient for the earth to remain in it for two days as the beam overtakes the earth due to the spinning of the sun. The magnitude of the trapped magnetic field is of the right order from astrophysical evidence. The derived radial velocity of the beam corresponds to a time of transit from the sun to the earth of about 1 day.

For an energy increment of $0{\cdot}58$ GeV in the beam, the calculated peak to peak amplitudes of daily variations of cosmic ray intensity for east and west are $2{\cdot}1$ and $3{\cdot}6$ %, respectively. Even though the ratio of calculated amplitude for west to the amplitude for east is $1{\cdot}7$ in general agreement with the observed ratio $1{\cdot}5 \pm 0{\cdot}3$, the absolute values of the calculated amplitudes are about twice the observed amplitudes of variation for east and west, namely $0{\cdot}9 \pm 0{\cdot}2$ and $1{\cdot}3 \pm 0{\cdot}2$ %, respectively. In the present calculation, however, we have not taken into account the smearing of the amplitude of variation due to atmospheric spread and the extension of the source. More precise and detailed calculations along the lines indicated by Brunberg (1958) are in progress.

Low east-west asymmetry occurs in conjunction with decreases of daily mean cosmic ray intensity and about 3 to 5 days after the onset of *SC* type magnetic storms. Moreover, on geomagnetically disturbed days we have a daily variation which can be attributed to a local source with an energy spectrum which has the same exponent as the background cosmic ray intensity. Qualitatively it appears plausible that a screening or scattering of low-energy particles as a result of magnetic fields in plasma clouds could be responsible for the decrease of east-west asymmetry. We would then expect a decrease of mean cosmic ray intensity as is observed.

4. Discussion and conclusion

In table 3 we summarize the experimental results derived from the study of the daily variation and the changes of east-west asymmetry observed with directional telescopes at Ahmedabad during 1957–8. High east-west asymmetry and primary anisotropy are observed 3 to 4 days before solar corpuscular streams envelop the earth. Low east-west asymmetry occurs 3 to 5 days after the onset of *SC* geomagnetic storms.

The present investigation shows that the daily variation of cosmic ray intensity at low latitudes corrected for normal meteorological effects can be attributed to two physical sources, one situated outside the influence of the geomagnetic field and the other within the influence of the geomagnetic field. Though the average daily variation can be attributed to an anisotropy of primary radiation there are some days on which the daily variation is caused by a local source. The existence of a local source has been suspected in the past by Parsons (1957), Sarabhai & Satyaprakash (1960) and others. The results presented in this paper lend strong support to this suspicion.

The present study gives support to the interpretation of the anisotropy and associated changes of asymmetry based on the influence of frozen magnetic fields in beams in interplanetary space in the neighbourhood of the earth. In the context of the conductivity of interplanetary space related to an extension of the solar corona or to an outward solar wind, particularly during a period of maximum solar activity, many workers have doubted the plausibility of the occurrence of a process involving the polarization of streams with trapped magnetic fields at large distances from the sun. A reconciliation of the present experimental evidence with this view requires that in the general outward flowing plasma wind from the sun there should be rarefied regions with almost no conductivity. These regions would extend radially over local zones of enhanced solar activity and streams can subsequently be ejected into them.

Fan, Meyer & Simpson (1960) have shown that when Forbush decreases are observed on the surface of the earth, the cosmic ray intensity is simultaneously depressed even at a distance of 5×10^6 km from the earth. The evidence excludes

TABLE 3. RELATION OF TWO TYPES OF DAILY VARIATION

	(1) external source	(2) local source
ratio of diurnal amplitude for west to that for east	$1 \cdot 5 \pm 0 \cdot 3$	$0 \cdot 8 \pm 0 \cdot 1$
difference between diurnal time of maximum for east and west	6 h	0
energy spectrum of variation	$a\epsilon^{-0 \cdot 8 \pm 0 \cdot 3}$	$a\epsilon^{0}$
location of the source with respect to the earth-sun line	$112 + 10°$ outside the influence of the geomagnetic field	0° within the influence of the geomagnetic field
associated index of geomagnetic disturbance C_p	low or medium C_p	high C_p
east-west asymmetry	above normal	normal

a geocentric source for Forbush decreases and requires the extension at great distances from the sun of plasma clouds or streams with trapped magnetic fields. This imposes limitations on the general plasma density and conductivity of interplanetary space of the same type as are required by the evidence derived from the anisotropy and increase of east-west asymmetry.

Although the mechanism of the local source of daily variation is not clear at the present time, the present results as well as those of Sarabhai & Satyaprakash (1960) demonstrate that the local source becomes prominent only during geomagnetically disturbed days. The decrease of intensity during days of low east-west asymmetry and the association of the latter with high index of geomagnetic disturbance and *SC* magnetic storms point to the scattering of cosmic rays in magnetic fields.

The authors are grateful to Dr K. R. Ramanathan, Dr H. S. Ahluwalia and Dr R. P. Kane for many valuable discussions and suggestions. Thanks are due to S. R. Thakore and his associates for the computational assistance rendered by them. The project was supported by the Department of Atomic Energy, Government of India.

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FORTY-NINTH INDIAN SCIENCE CONGRESS, CUTTACK, 1962

SECTION OF PHYSICS

PRESIDENT : DR. VICRAM A. SARABHAI, M.A. (Cantab), Ph.D.

Presidential Address

COSMIC RAYS AND INTERPLANETARY SPACE

Our atmosphere has rather restricted windows through which, from the surface of the earth, we can study the universe which lies beyond it. Visible light and short radio waves provide two important windows. Cosmic rays furnish a third. I shall be dealing here with information which study of cosmic ray time variations has given about the physics of the sun and of interplanetary space, a field which has interested me personally for the past 15 years and which is the central theme of research by the cosmic ray group at the Physical Research Laboratory, Ahmedabad. In order to understand how cosmic rays can yield information of our environment in the solar system and in the galaxy, we should first appreciate what these rays are.

2. WHAT ARE COSMIC RAYS ?

What we generally measure as cosmic rays at depths in the atmosphere exceeding a few gm/sq.cm. of air are secondaries produced through nuclear interactions of primary particles in the upper atmosphere. We shall be concerned here mainly with the primary intensity about which views have changed somewhat radically over past decades. Our ideas about the origin of cosmic rays have also changed considerably and a good account of these has recently been given by Ginzburg and Syrovatsky[1]. I cannot do better than draw on them to summarise some important observational evidence which is relevant to our task.

An estimate of the chemical composition of primary cosmic rays is given in Table 1. It indicates fluxes of cosmic ray primaries with various atomic numbers and compares abundances of elements in the universe—two sets of basic data which give a clue to the fragmentation probability and the nuclear lifetime of cosmic rays. The research group at the Tata Institute of Fundamental Research in Bombay has made important contributions in studying the chemical composition of cosmic rays. Cosmic rays are much poorer in light elements than the region of the universe known to us. The ratio of the number of protons and α pafticles to the number of heavy nuclei is on the average almost two orders of magnitude smaller in cosmic rays than in the universe. The groups of light ((L), medium (M), heavy (H) and very heavy (VH) nuclei are not subdivided in the table, but we should note that there is more boron than lithium and more carbon than oxygen in cosmic rays, whereas in the universe, on the average, the opposite is true.

TABLE 1

CHEMICAL COMPOSITION OF PRIMARY COSMIC RAYS COMPARED WITH UNIVERSAL ABUNDANCES. GINZBURG AND SYROVATSKY[1].

Group	Z	$\bar{A}$	Intensity, I (particles/1 m^2 sterad-sec)	Number of nucleons in the flux.	$I/I_H = N/N_H$	Average N/N_H in the universe
p	1	1	1300	1300	520	6830
α	2	4	88	352	35	1040
L	3–5	10	1.9	19	0.76	10^{-5}
M	6–9	14	5.6	78	2.24	10.1
H	$\geqslant 10$	31	2.5	78	1	1
VH	$\geqslant 20$	51	0.7	35	0.28	0.05

The total number of nucleons = 1827

Electrons and γ-rays are not shown in Table 1, for until recently we had no evidence in support of them. However, the very recent discovery (Earl[2] as well as Mayer and Vogt[3]) of relativistic electrons in primary cosmic rays is of major significance, even though it is not yet clear whether these are of galactic or solar origin. A search for γ-rays of $E \geqslant 10$ Mev is also important and experiments are now in progress to detect these.

At a given geomagnetic latitude (i.e. at specified magnetic rigidity) the nucleons contained in the nuclei with $Z \geqslant 2$ carry almost half the cosmic ray energy. Over a wide range of energies, the particle flux of cosmic rays has a power-law dependence on energy with the exponent of the differential spectrum having the same value $\gamma = 2.5 \pm 0.2$ for different cosmic ray charge groups, within the limits of accuracy of measurements. There is some indication that at the highest energy when $E \geqslant 10^{16}$ ev, the exponent increases to $\gamma = 3-3.2$. At most times, there is a low energy cut-off of the primary spectrum at about 0.7 Gev., but the cut-off is dependent on the cycle of solar activity and is clearly a modulation effect related to the solar system. So are the eleven year changes of energy spectrum and of cosmic ray intensity which are illustrated in Figures 1 and 2 respectively.

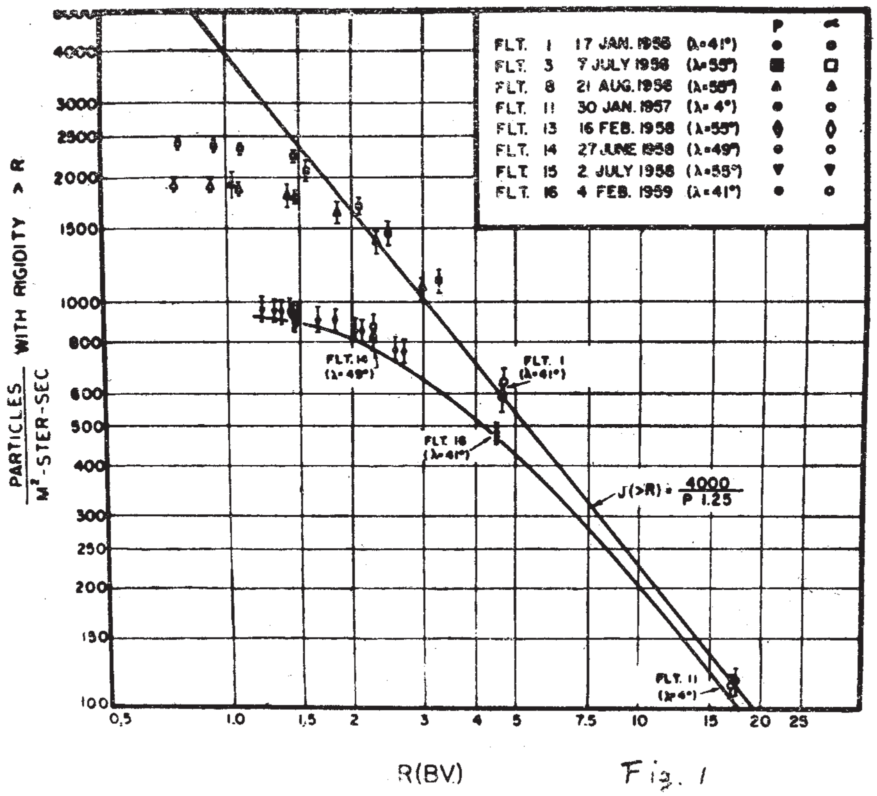

Fig. 1. Integral rigidity spectra of protons and particles during 1955-56 and 1958—F. B. McDonald[4].

An important additional piece of information concerns thesi dereal anisotropy of cosmic rays. Many attempts have been made to detect such an anisotropy. Chitnis, Clark and I[6] have studied at Kodaikanal the directions of arrival of cosmic ray primaries producing extensive air showers. The direction of arrival of each shower was measured by time delays in detection by 4 scintillators placed at the corners of a square. The results of this experiment are shown in Fig. 3. There is no evidence of anisotropy in the celestial arrival directions of over 100,000 primaries with energy of about 10^{15} ev. Very recently, however, it has been reported by the MIT group as well as by the group at Tokyo that a sidereal anisotropy may be present for cosmic ray primaries with energy in excess of 10^{17} ev.

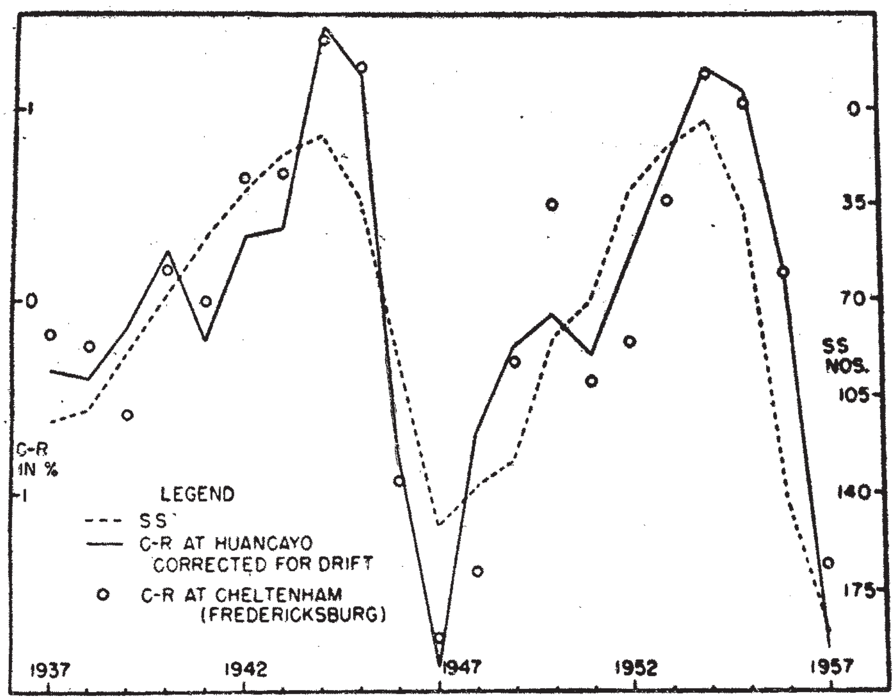

Fig. 2. Annual means of cosmic ray intensity (*C—R*) and sun-spot numbers (*SS*) —S. E. Forbush[5].

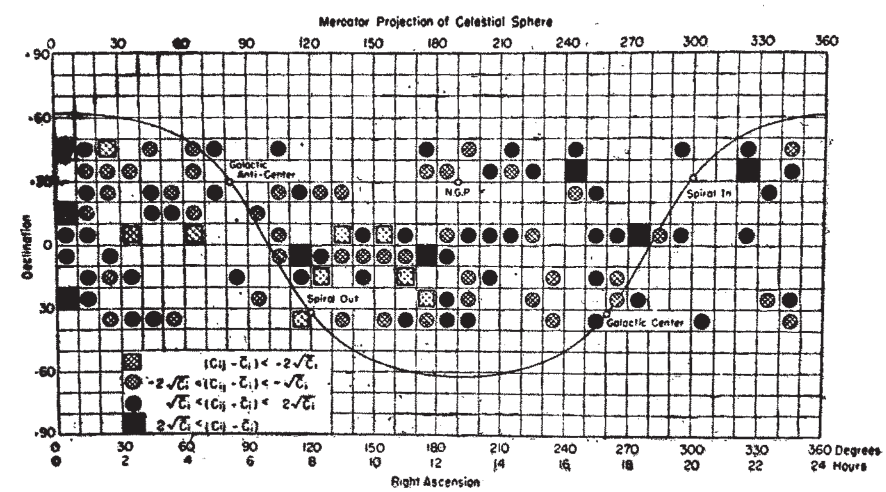

Fig. 3. Fluctuations from declination band averages of intensity of cosmic ray primaries of average energy 10^{15} ev, whose arrival directions are plotted on a mercator projection of the celestial sphere—E. V. Chitnis, V. Sarabhai and George Clark[6].

The above mentioned results, along with astronomical evidence concerning the size and shape of our galaxy, the density of interstellar gas as well as the orientation of dust particles in magnetic fields, lead to fundamental conclusions concerning the origin of cosmic rays. It would clearly take us away from our subject if I were to go into the details of this fascinating field. The conclusions however are very important to us. Cosmic rays in the energy region $E \geqslant 1-2$ Bev are believed to be mainly of galactic origin. The highest energy cosmic rays of $E \geqslant 10^{17}$ ev may be partly metagalactic. At the low energy end, the sun is known to be a source of cosmic rays; quite frequently emitting particles in the energy range 100–500 Mev, less frequently upto 10 Gev and on rare occasions up to 50 Gev.

We have become aware of the importance of solar cosmic rays relatively recently. It is now understood that the sudden enhancement of ionospheric ionisation over the poles leading to the phenomenon known as 'Polar Cap Absorption', the sudden increase of intensity of protons observed at high latitudes in the stratosphere and the sharp increase observed in neutron monitors from time to time are all evidences of the arrival on earth of solar protons of energy greater than 100 Mev, following the occurrence of certain types of flares generally accompanied by type IV radio emission. Fig. 4

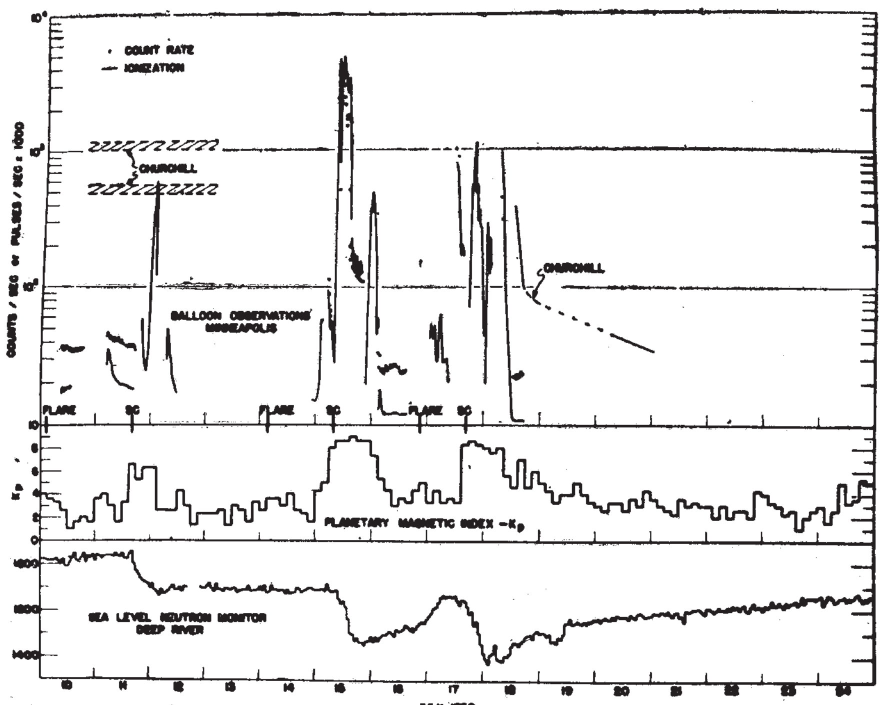

Fig. 4. Solar flare protons observed in the stratosphere over Minneapolis on July 11, 15 and 17, 1959 and by the neutron monitor at Deep River on July 17—J. R. Wickler, P. D. Bhavsar and L. Peterson[7].

from a study by Winckler, Bhavsar and Peterson[7] shows the enhancement of intensity due to soft solar cosmic rays at Deep River at geomagnetic latilatitude 60.5° and even at the latitude of 58.1° in the stratosphere when the geomagnetic cut-ff was temporarily reduced following the onset of a magnetic storm. The spectrum of solar cosmic rays is much steeper than the spectrum of galactic radiation. Indeed on some occasions and at certain energies, the flux of solar cosmic rays exceeds by many factors the galactic cosmic ray intensity.

3. Cosmic rays as probes of interplanetary electro-magnetic conditions

For deriving information about the sun and interplanetary space we are concerned mainly with cosmic rays in the energy range 0.5 to 100 Gev. We should at the outset appreciate some fundamental aspects of the interaction of charged particles with electric and magnetic fields.

Let us first note that a stationery magnetic field changes only the direction of momentum but not the energy of charged particles since the force on the particles is always perpendicular to their motion. Nevertheless a magnetised body such as the earth can act as a spectrometer for cosmic rays by turning back into space particles with less than a particular critical rigidity dependent on the direction and place of arrival.

When we have both magnetic fields and charged particles in a region, we have to appreciate that depending on the relative magnitudes of the magnetic and kinetic energy densities, the field determines the motion of the particles or, conversely, the plasma carries the field with it. Under the latter condition the magnetic field in a highly ionised medium can be looked upon as being frozen within the madium. In this connection, Obayashi and Hakura[8] have formulated an interesting diagram, which is reproduced in Fig. 5. This shows the step energy spectrum for solar particles and its implication for determining whether the particles control the magnetic field or the magnetic field controls the particles. Galactic cosmic rays have an energy density of about 0.5 ev/cm^3 so that the magnetic field plays a determining role in guiding the intensity. The same is the case with most solar proton radiations of energy $E > 10$ Mev. On the other hand solar plasma of lower particle energies with radial velocities of 300 to 2000 Km/sec has an energy density which dominates the magnetic energy density of commonly encountered fields. It then carries the field with it.

Changing magnetic fields offer a mechanism for the change of energy of charged particles, which interact with the field. Alfven showed that a magnetic field frozen in a moving plasma can produce change of energy of cosmic rays traversing through it. This is equivalent to the effect of an electric polarisation field across the boundaries of the plasma as observed from the earth with respect to which the plasma is moving. Moreover, through the mechansim proposed by Fermi, the kinetic energy of moving plasma clouds can be transferred to high energy particles which are guided by the magnetic fields frozen in the clouds.

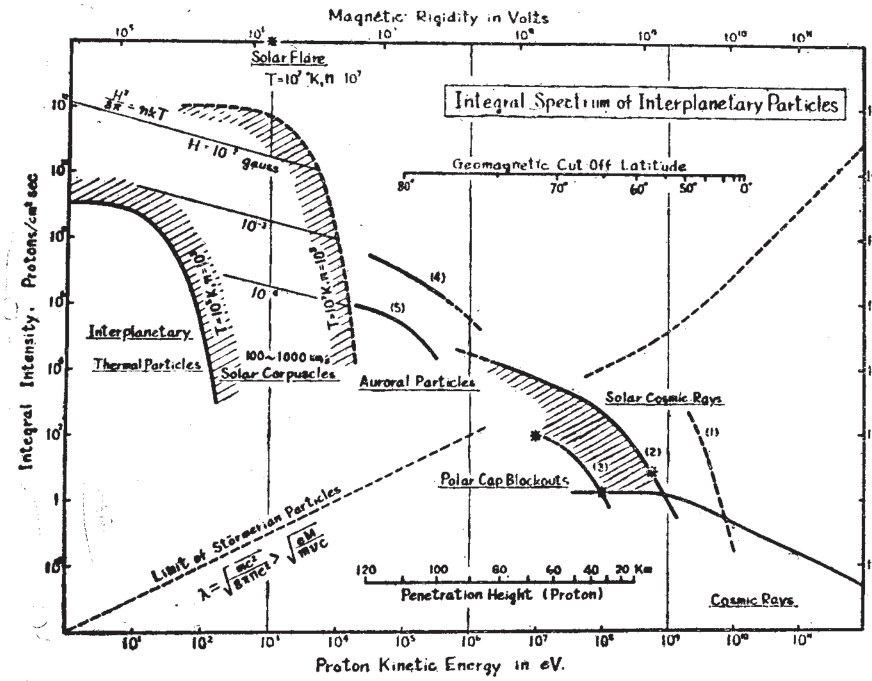

Fig. 5. The integral energy spectrum of solar particles associated with intense solar flares—T. Obayashi and H. Hakura[8].

With solar cosmic rays we derive information on the magnetic fields in interplanetary space by studying the directions of arrival and the isotropy of the radiation. We can also observe solar cosmic rays which are trapped by magnetic fields carried outwards from the sun by plasma clouds. An example of this is seen in Fig. 6 (Steljes, Carmichael and McCracken[9]). The maximum in neutron intensity at Deep River at 1600 U.T. on the 12th of November 1960 was due to solar cosmic rays produced in a large flare which started at 1320 U.T. No corresponding increase was seen in the intensity of mesons at MIT. However, a second increase of neutron intensity commenced at 1900 U.T. coincident with the occurrence of a Forbush decrease in MIT meson intensity. It has been interpreted that the cosmic ray flux in space increased at 1900 U.T. when a plasma cloud from the sun entailing magnetic fields and trapped solar particles enveloped the earth, producing a Forbush decrease.

With galactic intensity, we can look for changes of isotropy and of spectrum that arise from the movement of coherent or turbulent magnetic fields associated with the movement outward from the sun of plasma wind or streams or clouds or shock waves. We can then follow the magnetic field configuration as well as the movement of plasma and examine associated earth-sun relationships.

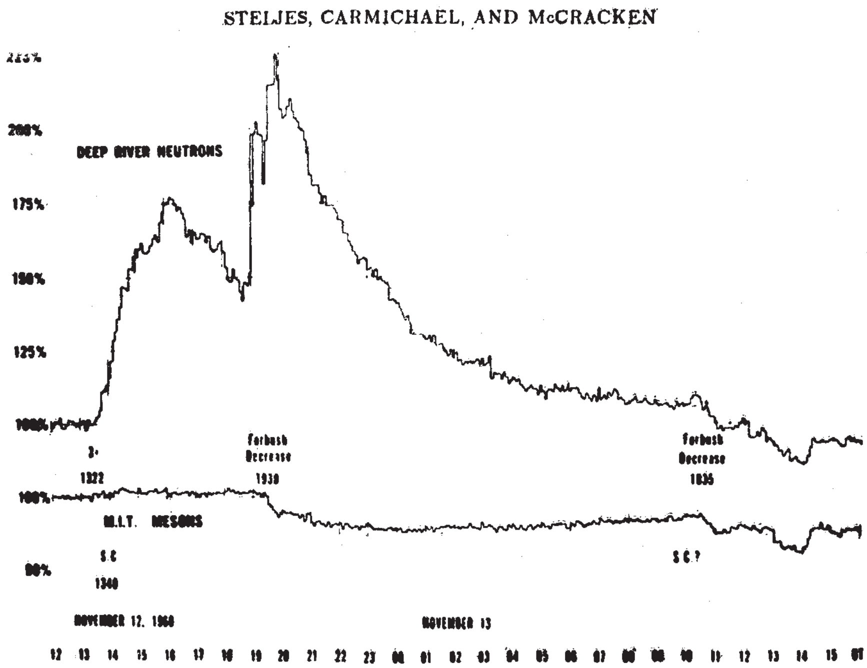

Fig. 6. The concidence in time of increase of Deep River neutrons and the Forbush decrease of *MIT* mesons beginning 1900 U.T. on November 12, 1960— J.F. Steljes H. Carmichael and K. G. McCracken[9].

The sun and interplanetary space thus provide us with a laboratory on a grand scale for studying phenomena under conditions which we do not hope to reproduce in the foreseeable future. And of the particle radiations which could be influenced by interplanetary electromagnetic conditions, cosmic rays are perhaps the most convenient to study with accuracy from the surface of the earth and their variations interpreted in a relatively unambiguous manner. This is reflected in the importance attached to gobal investigations of cosmic ray time variations during the IGY and the proposed International Year of the Quiet Sun.

4. Global studies cosmic ray time variations

I have remarked earlier that the earth with its magnetic field acts as a spectrometer for cosmic rays. Those who are familiar with the development of our understanding of the geomagnetic effects on charged particles incident from outside will recall that this subject received early attention from Brikland and Störmer, who tried to explain aurora. Störmer calculated orbits of particles in the geomagnetic field using numerical methods. But since galactic cosmic ray intensity is substantially isotropic in character, Lemaitre and Vallarta were able to simplify the problem, by reducing it to one involving the calculation of allowed and forbidden regions for particles of different rigidities.

The discovery of solar cosmic rays and the importance of studying transient anisotropies of solar and galactic cosmic rays have once again brought to the fore the need of calculating individual particle orbits and the asymptotic cones of acceptance of cosmic ray instruments at different parts of the world. Moreover, it is necessary to take account of higher order terms in the description of the real geomagnetic field and of the perturbations of the field due to causes external to the solid earth. Therefore several studies of particle trajectories involving modern high speed computers and analogue methods have recently been undertaken.

Fig. 7 from a recent study of McCracken for radiation with a spectrum characteristic of solar cosmic rays, brings out clearly the significance of experiments made at different locations. Very close to the geomagnetic

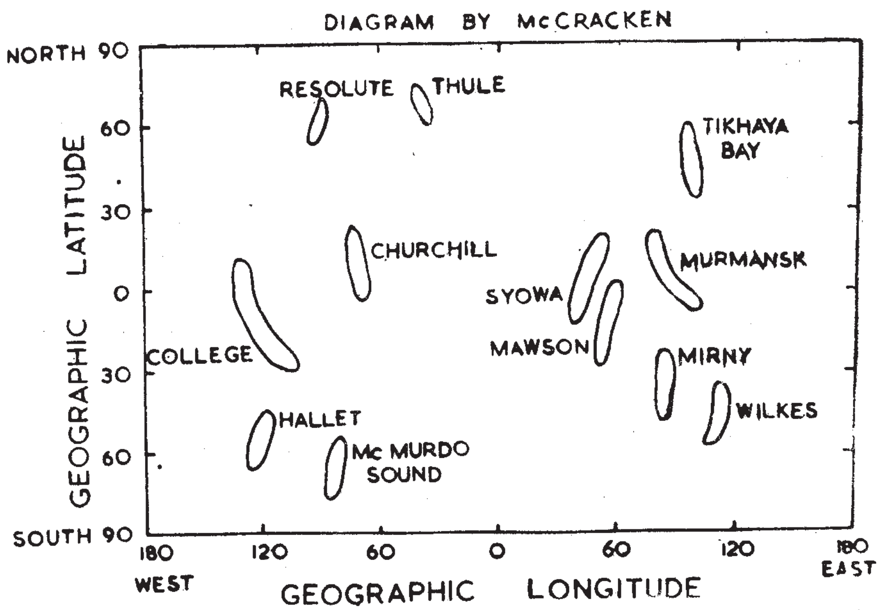

Fig. 7. Asymptotic cones of acceptance of neutron monitors at different locations for solar flare cosmic rays—Diagram by K. G. McCracken.

poles, cosmic ray telescopes look at a specific direction in space almost perpendicular to the plane of the ecliptic. Near the geomagnetic equator, cosmic ray telescopes look at intensity incident along the plane of the ecliptic

2

and scan the meridians of the cellestial sphere as the earth spins on its axis. At intermediate latitudes, the spatial response of cosmic ray telescopes is sensitively dependent on the energy spectrum of the incident radiation and the energy response of the detector.

At low levels in the atmosphere, neutron monitors which measure secondaries produced through a nucleonic cascade have an average energy response for primaries which is lower than the energy response for a mu-meson detector at the same location. For example, for a station at geomagnetic latitude 50° the mean response of a neutron monitor is about 11 Gev while for a mu-meson detector it is about 43 Gev. Since low energy primaries are deflected more than high energy primaries, the spatial response of a neutron monitor is subject to more drastic changes with energy spectrum than of a mu-meson detector.

For solar cosmic rays which are rich in low energy particles, it is most appropriate to make measurements at high latitudes and near the geomagnetic poles. On the other hand, the modulation of galactic cosmic rays involves plasma moving outwards from the sun and therefore cosmic ray primaries incident along the plane of the ecliptic are of special significance. For this reason it is particularly valuable to measure time variation of cosmic rays near the geomagnetic equator. In what follows I shall outline some new insights which have come from our work at low latitudes.

5. The daily variation of cosmic rays and meteorological effects

In 1948, when a systematic study of cosmic ray time variations was commenced at the Physical Research Laboratory, Ahmedabad, the view generally held amongst cosmic ray physicists was that galactic cosmic ray intensity was almost completely isotropic. Experiments were made largely with ion intensity was chambers or with wide angle telescopes and the solar daily variation was found to have an amplitude of about 0.2% when data were averaged over periods ranging from one to several years. Moreover, Duperier had just established the role of meteorological effects in producing cosmic ray variations. Since the time averaged daily variation was comparable in magnitude to some of the meteorological effects that could arise, it is not surprising that many cosmic ray physicists at the time did not believe that the observed solar daily variations could be associated with a solar anisotropy of primary cosmic rays. I felt differently for reasons which I will explain.

When I was conducting an experiment at Bangalore in 1944, on the low energy mu-meson component in the atmosphere, I became conscious of the large magnitude and regularity of the daily variation of cosmic rays which, at first sight, appeared to be related to the barometric pressure. Meteorological effects at an equatorial station are generally rather different from those at middle or high latitudes, where day to day changes of pressure are relatively more important than the daily variation. At Bangalore one could almost set one's clock by the phase of the semi-diurnal variation of barometric pressure occurring day after day. I looked for a relationship between this and the semidiurnal variation of mu-meson intensity. To my great surprise, I found that there was a positive correlation between the two in place of the usual negative effect which one would expect from an increase of mass absorption and a raising of the level of mu-meson formation in the atmosphere with an increase of pressure.

Three years earlier, but unknown to me because of the war, Rau had reported a similar result from observations made under 40 meters of water at Lake Constance in Germany. We were both led to a qualitative explanation invoking a consequence of the theory of atmospheric oscillations which requires a reversal of the phase of the semi-diurnal barometric oscillation above the 30 Km level in the atmosphere. It was argued that if the mean level of meson formation occurred above 30 Km, the survival probability of the unstable mu-meson would increase rather than decrease at a time at which ground level barometric pressure has a semidiurnal maximum. However, in 1947, when Nicolson and I[10] attempted at Cambridge to calculate the precise implications of this interpretation it became clear that the observed positive correlation could not be explained in any well understood way by the known daily variations of conditions in the atmosphere.

A little later, directional studies in East-West and North-South azimuths made by Malmfors[11] and by Elliot and Dolbear[12] showed that even though common meteorological effects were acting, the pattern of the daily variation was not the same in the different directions. Thus it was concluded that at least a part of the observed variation was non-meteorological in origin. More-over, the pattern of daily variation in East and West pointing telescopes had a phase shift which indicated that the variation was related to a solar anisotropy which was being scanned by the telescopes fixed to the spinning earth.

Today, in deriving information about the anisotropy of the primary radiation from the daily variation of meson intensity, the importance of applying corrections for the daily variations of barometric pressure and of atmospheric temperature at different levels is realised. Much progress has been possible in recent years through theoretical and experimental work by a number of workers. Duggal[13] has suggested a method which uses ground temperature and the altitude dependence of the daily variation of temperature derived by meteorologists. This appears to provide a good approximation of the true correction which generally is estimated to be under 0.2% in amplitude. I wish to acknowledge here the very valuable help we have received from Professor K. R. Ramanathan in this problem.

6. The study of time variations and anisotropy of primary radiation at law latitudes.

In starting a programme in India to observe the solar anisotropy of primary cosmic rays, we felt that it was necessary to develop an optimum experimental arrangement. In 1947 we did not have available to us studies on the geomagnetic deflections of cosmic ray primaries or on scattering of secondaries in the atmosphere, but it seemed that a very wide angle telescope or an ion chamber may not provide the best geometrical arrangement for studying the variation of intensity as the anisotropy is scanned. We, therefore, started with an instrument involving 4 vertical meson telescopes with 22° semi-angle of opening in the East-West plane and 37° semi-angle of opening in the North-South plane. This instrument, which is known in our group as the "Standard" counter telescope, has been installed at 3 stations northwards of the geomagnetic equator along the 75°E meridian through India.

Data are now available of the daily variation of meson intensity in the vertical direction, at Ahmedabad from 1951, at Kodaikanal from 1952 and at Trivandrum from 1955. The neutron monitor developed by Simpson was also later set up at Ahmedabad, Kodaikanal and Gulmarg for the IGY programme. Fig. 8 shows the locations of our instruments and the coverage they provide in terms of the primary galactic spectrum.

One of the first results from our standard units was the discovery of a long term change in the form of the daily variation. We could observe the change from year to year with diminishing solar activity approaching 1954 and we sought confirmation in the much longer series of observations with the ion chamber at Huancayo for which data from 1938 to 1943 were furnished by Forbush and Lange. In 1953, Kane and I[14] published the results of an analysis which are reproduced in Fig. 9. We showed for the first time that the diurnal component undergoes significant changes with a period of 11 years broadly in step with the cycle of solar activity. The changes occurred in amplitude as well as time of maximum and the world-wide character of the latter was most striking. Almost simultaneously and independently of us, Thambyahpillai and Elliot[15] reported results concerning the world-wide change of time of maximum of the diurnal component and made the important observation that there was possibly a 22 year period. Desai, Venkatesan and I[16] later confirmed this and demonstrated the close correspondence of changes of diurnl time of maximum and the intensity of the 5303°*A* green coronal emission from the sun.

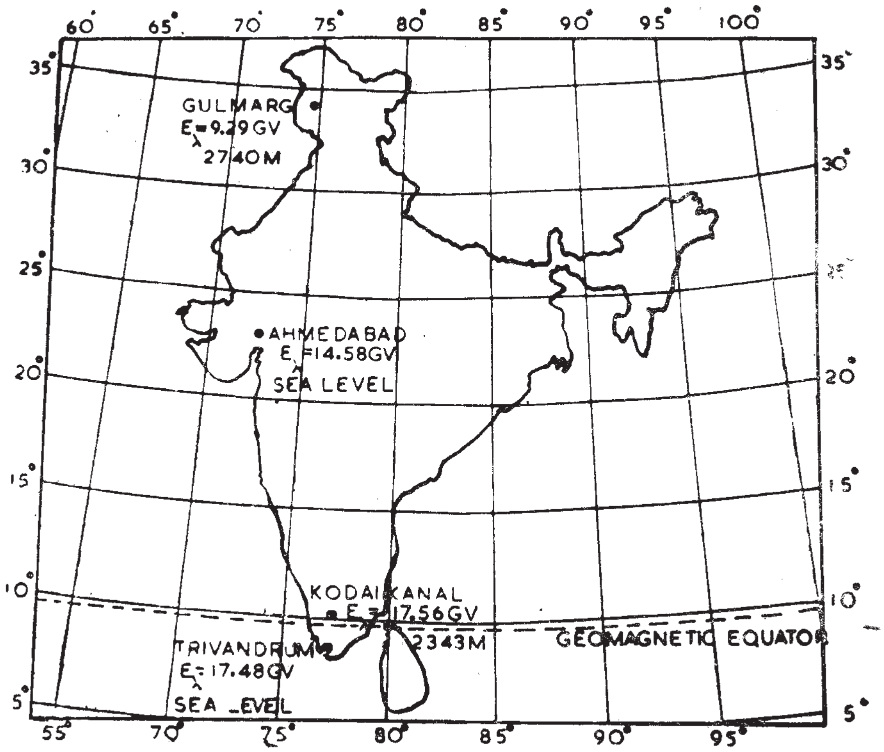

Fig. 8. Locations of Indian cosmic ray stations operated by the Physical Research Laboratory. The elevation of each station and the critical cut-off rigidity (Quenby and Webber) are indicated.

Comparison of our results obtained with counter telescopes and those from ionisation chambers demonstrated that the amplitude of the daily variation as well as its changes were seen very much more clearly with counter telescopes than with omnidirectional detectors. In an attempt, therefore, to push to a limit the technique of narrow angle telescopes, Bhavsar, Nerurkar and I[17] conducted experiments in 1954 with telescopes of different angles of opening in the E–W plane. This work immediately proved rewarding by showing that a high amplitude of daily variation was recorded with a reduction of the angle of opening. Moreover when the daily variation of intensity measured with narrow angle telescopes on each day was harmonically analysed, we found as shown in Fig. 10 that there were in 1954 two preferred hours of the time of maximum of the diurnal component. Thus the changes of the daily variation and of solar anisotropy were indeed present on a day to day basis as well as for the period of the solar cycle. This view was confirmed by other studies conducted about the same time. Firor *et al.*[18] reported that the daily variation observed with neutron monitors was very variable and occurred with a particular form on groups of days. Remy and Sittkus[19] reported similar results and Sekido[20] and his co-workers showed the differences in the daily variation measured with narrow and wide angle telescopes on geomagnetically disturbed and quiet days.

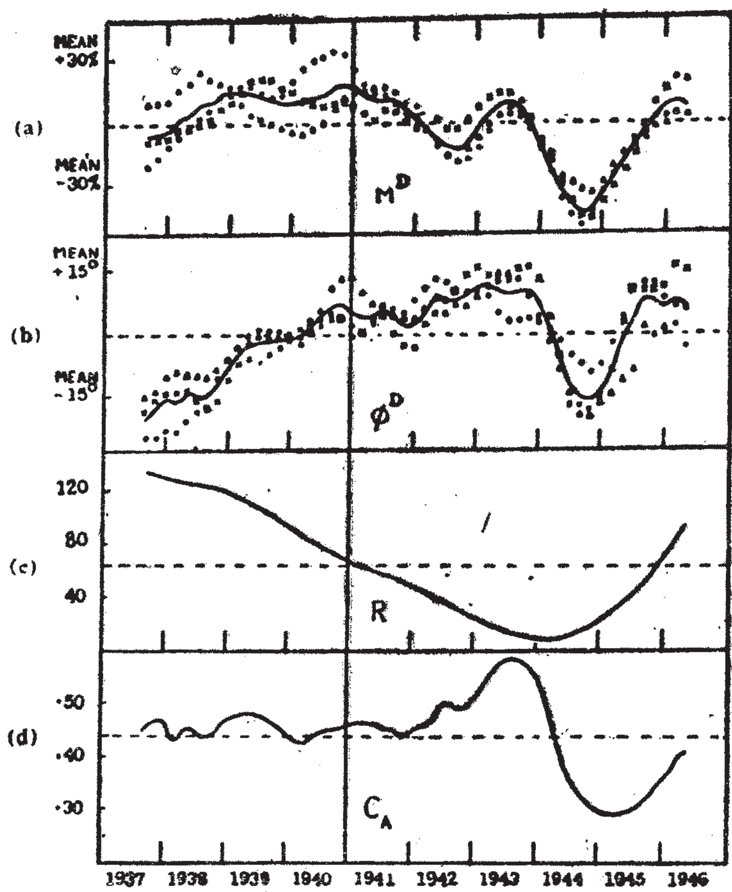

Fig. 9. 11 year cycle of change of the diurnal component of the solar daily variation of cosmic rays. This is seen from time-series for annual mean values during period 1937-1946 of (a) M^D meson diurnal amplitude ; (b) ϕ^D meson diurnal hour of maximum ; (c) R Zurich sunspot number ; (d) C_A American magnetic character figure. The results from individual stations are indicated by Δ for Huancayo, × for Cheltenham, and O for Christchurch.—V. Sarabhai and R. P. Kane[14].

By 1955 our own results and those obtained in other laboratories brought home the realisation that in the daily variation we were indeed observing some important property of primary cosmic rays which was controlled by the electromagnetic condition of interplanetary space. One could conclude that :—

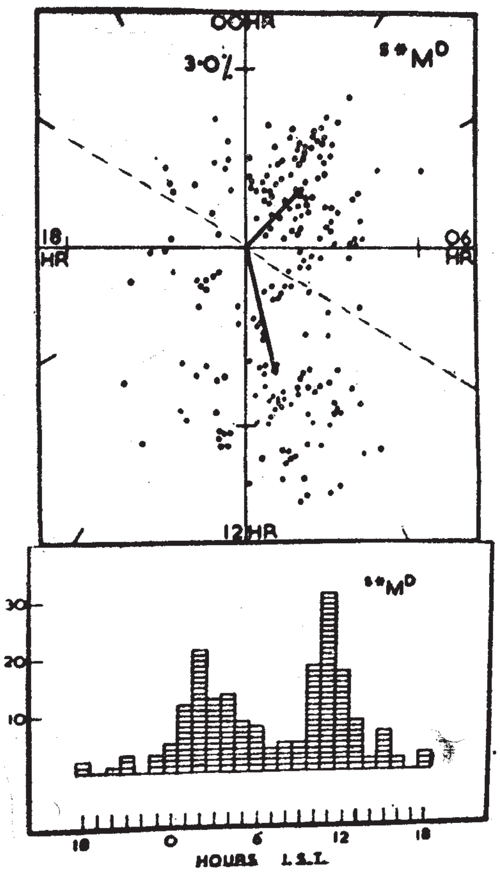

Fig. 10. (a) 24 hourly harmonic dial showing diurnal component on each day for a 5° narrow angle telescope.
(b) Histogram of occurrence of diurnal maximum for each of 24 hours of the day.
V Sarabhai and N. W. Nerurkar[17].

(a) The solar daily variation undergoes significant changes from year to year and from day to day. In consequence, time averages of data over an extended period can be quite misleading as regards the magnitude and sometimes even as regards the direction of the anisotropy.

b) The solar daily variation is often observed better with telescopes of moderate angles of opening than with wide angle instruments. Its amplitude is as large as 1% on some days and can be about 0.5 to 0.6% even when averaged over a year.

c) In view of the variability of the anisotropy, the optimum technique for observing it should involve the study of the solar daily variation on individual days with high counting rate instruments having restricted angles of opening. There is a significant semi-diurnal component in addition to the diurnal component in the daily variation and it is necessary, particularly at low latitudes, to consider both components.

From time to time doubts have been expressed whether the semi-diurnal component of the daily variation of cosmic ray intensity even at low latitudes can be ascribed to a physical cause of non-meteorological origin. In studies made at the Indian stations with meson and neutron intensity, the semi-diurnal variation has persistently been present with significant amplitude on many days, even after applying correction for meteorological effects. Ahluwalia[21] has recently demonstrated that the time of maximum of the semi-diurnal variation has a greater variability on geo-magnetically disturbed days when compared to geomagnetically quiet days. This is difficult to reconcile with a meteorological origin of the variation.

Very recently, from directional studies with telescopes pointing to North and South azimuths at Ahmedabad, Gottlieb and I[22] have shown that the amplitude of the daily variation on individual days is smaller for cosmic ray primaries inclined to the plane of the ecliptic than for those arriving along the plane. This supports the conclusion of Dorman[23] and recently of Sandstrom *et al.*[24] from time averaged data that the anisotropy is strongest along the plane of the ecliptic.

7. Correlated changes of energy spectrum, of intensity and of anisotropy of cosmic radiation

We have seen examples in Figures 1, 2 and 9 of long term changes of energy spectrum, of intensity and the direction of anisotropy of cosmic radiation. These changes are related to the cycle of solar activity. Similar associated changes can be expected during other kinds of time variations of cosmic rays except when special types of processes of modulation are operative. For several years, therefore, it has been an important objective of our programme to seek relationships between these changes during cosmic ray storms and during variations of smaller magnitude which often have a 27 day recurrence tendency. We have been interested in the question whether the day to day changes of intensity are always decreases or decreases as well as increases with respect to the galactic intensity at the appropriate period of the solar cycle. We have moreover wanted to know the relationship of the changes with solar and geomagnetic activity.

In looking at data on a day to day basis, we were confronted with an appreciable level of back-ground noise, and a daily variation which contained on many days both a diurnal and a semi-diurnal component almost to an equal degree. We therefore required a method of analysis which could take account of the daily variation unresolved into its harmonic components and could show up the real cosmic ray effects at an adequate level of statistical significance.

Satyaprakash and I[25] have examined data from a neutron monitor at Kodaikanal through histograms of positive and negative bi-hourly deviations of intensity (from the day's mean), which exceed the 2σ level of significance. The patterm of the histograms clearly indicates the association of individual bi-hourly deviations with a true daily variation. This has shown on a marginal level of significance, like the earlier work with Bhavsar[26], that there are 2 types of daily variations, one which can be associated with increase of daily mean intensity and another with decrease of intensity. This has since been confirmed more rigorously with Ahluwalia[27] using Huancayo neutron monitor data.

The most convincing demonstration of correlated changes however comes from a study conducted with Rao[28] at Ahmedabad using East and West pointing telescopes inclined at 45° to the zenith. The experiment clarifies three important aspects of the day to day modulation of galactic cosmic rays.

a) By comparing the pattern of variation exhibited by East and West pointing telescopes, one can determine whether the modulation occurs at a great distance (when the changes in east precede the changes in west by about 6 hours) or whether it takes place within 1 or 2 earth radii (when the patterns almost coincide in time).

b) When the modulation is at some distance from the earth, one can allow for the deflection of charged primaries in the geomagnetic field and determine the position of the source of modulation with respect to the earth-sun line.

c) Since the geomagnetic cut-off in east is greater than the geomagnetic cut-off in west (at the geomagnetic equator in India the cut-offs for east and west are 23.1 and 11.2 Gev respectively), one can make a two point determination of the spectrum of variation of the primaries from the east-west asymmetry on each day.

Using this simple, but powerful tool, we have got some interesting results. Fig. 11 shows on a polar histogram that during 1957-58 there were many days when the daily variation at Ahmedabad was consistent with an anisotropy of primary radiation. The source of anisotropy was situated on the average at an angle of 112° to the west of the earth-sun line. However, there were a significant number of days when the daily variation appears to have been caused by a local source of non-meteorological origin in the direction of the sun.

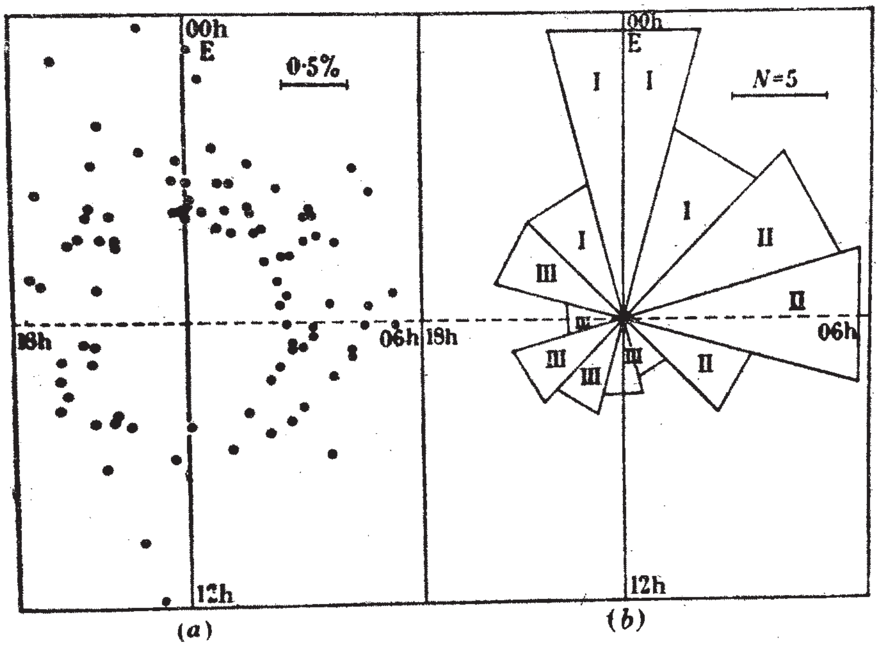

Fig. 11. (a) The distribution of diurnal component of daily variation for west relative to that for east, assumed to be along 00.00 *h* direction, on individual days when the amplitudes of variation for east and west are simultaneously significant at the 2 level.

(b) Harmonic dial representation of the histogram of occurrence of the diurnal maximum for west relative to that for east, assumed to be along the 00.00 *h* direction, on individual days when both east and west have significant amplitudes. U. R. Rao and V. Sarabhai[28].

Fig. 12 shows the changes of intensity which are associated with a steepening of the spectrum (high East-West asymmetry) and with a flattening of the spectrum (low East-West asymmetry). The relationship between changes of spectrum, intensity and geomagnetic field is clearly brought out in the diagram. Low asymmetry epochs occur generally 3 to 5 days after the onset of cosmic ray storms associated with SC magnetic storms. On other hand, high East-West asymmetry occurs when geomagnetic conditions are relatively undisturbed and 3 to 5 days before geomagnetic disturbances set in.

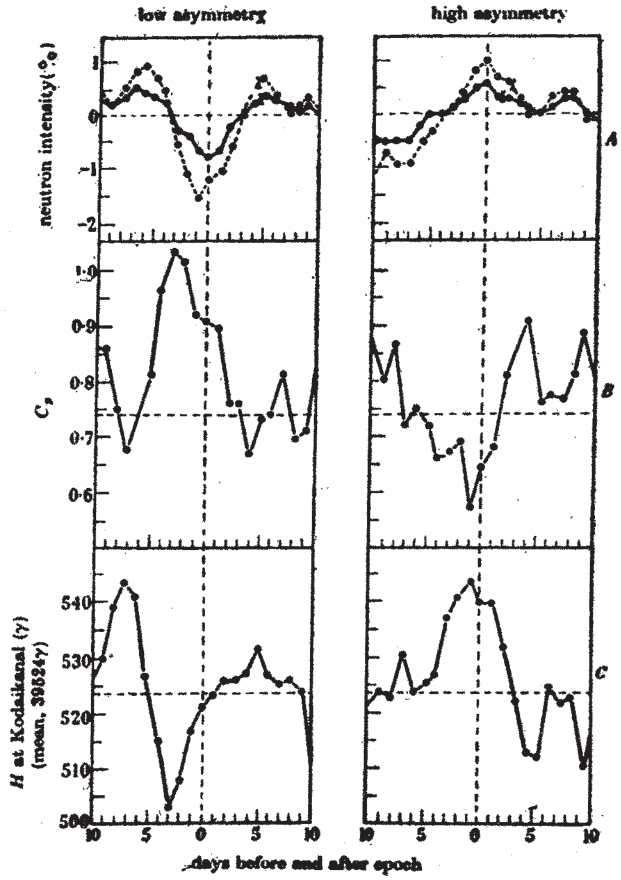

Fig. 12. The Chree analysis for epochs corresponding to days of low and high east-west asymmetry of (A) daily mean neutron intensity at stations situated in equatorial (——) and middle latitude belts (...), (B) C_p and (C) H, the daily mean intensity of the horizontal component of the geomagnetic field at Kodaikanal.
U. R. Rao and V. Sarabhai[28].

The relationship of the two types of daily variation observed by us is summarised in Table 2.

In the past, many investigators have used the latitude effect of a cosmic ray intensity variation to determine its energy spectrum. This procedure is valid only if the modulating mechanism produces the changes of intensity isotropically. In a recent study of large cosmic ray storms, Pai, Rao and I[29] have demonstrated that the modulating mechanism has an anisotropy perpendicular to the ecliptic during the onset of the storms and during the late stage of recovery of intensity. The modulation however occurs isotropically in the first stage of recovery extending from 2 to 5 days after onset. We find that a spectrum of the form $a\epsilon^{\circ}$ with $a = 0$ for $E \geqslant E_{max}$ ($\approx$40 to 60 Gev), as suggested by Dorman fits global changes better than a spectrum $a\epsilon^{-x}$ where x has a value ranging from 0.7 to 1.0. There appears, therefore, to be a real difference in the spectrum of variation produced during large cosmic ray storms and smaller day to day changes of intensity.

TABLE 2

RELATION OF TWO TYPES OF DAILY VATIATION

	(1) External source	(2) Local source
Ratio of diurnal amplitude for west to that for east.	1.5 ± 0.3	0.8 ± 0.1
Difference between diurnal time of maximum for east and west.	$6h$	0
Energy spectrum of variation.	$a\varepsilon^{-0.8\pm0.3}$	$a\varepsilon^{\circ}$
Location of the source with respect to the earth-sun line.	$112+10^{\circ}$ outside the influence of the geomagnetic field.	0° within the influence of the geomagnetic field.
Associated index of geomagnetic disturbance C .	Low or medium C_p	High C_p
East-West asymmetry.	Above normal.	Normal.

We moreover find that during a major storm, plasma is ejected or a shock front travels outwards over a wide cone such that it changes magnetic fields in a substantial part of interplanetary space. This is in conformity with recent evidence from space probes concerning cosmic ray decreases at great distances from the earth (Fan *et al.*[30]).

8. Solar and terrestrial relationships of changes of cosmic ray anisotropy

A major experimental difficulty in studying the anisotropy of cosmic radiation through the daily variation during cosmic ray or geomagnetic storms lies in separating local time changes from universal time changes of intensity. Many workers have reported interesting relationships between the changes of daily variation and geomagnetic disturbances. In general, an enhanced amplitude and an earlier time of maximum of the diurnal component have been reported during days which are geomagnetically disturbed. Sastry[31], Duggal[13], Satyaprakash[25] Ahluwalia[32] and Razdan[33] have sought confirmation of the reported relationship from studies made in India. Kane[34] has attempted the same task using a more rigorous technique, first suggested by Sekido and his-workers, which involves the use of data from 3 comparable stations situated meridianally 120° apart. No clear cut one to one relationship between the magnitude of the planetary index of geomagnetic disturbance and the daily variation can be seen in data collected since 1955. However, the 27 day recurrence tendency of many cosmic ray changes of intensity and of the occurrence of daily variation with large amplitude on groups of days is well established.

An experimental observation of considerable importance concerns the change through the solar cycle of the strength of the source of daily variation on individual days. Razdan and I[35] have recently shown that the daily variation measured with wide angle instruments on individual days is no smaller during sun-spot minimum than during the periods immediately preceding and following it. Moreover, there is evidence from narrow angle telescopes at Ahmedabad that the daily variation on individual days decreases from sun-spot minimum to maximum while the direction of anisotropy also changes significantly.

9. ELECTROMAGNETIC STATE ON INTER-PLANETARY SPACE

I have described many features of cosmic ray intensity variations and anisotropy and it is important before I conclude to summarise what we have gained from the interpretation of these cosmic ray effects. The 11 year cycle of change of intensity and spectrum of cosmic rays, and preliminary results dealing with the gradient of this change in the solar system indicate that the main modulation takes place in a heliocentric barrier situated beyond 1 A.U. from the sun. Cosmic ray storms involve wide regions of interplanetary space and appear to be related to the screening of galactic cosmic rays by a big bubble of plasma or by a shock front in an existing plasma wind as described by Parker[36]. When the bubble or shock front has passed beyond the distance of the earth, we get a strengthening of the heliocentric barrier. The directions of arrival of solar cosmic rays have shown that in general there is connection between the earth and the sun through guiding magnetic lines of force. Some times a shock front or bubble of plasma can itself carry with it trapped solar particles.

For the interpretation of the anisotropy and its correlated changes, we have the model of Alfven, which has been treated in its most elaborate form by Dorman.[23] As has been recently demonstrated by Rao and I[28], increases in east-west asymmetry and the associated daily variation for east and west directions can be fairly well explained by the acceleration of cosmic ray particles cossing beams of solar plasma in the neighbourhood of the earth. For beams of width 5×10^{12} cm with a frozen magnetic field of the order of $10^{-4}G$, a radial velocity of about 1.5×10^{8} cm/s is required. The process is possible only if the ejection of beams takes place in rarefied regions of interplanetary space which extend radially over active solar regions. The change of the amplitude of the daily variation from solar minimum to maximum proceeds in the correct direction when one considers the average plasma density that may be expected in interplanetary space at the two periods. A reversal of the component of the frozen magnetic field perpendicular to the plane of the ecliptic provides a means for a major change of direction of the anisotropy as was suggested by Nerurkar.[37]

An alternative interpretation of the daily variation which is attractice has come recently from Ahluwalia and Dessler.[38] This involves a helical co-rotating solar magnetic field stretched by a radially moving solar plasma wind. The change of intensity of cosmic rays and the amplitude of the daily variation can be related to the radial velocity of the plasma wind and the intensity of the magnetic field. The values of these parameters required to explain a diurnal variation of about 0.5 to 0.8% appear plausible and the time of maximum agrees with observation at many periods of the solar cycle. However the full implications of this interpretation have still to be examined.

Perhaps the true picture of interplanetary conditions involves regions with different radial velocity of plasma extending over different meridianal sections of the sun. There would be some regions where this velocity would be quite small. Local magnetic fields could also prevent the outward flow of plasma. Over these regions, there would occasionally be a major outburst of plasma carrying frozen magnetic fields and a regime of the type described by Dorman.

10. Conclusion

It would be misleading if I were to convey that the broad picture indicated in the previous section is at this stage anything more than a tentative piecing together of diverse facts, some of which have still to be well established. The lacuna arises from several factors :—

a) Rather imperfect coverage of cosmic ray stations on the globe.

b) Insufficient counting rates of instruments measuring intensity changes.

c) Dearth of studies of time variations of directional mu-meson intensity at low latitudes.

It is expected that these shortcomings will be at least partially corrected before the forthcoming International Year of the Quiet Sun. An experiment is now being conducted at MIT with a mu-meson detector, having a counting rate of 1000 per second. It is hoped shortly to study the time variations of a large scientillator array at Chacaltaya in Bolivia, with a counting rate of 30,000 mu-mesons per second. It should therefore soon be possible to determine with accuracy the direction and magnitude of the solar anisotropy of cosmic rays on each day. It is, I believe, realistic to expect that cosmic rays will in time provide the most effective means for the regular sounding of interplanetary electromagnetic conditions.

In conclusion, I wish to express my gratitude to Professor K. R. Ramanathan and to my students and collaborators at the Physical Research Laboratory, Ahmedabad, and at the Massachusetts Institute of Technology, Cambridge. In particular, I should mention R. P. Kane, U. D. Desai, D. Venkatesan, N. W. Nerurkar, P. D. Bhavsar, Satyaprakash, E. V. Chitnis, George Clark, R. Palmeira, T. S. G. Sastry, S. P. Duggal, U. R. Rao, H. S. Ahluwalia, H. Razdan, G. L. Pai and B. Gottlieb. I also wish to acknowledge my deep gratitude to the Department of Atomic Energy of the Government of India for generous support to our work.

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INTERNATIONAL CONFERENCE ON COSMIC RAYS AND THE EARTH STORM Part II

II-4-2. Anisotropy and Changes of Energy Spectrum During Cosmic Ray Storms

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§ 1. Introduction

Many studies have been conducted primarily from measurements with detectors at intermediate and low latitudes, of cosmic ray storms or Forbush decreases at the minimum of intensity which occurs on the first or second day after the onset of a storm. McCracken[1], McDonald and Webber[2], Lockwood[3] and others have suggested from observations made with neutron monitors that the global changes during cosmic ray storms can be explained by a spectrum of variation

$$\frac{\delta D(E)}{D(E)}=aE^{-x} \qquad (1)$$

where 'x' has a value ranging from 0.7 to 1.0. This model with an exponent significantly different from zero and with no other constraints on the spectrum of variation, is referred to as Model 1 in this communication. On the other hand, from a comparison of data from neutron monitors and meson detectors at latitudes $\lambda=0°$ and $\lambda=50°$ during a large number of storms, Dorman[4], Blokh *et al*[5] and others have pointed out that an exponent 'x' different from zero does not explain the observed relative decreases. Their proposal which we designate as Model 2 involves a spectrum of variation

$$\frac{\delta D(E)}{D(E)}=-a \text{ for } E\leq E_{\max}$$
$$= 0 \text{ for } E>E_{\max} \qquad (2)$$

where $E_{\max}$ differs from storm to storm, but has a value approximately equal to 40 GV. They have, moreover, related $E_{\max}$ and 'a' to the physical characteristics of the solar plasma stream responsible for the storm and to the position of the earth with respect to the stream.

In seeking to explain a change of cosmic ray intensity in terms of a physical model, it is important to have information not only on the spectrum of the primary intensity during the change, but also on the position and the symmetry of the modulating mechanism with respect to the sun, the earth and the plane of the ecliptic. For estimating the spectrum of variation, it is desirable to have data from detectors with as large as possible difference in primary energy response. Moreover, the detectors which are compared should sample cosmic ray primaries from essentially the same region of the celestial sphere. For studying the symmetry of the modulating mechanism, the detectors should sample restricted regions of space. These considerations imply that unless the modulation is isotropic, we cannot use the latitude effect of a change to determine the spectrum of variation. Generally we should rather compare pairs of detectors with differing energy response characteristics, both located at appropriate positions on the earth so that the information which is derived can be related to one and the same region of the celestial sphere.

A meson and a neutron monitor at a station such as Resolute, very close to the geomagnetic pole, satisfy our requirements rather well. A similar pair of detectors at the geomagnetic equator at a place such as Huancayo or Lae or Trivandrum furnishes information concerning a belt of the celestial sphere in the range of declinations ±30°. On the other hand, for stations at intermediate latitudes, the spatial response is very sensitive to the spectrum of variation and only under certain conditions it is appropriate to compare neutron and meson intensities to

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Table I. Particulars of stations giving the geographic and geomagnetic coordinates, the magnetic cut-off rigidities, mean energy of response for mesons (M) and neutrons (N) and the name of the principal investigator.

Station	Altitude (meters)	Geographic		Geomagnetic		Magnetic cut-off rigidity Q & W (BeV)	Component.	Mean energy of response (BeV)	Investigator
		Lat. o	Long. o	Lat. o	Long. o				
I. *Equatorial Region*									
Trivandrum	S.L.	8.48	76.95	-1.13	147.5	17.48	M	59.9	Dr. V. Sarabhai.
Lae	S.L.	-6.72	147.0	-15.72	218.6	14.89	N M	41.8 50.7	Dr. A. G. Fenton.
Huancayo	3400	-12.05	284.6	-0.69	354.7	14.18	N	38.3	Dr. J. A. Simpson.
II. *High Latitude Region*									
Chicago	S.L.	41.83	272.3	52.56	338.2	1.54	N	11.6	Dr. J. A. Simpson.
Leeds	100	53.82	358.5	56.45	84.7	1.71	N	11.6	Dr. P. L. Marsden
Ottawa	101	45.40	284.40	56.70	352.57	0.68	N M	11.2 43.7	Dr. D. C. Rose.
Mt. Wellington	725	-42.87	147.33	-51.40	225.78	1.47	N M	11.6 43.7	Dr. A. G. Fenton.
Sulphur Mt.	2283	56.10	244.40	58.18	301.86	0.80	N M	11.2 43.7	Dr. D. C. Rose.
Climax	3400	39.37	253.8	48.17	317.0	2.77	N	10.3	Dr. J. A. Simpson.
III. *Polar Region*									
Mawson	S.L.	-67.60	62.8	-73.22	104.5	0.57	N	10.9	Dr. A. G. Fenton.
Resolute	17	74.68	265.05	82.99	291.3	0.00	N M	10.9 43.7	Dr. D. C. Rose.
Churchill	39	58.80	265.9	68.71	324.3	0.11	N M	10.9 43.7	Dr. D. C. Rose.

derive the spectrum.

We have applied considerations discussed above to study 6 major cosmic ray storms using the superposed epoch method. The storms that have been analysed occurred on 28-9-1957, 21-10-1957, 25-11-1957, 19-12-1957, 25-3-1958 and 16-8-1958. Data from 3 equatorial stations, 6 stations in geomagnetic latitude range 50±5° and 3 polar stations which are indicated in Table I have been used. Results of the Chree analysis are shown in Fig. 1 for equatorial, high latitude and polar stations; separately for neutron monitors and meson telescopes. We are grateful to Dr. A.G. Fenton, Dr. J.A. Simpson, Dr. P. L. Marsden and Dr. D. C. Rose for furnishing the data for our analysis.

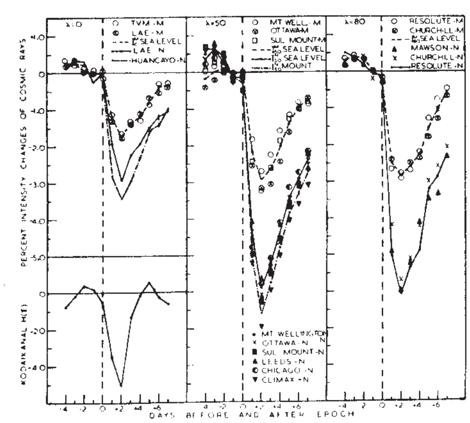

Fig. 1. Results of Chree analysis of the neutron and meson intensity changes for 6 cosmic ray storms studied together. The values indicated are percent deviations from the mean value on −2, −1 and 0 day with respect to the epoch.

§ 2. Relative changes during cosmic ray storms

For studying the modulation of cosmic ray primaries incident almost perpendicular to the plane of the ecliptic, we consider the ratio of neutron intensity change at Resolute and the mean change of meson intensity at Resolute and Churchill. We disregard the neutron intensity change at Churchill since, due to deflection in the geomagnetic field, this detector responds to low declinations in the celestial sphere. For studying the modulation of primaries travelling along the plane of the ecliptic we consider the ratio of neutron intensity change at Lae or at Huancayo with the mean decrease of meson intensity at Trivandrum and Lae, both the latter intensities having been corrected for upper air temperature effects using radiosonde data. For stations at high latitudes, we consider the ratio of the mean decrease of neutron monitors at Ottawa, Chicago, Mt. Wellington and Leeds and the mean decrease of the meson intensity at Ottawa and Hobart.

Fig. 2 indicates the ratios of changes in neutron and meson intensity for equatorial, high latitude and polar stations. It will be observed that at all places the ratio remains fairly constant from +1 to +5 day, but thereafter the ratio increases significantly on +6 and +7 days. Thus the characteristics of the spectrum of variation undergo systematic changes after the intensity has recovered by about 50 per cent. This coincides with the complete recovery of the horizontal component of the geomagnetic field at the equator.

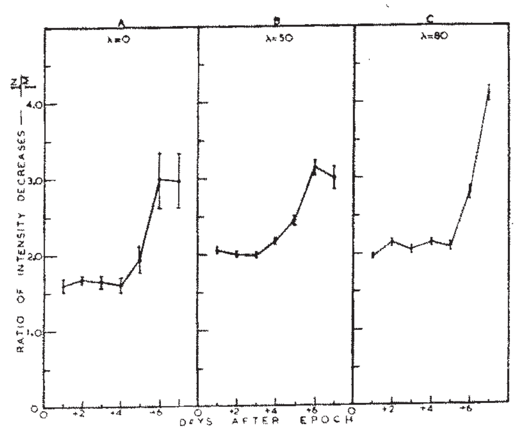

Fig. 2. Ratio of intensity decreases from +1 to +7 day for neutron and meson detectors at the same latitude and same elevation. (a) Equatorial region ($\lambda=0$), (b) High latitude region ($\lambda=50$) and (c) Polar region ($\lambda=80$).

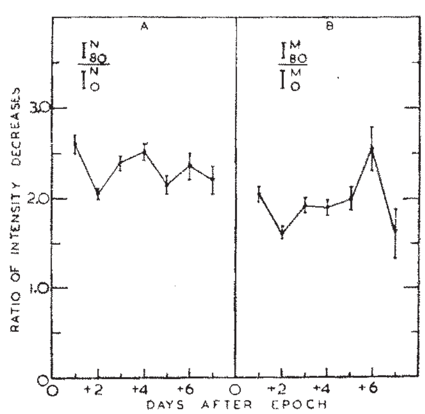

Fig. 3. The ratios of intensity decreases $\frac{I_{80}^N}{I_0^N}$ and $\frac{I_{80}^M}{I_0^M}$ for stations at the same elevation from +1 to +7 day of with respect to the epoch.

The latitude effect of changes for sea level stations for neutron monitors and meson detectors is shown in Fig. 3. It will be observed that the ratios I_{80}^N/I_0^N and I_{80}^M/I_0^M are fairly constant from +1 to +7 days in contrast to the marked increase in the ratios I_0^N/I_0^M and I_{80}^N/I_{80}^M on +6 and +7 days. This indicates that the recovery of the cosmic ray storm at the poles takes place proportionately quicker than at the equator. In other words, the effect on cosmic ray primaries travelling along the plane of the ecliptic is longer lived than for primaries arriving from perpendicular directions.

§ 3. The spectrum of variation

Using geomagnetic cut offs according to Quenby and Webber[6] and the coupling coefficient as given by Dorman[7], the spectrum of variation has been derived for Model 1 and for Model 2 for each latitude belt for seven successive days following epoch. The characteristics of the spectrum are indicated in Tables II (a) and (b) for the two models respectively.

For Model 1, it is difficult to reconcile the decrease at mountain elevations with the decreases observed at sea level stations at a comparable latitude unless we assume that coupling coefficients for stations at mountain elevations are in error. Using coupling coefficients derived by Dorman[7] or the yield functions derived by Quenby and Webber[6] no satisfactory spectrum of variation can explain the relative changes in neutron intensities at Climax and Chicago or the relative changes in the neutron intensity at Huancayo and the meson intensity at Trivandrum or Lae. Even if we disregard this discrepancy for stations at mountain elevations and confine our study to sea level stations, we find that for Model 1, 'x' and 'a' in the spectrum of variation on any particular day significantly differ for cosmic ray primaries incident along the plane of the ecliptic and perpendi-

Table II.a The exponent 'x' and the strength of the source 'a' calculated from neutron and meson intensity changes at $\lambda=0$, $\lambda=50$ and $\lambda=80$ according to Model 1 when the spectrum of variation is $\frac{\delta(DE)}{D(E)}=aE^{-x}$

Day	$\lambda=0$		$\lambda=50$				$\lambda=80$	
	Lae (N) / ½ (Lae+TVM) (M)		Ottawa (N) / Ottawa (M)		Mt. Wellington (N) / Hobbert (M)		Res. (N) / ½ (Res.+Chur.) (M)	
	x	a	x	a	x	a	x	a
+1	1.4	2.92	0.4	0.135	0.6	0.20	0.5	0.180
+2	1.4	4.43	0.5	0.224	0.6	0.29	0.5	0.209
+3	1.4	3.39	0.4	0.160	0.6	0.25	0.5	0.187
+4	1.4	2.93	0.4	1.133	0.8	0.34	0.5	0.168
+5	1.8	8.04	0.6	0.170	0.8	0.25	0.5	0.112
+6	2.8	132.50	0.8	0.218	0.9	0.25	0.7	0.152
+7	2.8	113.90	0.8	0.160	0.7	0.13	1.0	0.231

Table II. b The value of E_{max} and the corresponding value of 'a' calculated from neutron and meson intensity changes at $\lambda=0$, $\lambda=50$ and $\lambda=80$ according to Model 2, where the spectrum of variation is $\frac{\delta D(E)}{D(E)}=-a$ for $E\leq E_{max}$ and $\frac{\delta D(E)}{D(E)}=0$ for $E>E_{max}$.

Day	$\lambda=0$		$\lambda=50$		$\lambda=80$	
	E_{max} Bev	a	E_{max} Bev	a	E_{max} Bev	a
+1	37.5	0.050	40	0.062	45	0.065
+2	37.5	0.074	40	0.083	40	0.082
+3	37.5	0.057	40	0.075	40	0.074
+4	37.5	0.050	35	0.066	40	0.066
+5	32.5	0.043	30	0.055	40	0.042
+6	25.0	0.046	25	0.050	30	0.043
+7	25.0	0.039	30	0.035	22.5	0.038

cular to it. This would mean that the plasma cloud in interplanetary space, which is believed to screen galactic cosmic rays, produces a steeper variational spectrum along the plane of the ecliptic than along a perpendicular direction. The exponent of the spectrum increases for all directions after the initial partial recovery of the intensity.

For Model 2, on +1 day, E_{max} is greater at the poles than at equator. During the second phase extending from +2 to +4 days, an almost identical E_{max} can explain changes at mountain elevations and at sea level, at equatorial, high latitude and polar regions. Thus, unlike the discrepancy which arises in attempting to explain on the basis of Model 1, Model 2 fits the available global data remarkably well. For the average of the 6 storms considered by us, $E_{max}\sim40$ GV and the spectrum of variation is isotropic during the second phase which covers the three days following onset of the storm. Thereafter the recovery takes place more rapidly at the poles than at the equator. Thus, on this interpretation, the modulating mechanism has no marked anisotropy perpendicular to the plane of the ecliptic during the initial phase of recovery of the storm. An anisotropy for directions of arrival along and perpendicular to the plane of the ecliptic is indicated only during onset on +1 day and during the second stage of the recovery.

§ 4. Conclusions

Experimental evidence and plausibility on general physical considerations favour Model 2 in preference to Model 1. For Model 2, Dorman has related E_{max} and 'a' to the characteristics of the solar plasma stream. The most important assumptions are that the stream envelops the earth for the entire duration of the storm and the relative changes of intensity occur due to the relative change of position of the earth with respect to the stream as it overtakes the earth with the spinning of the sun. E_{max} is connected with the gyroradius of a cosmic ray primary in a stream with magnetic field H_1 and a minimum distance l_1 of the edge of the stream from the earth.

Experimentally we find that E_{max} is nearly constant for the first five days. This would mean that $H_1 l_1$ is constant and does not vary with the relative motion of the stream with respect to the earth during this period. It seems plausible that this constancy arises from the stream originating in the sun and from l_1 being incapable of exceeding the earth sun distance.

Gold[8] has pointed out how a stream ejected from the sun would get disconnected from the sun in a time of the order of 3 to 5 days. This must represent a point of time at which a major change in the effective length 'l' would occur. If during the first five days, we assume that 'l' is the earth sun distance, the average value of the trapped magnetic field would be 1.78×10^{-5} gauss.

An interesting implication arises in the interpretation of cosmic ray storms in the manner suggested above. We would require for $E_{max} \sim 40$ GV at the poles, a beam perpendicular to the ecliptic of extent comparable to an astronomical unit. On these considerations, it would appear that during a major storm, plasma is ejected or a shock front travels outwards over a wide cone such that it changes magnetic fields in a substantial part of interplanetary space. This is in conformity with recent evidence from space probes concerning cosmic ray decreases at great distances from the earth.

Acknowledgments

It is a pleasure to acknowledge the benefit of many useful discussions with Dr. K. G. McCracken, Dr. K. R. Ramanathan and Dr. R. P. Kane. We are grateful to the staff of the computation section of the laboratory for assistance. The financial support from the Department of Atomic Energy, Government of India, is gratefully acknowledged.

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Discussion

Roederer, J.G.: Were the recovery times of the six storms comparable value? We found similar results with yours, but the numerical values and characteristics differ from storm to storm.

Sarabhai, V.A.: The values would differ from storm to storm.

Marsden, P.L.: What effect does likely arise from the movement of earth relative to the beam?

Does day +4 correspond to position of earth in centre of beam?

Sarabhai: This depends on the model we take. We have made a calculation of the type conducted by Bloch and Dorman. I, however, find this rather artificial. I suggest that the cosmic ray changes are produced not only by the isorotation of the beam but also by the radial motion outwards.

Ehmert, A.: I agree that it is useful to start from neutron and meson research. But diurnal variation within such storms has another energy response and for storms with strong and without diurnal variations you come near to model 2 and 1 respectively.

Sarabhai: It is clear that apart from the large storms where Model 2 seems applicable, there are longer lasting streams, where Model 1 type spectrum is applicable to smaller modulation effects.

Sandström, A. E.: Concerning Dr. Marsden's remarks on the diurnal variation on days following closely upon an F, d. I wish to point out the following; The variations on days following closely upon an F, d. often have an *U, T.* variation and the daily variation.

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II-3B-7. Cosmic Ray Effects Associated with Polar Cap Absorption Events

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§ 1. Data

We have studied cosmic ray effects associated with polar cap absorption during the period May 1957 to July 1959. Of the 24 intense PCA events listed by Reid and Leinbach[1], cosmic ray intensity data extending continuously from −5 to +10 days of each event are available for 21 events at Trivandrum, Huancayo and Climax. However, events on August 29, September 9 and 26 in 1957, August 21 in 1958 and July 14 and 16 in 1959 are preceded in each case by another PCA event within 10 days. These have been eliminated from the study since we are interested in the day-to-day changes of daily mean cosmic ray intensity up to 10 days following these events. Data from Trivandrum (Geographic lat. 8.48°, long. 76.95°, Geomagnetic lat. −1.13°, sea level) relate to μ meson intensity measured with vertical counter telescopes and corrected for changes of barometric pressure and upper air temperature using radio-sonde data. Data for Huancayo (Geographic lat. −12.05°, long. 284.6°, Geomagnetic lat. −0.69°, 3400 meters) and for Climax (Geographic lat. 39.37°, long. 253.8°, Geomagnetic lat. 48.17°, 3400 meters) relate to neutron monitor intensity corrected for changes of barometric pressure. We are grateful to Dr. J. A. Simpson for the use of the neutron monitor data.

We have initially examined changes of intensity at Climax for the classification of PCA events in terms of their association with changes of daily mean cosmic ray intensity. This is because, of the three stations considered, the Climax neutron monitor has the lowest mean energy of response and therefore exhibits the largest changes of intensity. We find that six PCA events are not followed within one or two days by cosmic ray decreases exceeding 2.5% in 24 hours at Climax. These are referred to as 'group A' events. The intensity changes at Climax for each of these events are shown in Fig. 1. The other nine PCA events are followed within one or two days by cosmic ray intensity decreases exceeding 3% in 24 hours at Climax. These are referred to as 'group B' events.

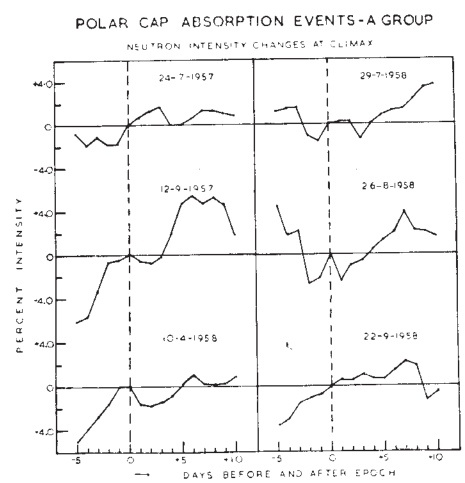

Fig. 1. Daily mean neutron intensity changes from −5 to +10 days at Climax corresponding to each polar cap absorption event of group A. All intensities are shown as derivations from the values on epoch day.

The associated solar and terrestrial relationships of the individual PCA events in each group are shown in Table I. Chree analysis has been done from −5 to +10 days for A and B groups separately for the daily means of the following:

(1) Cosmic ray intensity
- (a) Meson intensity at Trivandrum
- (b) Neutron intensity at Huancayo
- (c) Neutron intensity at Climax

(2) H, the intensity of the horizontal component of the earth's magnetic field at Kodaikanal

(3) Ionospheric absorption* at 25 Mc/s

* We are indebted to Professor K. R. Ramanathan and Dr. R. V. Bhonsle of the Physical Research Laboratory, Ahmedabad, for this data.

Table I. Table showing the particulars of different events connected with polar cap absorption events.

Date of event	PCA starts at UT	Max. absor. at 27.6 Mc/s (db)	Probable flare				Magnetic storm				Delay in events in hours.	
			Time UT	Impor- tance.	Helio. Lat.	Helio. Long.	Date	Time UT	Type	Fig. of activity	T_1	T_2
					GROUP A							
24- 7-57	2015	2.0	1816	3	S 24	W22	—	—	—	—	02	—
12- 9-57	1200	0.5	0709	2	N12	W15	13	0049	SC	s	05	13
10- 4-58	1130	3.0	1010	1+	N18	W78	16	0418	C	ms	01	—
29- 7-58	0405	0.7	0303	3	S 14	W43	—	—	—	—	01	—
26- 8-58	0100	10.0	0005	3	N20	W54	27	0301	SC	m	01	26
22- 9-58	1430	4.0	0741	2+	S 17	W42	25	0409	SC	ms	04	62
					GROUP B							
29- 8-57	1300	9.0	1031	3	S 24	E 22	29	1920	SC	m	02	06
21- 9-57	1930	5.0	1332	3	N13	W08	21	1006	SC	s	06	18
21-10-57	0700	5.0	1637 (20th)	3+	S 25	W45	21	2235	SC	m	14	16
10- 2-58	0700	12.0	2108 (9th)	2+	S 13	W14	11	0124	SC	s	10	13
25- 3-58	2230	12.0	0950 (23rd)	3+	S 15	E 20	—	—	—	—	61	—
7- 5-58	0130	15.0	0039	3+	N24	W02	8	0751	SC	s	01	30
16- 8-58	0600	13.0	0432	3+	S 14	W53	17	0818	SC	ms	01	24
11- 5-59	0130	15.0	2055 (10th)	3+	N23	E 47	11	2330	SC	ms	05	22
10- 7-59	0700	15.0	1937 (9th)	2+	N19	E 67	11	1628	SC	m	05	33

T_1—Delay between flare and PCA. T_2—Delay between PCA and magnetic storm.

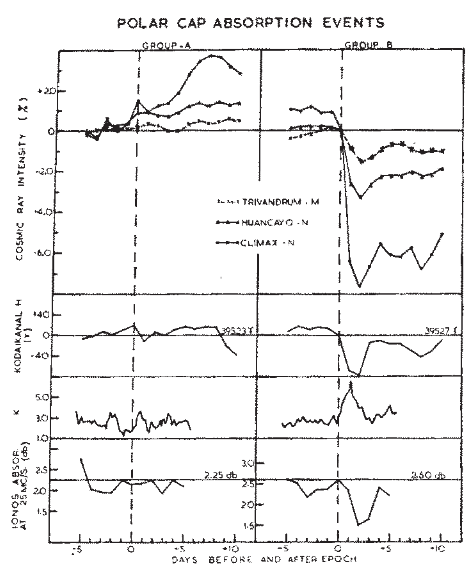

Fig. 2. Results of Chree analysis of daily mean intensity of mesons at Trivandrum, neutrons at Huancayo and Climax, ionospheric absorption at 25 Mc/s at Ahmedabad, horizontal component of earth's field at Kodaikanal and three hourly K_p indices for group A and group B PCA events.

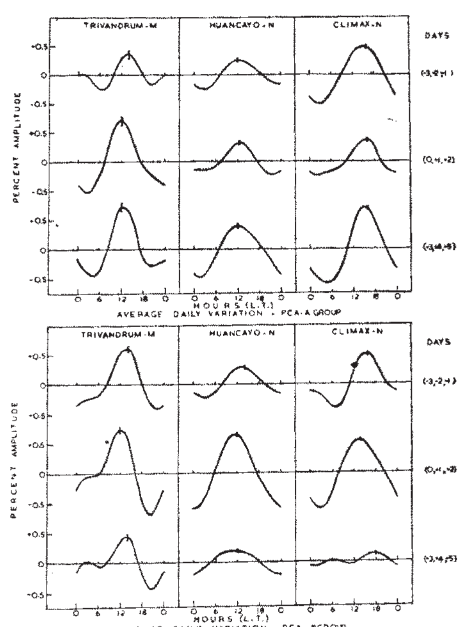

Fig. 3. Average daily variation for group A and group B PCA events for three day groups comprising (−3, −2, −1) days, (0, +1, +2) days and (+3, +4, +5) days respectively.

cosmic radio noise at Ahmedabad.

(4) Three hourly K_P indices.

We show in Fig. 2 the results of the Chree analysis of daily mean values. In Fig. 3 we indicate the average daily variation for meson intensity at Trivandrum and for neutron intensity at Huancayo, and Climax for three day groups comprising (−3, −2, −1), (0, +1, +2) and (+3, +4, +5).

§ 2. The Results

We can observe the following characteristics of associated changes for the two groups of PCA events separated in terms of their cosmic ray effects.

(1) *Characteristics of group A events*

1. Meson and neutron intensities are above normal on epoch day. They increase from +4 to +8 day. On +7 day, the intensity at Climax is 3.5% above mean.

2. Peak to peak amplitude of the daily variation of cosmic ray intensity and the diurnal and semidiurnal components are large for the group comprising +3, +4 and +5 days at equatorial and high latitude stations.

3. H, the horizontal component of the geomagnetic field at Kodaikanal is depressed by about 30 γ on +1 day but no major cosmic ray storm follows the PCA event.

4. There are no major changes in K_p.

5. Only three events are having SC storms following them within one or two days, out of which only one is listed as severe.

6. There are no clear changes in the ionospheric absorption of 25 Mc/s cosmic radio noise at Ahmedabad.

7. Absorption at 27.6 Mc/s is comparatively low, the mean value for 6 events being <3 db.

8. All probable flares corresponding to these events occurred on the western half of the solar disc.

9. The average delay between the occurrence of probable flare and PCA is small, being only $2\frac{1}{2}$ hours for the six events.

(2) *Characteristics of group B events*

1. Cosmic ray intensity decreases abruptly on +1 day and reaches a minimum value on +2 day. The recovery of the intensity is slow.

2. Peak to peak amplitude of the daily variation of cosmic ray intensity is maximum for the group of days comprising epoch, +1 and +2 days. Since the daily mean intensity simultaneously undergoes a very large change, the large amplitude of daily variation can arise due to curvature effect as discussed by Kane[2]. The amplitude of variation for this period cannot therefore be directly interpreted in terms of the primary anisotropy.

3. Kodaikanal H is depressed by about 70 γ on +1 day, the depression being much larger than in group A events. Geomagnetic field recovers in a manner characteristic of the main phase of a geomagnetic storm.

4. K_p reaches maximum value on +1 day, and is significantly high on +1 and +2 days.

5. Eight out of nine events are followed by SC storms. Most of them are either moderately severe or severe.

6. Daily range and the daily mean ionospheric absorption of cosmic radio noise at Ahmedabad are low on +2 and +3 days.

7. Ionospheric absorption at 27.6 Mc/s is large, the average for nine events being >11 db.

8. The associated flare has no preference for either the eastern or the western limb on the solar disc.

9. The delay in the PCA event after the occurrence of the flare is comparatively large. On one occasion, it is ~60 hours. The average time delay for the nine events is ~12 hours and excluding the one event, the average delay is ~8 hours.

§ 3. Discussion

Obayashi and Hakura[3] have considered the association of geomagnetic storms and Type IV solar outbursts with PCA events. They have suggested that there are at least two types of solar corpuscular clouds responsible for earth storms. The high energy type characterised by particles in the energy range 10 to 100 GV carry frozen magnetic fields and produce PCA events and cosmic ray storms. The low energy type produce magnetic storms and through a distortion of the outer geomagnetic field tend to enhance the cosmic ray intensity observed on the earth. They have also pointed out that many events involve the ejection from the sun of both types of clouds.

Since we have considered only PCA events, we have according to Obayashi and Hakura, either high energy corpuscular clouds or a combination of high and low energy clouds. We find that amongst these, many with the highest energy, *i.e.* which generally have the shortest time as in group A, produce minor geomagnetic effects and almost no cosmic ray effects. Thus Obayashi and Hakura's classification can be extended to a third category, consisting of events where relativistic protons are emitted without the arrival at the earth of either low or high energy plasma clouds. The steadily rising cosmic ray intensity in group A events from −2 to +7 days represents in many cases a recovery from earlier cosmic ray storms. This indicates that the conditions for the arrival of relativistic protons by themselves are most appropriate when the interplanetary magnetic fields have been stretched out towards the earth through earlier high or low energy plasma clouds.

Alternatively, it could also indicate the presence in interplanetary space of scattering regions of plasma clouds with magnetic fields left over from the plasma cloud resposible for the earlier Forbush decrease. The 'A' type PCA events which do no produce significant changes of daily mean cosmic ray intensity or of geomagnetic field are nevertheless associated with anisotropy of cosmic rays 3 to 5 days after the flare.

The authors are grateful to Dr. U. R. Rao for many helpful discussions and to the staff of the Computation Section of the Laboratory for assistance. It is a pleasure to acknowledge the support from the Department of Atomic Energy, Government of India.

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INTERNATIONAL CONFERENCE ON COSMIC RAYS AND THE EARTH STORM Part II

II-4-30. Review of Cosmic Ray Daily Variation and Geomagnetic Effects

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§ 1. Introduction

In discussing the daily variation of cosmic rays we shall consider local time effects. These are not only diurnal, but often involve a semidiurnal variation as well, particularly at low latitudes.

The meteorological effects which cause variations of intensity of local neutrons or of mu meson or of the soft component are now reasonably well understood and I will not discuss these. The correction of the daily variation of meson intensity for temperature effects nevertheless posses some problems, since the experimental determination of the daily variation of air temperature at different levels in the atmosphere is beset with many difficulties. Most workers would agree that the total temperature correction is not likely to exceed 0.2% and this introduces some ambiguity when the true daily variation is of the same order of magnitude. Rao and Sarabhai[1] have recently suggested a method which uses ground temperature and the altitude dependence of the daily variation of temperature derived by meteorologists. This appears to provide a good approximation. But, in any case, the daily variation of cosmic ray intensity on individual days has often an amplitude exceeding 0.5% and residual errors due to meteorological effects are then quite negligible.

The main interest in the daily variation of cosmic rays is to study anisotropies and local time dependent periodic changes of the geomagnetic field or of electric fields in the exosphere which may affect cosmic rays. Some evidence for processes of the latter type following geomagnetic storms has recently been obtained from east-west directional studies at low latitudes.

We have heard in the plenary session on particles of the great importance from the standpoint of interpretation of measurements of energy spectrum and of initial anisotropy in the arrival of solar particles. For the modulation of galactic cosmic rays this is equally so. Most processes involve the outward transport of energy and magnetic fields in interplanetary space. In general we should expect strong anisotropy of the galactic radiation as these sweep past the earth. But the anisotropy would be transient, so that characteristically it could be expected to last from a few hours to perhaps a few days. One might expect that these transient anisotropies would be distributed in a most complicated manner. The surprising feature is that there is a distinct pattern. Hence even when time averaged data is examined we can discern a story. If, in the past, this has not excited the interest of many experimenters and theoreticians in this field, it is perhaps because time averaging kills in a most drastic way many interesting features such as the magnitude of the effect.

§ 2. Local Time Effects and Anisotropy of Cosmic Rays

A major experimental difficulty in studying the daily variation of cosmic rays is in separating local time (L.T.) effects from universal time (U.T.) effects due to the isotropic modulation of intensity observed simultaneously on a world-wide basis. The problem has been tackled in two ways:

(a) Sekido and his coworkers have suggested the estimation of the U.T. effect by combining the results from three comparable stations situated meridianally 120° apart. The L.T. effect at each station can then be estimated by correcting for the U.T. effect.

(b) Anisotropy can be detected by the occurrence of a characteristic phase difference in the pattern of variation of intensity in east and west pointing telescopes as these telescopes scan interplanetary space with the spinning of the earth.

At this Conference evidence derived from both methods has been presented.

Using triplets of stations appropriately situated, one in middle latitude and another near the equator, Kane[2] has estimated data for the I.G.Y. period to seek confirmation of many earlier reported features of the daily variation and its solar and terrestrial relationships. Using a rigorous technique, he confirms the world-wide occurrence of daily variation of large amplitude on groups of days with a 27 day recurrence tendency. On the other hand, he does not find significant relationships with solar features or geomagnetic disturbance.

A new result of great interest has been reported by Regener[3], who has conducted experiments with telescopes pointing to east and west directions, underground at the geomagnetic equator. Regener finds that, even for intensity of primaries with average energy of about 2×10^{11} e.v. arriving along the plane of the ecliptic, there is a solar anisotropy which shows itself in daily variation with characteristic phase shift for the two inclined telescopes.

§3. Solar Anisotropy and Declination

A number of interesting communications have been presented concerning the change in the magnitude of the anisotropy with declination in the celestial sphere. From world-wide data averaged over many years Dorman had pointed out that the anisotropy is strongest along the plane of the ecliptic. Sandström *et al*[4] have given a very convincing demonstration of this by conducting simultaneous studies with directional telescopes at three stations covering the latitude belt 60° to 89°N. They find that the east telescope at Uppsala, which looks into the plane of the ecliptic, has a very much larger daily variation than telescopes at Murchison Bay, which look at asymptotic directions almost perpendicular to the ecliptic.

Using telescopes pointing to south and to north directions inclined at 45° to the zenith, Sarabhai and Gottlieb[5] have conducted an investigation at 10°N geomagnetic latitude. They have reported at this Conference that south pointing telescopes, which look along the plane of the ecliptic, exhibit a higher amplitude of the daily variation than north pointing telescopes, which look at asymptotic directions inclined at about 30° with the plane of the ecliptic. Thus they confirm for time averaged data and on a day-to-day basis that the anisotropy is strongest along the plane of the ecliptic.

Two papers relate to the latitude effect of characteristics of the daily variation observed by the I.G.Y. network of neutron monitors. The results presented by Pomerantz *et al*[6] are consistent with the decrease of anisotropy for asymptotic directions with high declination in the celestial sphere. Kanno and Murakami[7] have derived a world map showing lines of constant time of maximum of the average diurnal component. The significance of their approach is that it can perhaps indicate the shear or deformation westwards of the geomagnetic field by the solar emissions in interplanetary space which envelope the earth. However, the I.G.Y. data which has been used is not adequate either with regard to coverage or accuracy to furnish positive evidence in this regard.

§4. Solar and Terrestrial Relationships of the Daily Variation

A group of papers presented at this Conference are concerned with a re-examination of many of the earlier reported solar and terrestrial relationships of the daily variation of cosmic ray intensity, which mainly relate to data prior to 1955. The communications of Kane[2] and of Sandström[8] make it clear that during the period of the I.G.Y. and the years following it, the relationship between the characteristics of the daily variation and the degree of geomagnetic disturbance, for example, is not clearly established. Crowden and Marsden[9] also report a relationship between daily variation and cosmic ray storms which differs from earlier studies. The more rigorous statistical techniques of analysis which are now used may have something to do with this; but it is more than likely that there is a real difference between the conditions during the present solar cycle and the preceding one.

§5. Geomagnetic Effects

In the interpretation of the daily variation in terms of anisotropy of primary radiation, it is important to be able to make appropriate allowance for geomagnetic effects. The experiments of Brunberg and Dattner have provided an invaluable basis for making these corrections. These are now being refined and extended by using analogue methods and numerical calculations with computers. A representation of the geomagnetic field involving 6 terms of harmonic expansion of the surface field is being used in place of the dipole field. Elliot has reported the early results from a terella set up by Bland[10] at London. This has permitted the examination of penumbra effects in an elegant way. Further work involving imposed external fields will be very eagerly awaited by the many workers in the field of cosmic ray variations. Quenby and Wenk[10] as well as McCracken and Fréon[11] have made numerical calculations which are of great value. Komori[12] has considered the energy balance of the cosmic ray secondary components in the atmosphere to provide further confirmation of the calculations of cut offs by Quenby and Webber.

§ 6. The Lunar Daily Variation

The lunar daily variation of cosmic ray intensity is of considerable interest since it can throw light on the lunar oscillations of the atmosphere as well as on the meteorological corrections to be applied to cosmic ray intensity. Bagge[13] has reported at this Conference a study of the lunar tide in cosmic rays. The effect as yet cannot be followed clearly and consistently; but I hope that he will continue interest in this important field of geophysics.

§ 7. Summary of Present Position

I believe that the following summary of position in this field would be widely acceptable:

(a) The solar daily variation of cosmic ray intensity can generally be attributed to an anisotropy of primary radiation. The anisotropy is of a variable character and is quite marked on groups of days which occur with a 27 day recurrence tendency.

(b) The degree of anisotropy is dependent on the declination of the asymptotic direction of cosmic ray primaries. The anisotropy is strongest for primaries along the plane of the ecliptic.

(c) There are undoubted relationships between the daily variation of cosmic rays and solar and geomagnetic activity, and with the isotropic changes of intensity, such as occur in cosmic ray storms. These relationships however appear to be time dependent and their precise nature is somewhat obscure.

(d) There is a suspicion that daily variation of cosmic ray intensity on some days following geomagnetic storms cannot be attributed to an anisotropy of primary radiation. A confirmation of the local non-meteorological source of daily variation is required.

§ 8. The Future

(a) There is great need to improve the I.G.Y. network of stations, both with regard to coverage and in regard to experimental technique. It is now necessary to have instruments with really high counting rates to permit us to follow the changes of anisotropy which are constantly occuring and which can give very valuable information on movements of plasma in interplanetary space. We require more neutron monitors appropriately situated to study the directions of arrival of solar particles. Data from these in conjunction with data from meson telescopes would permit reliable spectrum determination of cosmic ray variations. The establishment of instruments very close to the geomagnetic poles and in the equatorial belt are of particular significance. High counting rate meson telescopes pointing to inclined directions east, west, north and south furnish very important data concerning the modulation of galactic intensity. Moreover, the east-west asymetry, which is derived from studies in inclined directions, is an important tool for continuously following the changes of energy spectrum of the primary radiation.

(b) There is today a great lacuna in the theoretical interpretation of anisotropy. Dorman has worked out in detail the implications of his model which is based on basic ideas originally put forward by Alfvén. However, in view of the reservation entertained by some theoretical workers concerning the plausibility of electric field effects in the context of the conductivity of interplanetary space it is important that alternative theories of anisotropy be worked out in some detail. Experimental workers in this field would, I am sure, welcome an elaboration of the models proposed by Parker and by Gold to predict the anisotropy, that would be expected.

(c) Further advance in the reliability of interpretation of experiments on daily variation depend vitally on a more accurate understanding of geomagnetic and atmospheric transition effects. The coupling coefficients and the multiplicity functions which are applied to interpret measurements at mountain elevations and at equatorial stations are mainly derived from extrapolation, and experimental verification wherever possible is necessary.

(d) We have listened at this Conference to experiments being conducted to determine the anisotropy in the arrival of gamma rays and very high energy cosmic ray primaries. Another challenging experimental task is to observe neutrons from the Sun, which are expected from charge exchange following the production of high energy protons. In India an approach is now being undertaken through collaboration between the Tata Institute of Fundamental Research and the Physical Research Laboratory for the detection with photographic plates at balloon elevations. At all events it is pretty clear that we shall be quite busy for many years to come.

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9) J. B. Crowden and P. L. Marsden: Kyoto Conference, MO II-4-27.
10) C. G. Bland, J. J. Quenby and C. J. Wenk: Kyoto Conference, MO II-4-18.
11) K. G. McCracken and A. Freon, Kyoto Conference, MO II-4-19.
12) H. Komori: Kyoto Conference, MO II-4-20.
13) E. Bagge: Kyoto Conference, Mo II-4-28.

Discussion

McCracken, K.G.: Dr. Sarabhai has made a very good point regarding the necessity for study of the diurnal variation on a day to day basis. I would go one step further, and suggest that it should be studied on an hour to hour basis. We know that the phase of the diurnal variation can change markedly within a day, and this means that the anisotropic nature of the radiation is changing rapidly with time. These changes in anisotropy are undoubtedly due to changes in the interplanetary electromagnetic field, presumably induced by the motion of plasma from the sun, and we know that such plasma travels a distance of about 1AU in 24 hours. A clear understanding of the process producing the diurnal variation needs establishment of the experimental correlations between the position of the plasma cloud and the phase of the diurnal wave. The nature of the anisotropy can be studied by employing the data observed simultaneously by a number of detectors situated at different longitudes.

Elliot, H.: With regard to Dr. McCracken's remarks, I want to say following. The interplanetary magnetic field configurations responsible for the cosmic ray modulation are certainly very complicated. It is essential to try to establish broad general patterns in the first instance and this is what we do in investigation the time averaged behaviour of the daily variation. When the general pattern has been established then of course we should look at progressively finest detail.

Korff, S.A.: In considering relation from great distances, a proton at 10^{14} e.v. in a field of 0.1 gamma is bent into a curve of less than a light-year in radius, so that radiation from distant sources will have arrival directions scrambled.

Do the searches for galactic sources take account of this effect? If there seems to be a higher counting rate from the galactic plane, how should this be interpreted in view of these curvatures?

Sarabhai, V.A.: I was only referring to the modulation of a galactic intensity which for the reasons stated by you should be nearly isotropic till it interacts with plasma and magnetic fields in interplanetary space.

I suggest that experimental evidence indicates day to day processes of modulation being more effective along the plane of the ecliptic.

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International Conference on Cosmic Rays and the Earth Storm Part II

II-4-3. Time Variation of Cosmic Ray Intensity from North and South Directions at Low Latitudes

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Following the interesting results which emerged from a study by Rao and Sarabhai[1,2] of the time variations of cosmic ray muon intensity for East and West directions at Ahmedabad (Long. 75°E, Geomag. lat. 14°N, sea level), we have conducted an investigation, with the same apparatus, of variations of South and North intensities. We present here some preliminary results of data obtained during 1959 and 1960 with telescopes of semi-angle 20×45° inclined at 45° to the zenith.

§ 1. The average daily variation for South and North.

In Fig. 1 we show the mean daily variation for South and for North for 93 days of operation during 1959, for 169 days of operation during 1960 and for the combined period of 252 days during 1959–1960. The average daily variation has been corrected for the

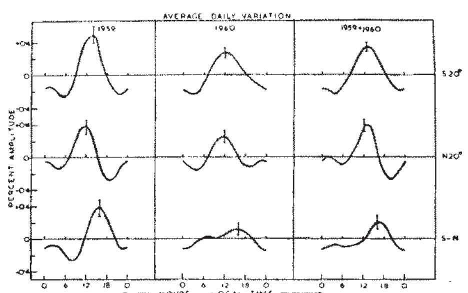

Fig. 1.

daily variation of atmospheric pressure and of temperature in the atmosphere at different levels. For the latter, the procedure described by Rao and Sarabhai[1] has been adopted. The daily variation for (S–N), being the difference of the average daily variations for South and North directions, is also shown in the figure. It would be observed that during each year individually and for the combined period, the average daily variation for South is consistently greater than the average daily variation for North. This is more pronounced in 1959 than in 1960. The times of maxima of the variations for South and North are not very different, and in consequence the average (S–N) daily variation is approximately similar in form to the average daily variation in either direction.

§ 2. The distribution of (S–N) bihourly intensity at 8 and 16 hours on individual days.

The average (S–N) variation has a minimum at 8 hours and a maximum at 16 hours. In order to test whether the (S–N) difference that is observed in the average daily variation is present on a statistically significant basis for changes occurring at the particular hours on individual days, we have considered the per cent bihourly deviations for North and South directions for 8 hours and 16 hours. In Fig. 2 we show the histograms of (S–N) bihourly intensities at 8 and 16 hours. The histograms at the two hours have been compared with each other for 1959 and 1960 and for the combined period 1959–1960. Applying the χ^2 test to the histograms, we have verified that the histogram for (S–N) intensity at 8 hours is different from the histogram at

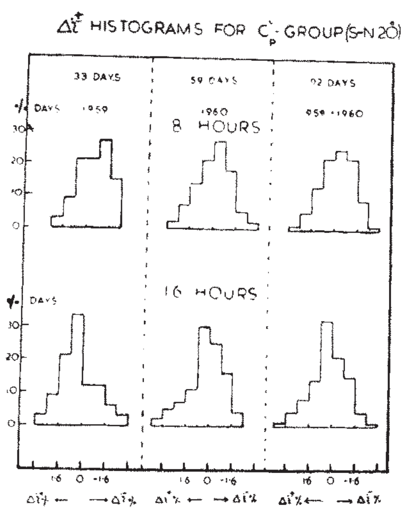

Fig. 2.

16 hours for the combined period of 1959–1960 at a 5% level of significance. During 1959, the level of significance is even higher, but the histograms are not significantly different during 1960.

Since Rao and Sarabhai have shown that the daily variation can be attributed to an anisotropy of primary radiation on days of low or moderate geomagnetic disturbance indicated by a value of $C_p<1$, we have conducted the analysis for days which are not geomagnetically disturbed. We find that during 1959 as well as 1960, the histograms at the two hours are different at a 5% level of significance. We thus conclude that the features seen in the average daily variation, indicative of the daily variation for South being larger than the daily variation for the North, are present on individual days, particularly those which are not geomagnetically disturbed.

§ 3. The (S–N) daily variation on individual days.

We have conducted harmonic analysis of daily variation for South and for North on each individual day and vectorically determined the characteristics of the harmonic component of the (S–N) variation. We show in Fig. 3 the histograms of the diurnal amplitude r_1(S–N) and its time of maximum

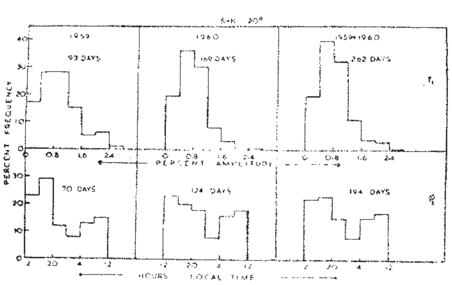

Fig. 3.

ϕ_1(S–N), the latter for those days on which the amplitude r_1(S–N) is greater than the standard error of 0.6%. The histograms show that in 1959 and in 1960 there are large numbers of days on which the daily variations for South and North are significantly different. Moreover, the (S–N) variation has a time of maximum for the diurnal component which is not randomly scattered. The ϕ_1(S–N) histograms for 1959, 1960 and for 1959–1960 have been statistically tested for lack of randomness and at a better than 5% level significance the preponderance for the occurrence of (S–N) maximum at 16 hours is established in each case. Thus the study made on the basis of individual days confirm the existence of significant difference between South and North daily variations which was seen in the average daily variation.

§ 4. Discussion.

By consideration of the geomagnetic drift for primary particles responsible for intensity for South and North telescopes, we find that at Ahmedabad, South looks almost along the plane of the ecliptic while North looks at a region of the celestial sphere with declination greater than 30°. Thus, a comparison of daily variation for South and North on individual days when the daily variation can be associated with an anisotropy of primary rays helps us to study change of strength of source of daily variation with declination. The smaller amplitude for North compared to South is in agreement with conclusions in this regard from a comparison of the global distribution of the amplitude of the daily variation made by Dorman[3] and others.

Work is in progress to study the solar and terrestrial relationships of days when the daily variation for South has a large amplitude and the daily variation for North is in one case similar to South and in another case dissimilar to it, *i.e.* r_1(S–N) is large or small simultaneously with r_1(S) being large. We are also examining the data to look for evidence for change in the orientation of the trapped magnetic field in solar streams according to the suggestion of Dorman[3].

The authors are grateful to Dr. R.P. Kane for helpful discussions and to Mr. B. G. Thakore and Mr. D.D. Dave for computational assistance. The support from the Department of Atomic Energy is gratefully acknowledged.

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3) L. I. Dorman: Cosmic ray variations published by State Publishing House, Moscow. (1957).

Discussion

Parsons, N. R.: Are the asymptotic longitudes scanned by N and S telescopes approximately the same?

Sarabhai, V.A.: This is nearly so at the latitude of Ahmedabad. For the diurnal component the difference in time of maximum due to this would be insignificant.

THE ASYMMETRIC INTERACTION OF THE MAGNETOSPHERE WITH SOLAR PLASMA

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It is generally accepted that geomagnetic storms are produced by the interaction of solar plasma with the magnetosphere. We look in this study for some observational clues which might enable us to use the perturbations in the magnetosphere to probe interplanetary plasma.

The times of onset of sudden commencement (SC) and gradual commencement (GC) storms during the period 1950 to 1961 have been studied for seven stations indicated in Table I. It is seen that the number of storms reported during this period of 12 years at Huancayo or Tucson is much greater than at Kodaikanal or Watheroo. The difference is particularly large for GC storms.

Fig.1 shows the frequency of occurence at different hours UT of SC, GC and all storms (SC + GC) which are recorded at each station. χ^2 test shows that SC + GC storms show distributions different from random at 95% level of significance at all stations excepting Watheroo. For Huancayo, Kodaikanal and Sitka the maximum frequency occurs around 0200 to 0600 UT and minimum at 1800 UT. This effect is most noticeable for GC storms. SC storms, in fact correspond more closely to a random distribution except for a distinctly higher frequency soon after midnight UT. On the whole, the deviation from random occurrence is more pronounced for equatorial and high latitude stations than for stations at middle latitudes.

We have been concerned that the world-wide occurrence of sudden commencement and the simultaneity of the storms at different stations is apparently by no means a consistent feature even of the so-called SC storms as reported by the different observatories. We have satisfied ourselves that in several cases the difference arises from subjective judgement in classification. For truly world-wide storms which have identical classification and time of onset at two widely separated stations, the histograms of the time of onset in UT are shown in Fig.2. The majority of these storms are of SC type. Apart from a dominant peak of frequency seen after Greenwich midnight, the histograms indicate close to random occurrence, whenever a pair such as Kodaikanal and Huancayo situated about 150° apart in longitude is considered.

We have two possibilities of explaining the observations. We can attribute the lack of randomness of occurence to different conditions of transmission of hydromagnetic waves through the equatorial ionosphere which has marked longitudinal asymmetry. Or alternately, we can attribute the results to a longitudinal asymmetry of interaction of the magnetosphere with solar plasma. We examine here some implications of the latter alternative.

In Fig.3, is indicated the equatorial distance from the earth's surface of a typical L shell corresponding to H =0.2 gauss for different longitudes. The broad conclusion of the present investigation therefore is that the probability of recording the quasi-world-wide geomagnetic storm is largest when the region of high field is pointing towards the sun and the region of low field is in the antisolar direction. For sudden commencement storms alone, there is a high probability of interaction when the South Atlantic anomaly is in the antisolar direction. Moreover, the geomagnetic storm has many distinctly regional and sometimes even local characteristics.

These conclusions are in some respects unexpected. If the sudden commencement is only due to the initial impact on the magnetosphere of a solar plasma cloud with a sharp front which is then transmitted through hydromagnetic waves in the magnetosphere(Dessler and Parker 1959) the high frequency of such impacts when the South African anomaly is in the anti-solar direction is difficult to understand. The longitudinal asymmetry of quasi-world-wide magnetic storms must suggest that the longitudinal asymmetry of the magnetosphere plays an important part in its interaction with the plasma. Moreover, since the relative magnitude of the longitudinal asymmetry at seven or eight earth radii calculated on the basis of the eccentric dipole or the Finch and Leaton representation of the internal field becomes quite small, we should probably conclude that the asymmetry gets amplified by secondary processes occuring within the magnetosphere. If, on the other hand, we attribute our results to a relatively important role in geomagnetic storms of induced currents in the earth's crust, we would have to alter drastically the quantitative and perhaps some qualitative aspects of current theories of geomagnetic storms which attribute most of the effects to factors external to the surface of the earth.

The authors are grateful to Prof.K.R. Ramanathan and R.G. Rastogi for helpful discussions. Financial assistance from the Department of Atomic Energy, Government of India is also gratefully acknowledged.

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Table I

The geographic and geomagnetic coordinates and the number of storms recorded during 1950 to 1961 at stations considered for the study.

Stations	Geographic		Geomagnetic		No. of Storms		
	Latitude	Longitude	Lat.	Long.	SC	GC	SC+GC
Huancayo	−12° 03'	284° 40'	−0.6°	353.8°	200	230	430
Kodaikanal	+10° 14'	77° 28'	+0.6°	147.1°	167	94	261
Apia	−13° 48'	188° 14'	−16.0°	260.0°	168	200	368
Watheroo	−30° 19'	115° 53'	−41.8°	158.6°	153	106	259
Hermanus	−34° 26'	19° 14'	−33.7°	81.7°	214	306	520
Tucson	+32° 15'	249° 10'	+40.4°	312.2°	153	200	353
Sitka	+57° 04'	224° 40'	+60.0°	275.4°	130	308	438

DISCUSSION

EMERT: **Magnetic storms are very complex and at least a part of the different influences as ionospheric currents and earth currents have zones in respect to the direction of the sun, where they vanish as is known from Vestines current system of bay-like disturbances. What you do is a selection according to special directions against the plasma direction and this is a promising approach.**

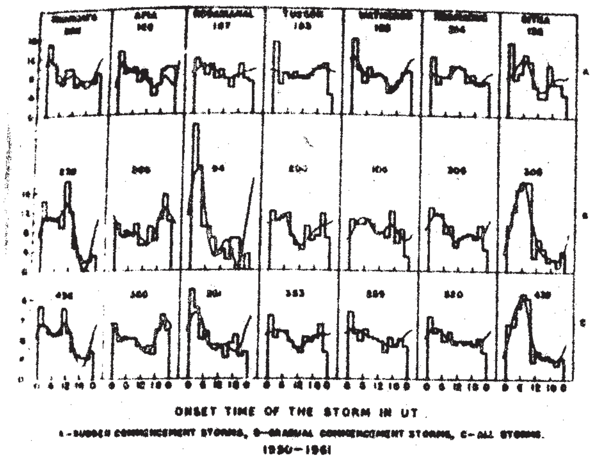

Fig.1: Histograms of the frequency of the onset times in UT of the SC, GC and SC + GC storms during 1950–61.

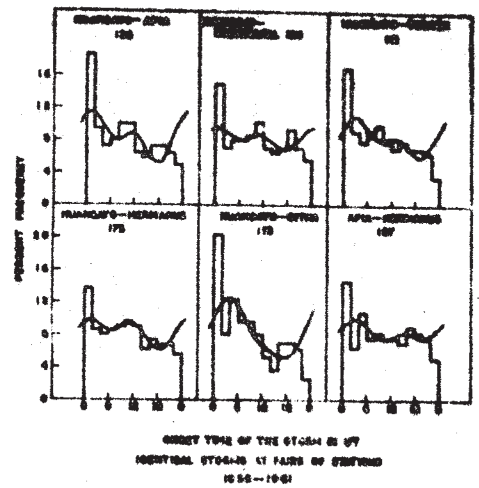

Fig.2: Histograms of the frequency of the onset times in UT of the identical SC and GC storms put together at pairs of stations considered.

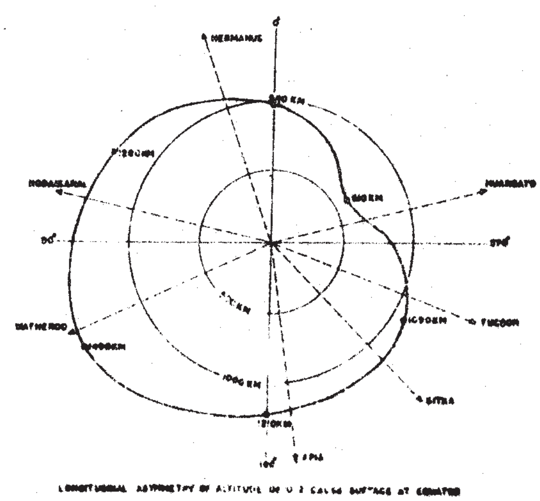

Fig.3: The distance of the shell of constant field of 0.2 gauss around the world (invariant equator) along with the relative positions in longitude of the stations considered for the analysis.

Letters

Some Consequences of Nonuniformity of Solar Wind Velocity

VIKRAM SARABHAI[1]

Laboratory for Nuclear Science
Massachusetts Institute of Technology, Cambridge, Massachusetts

Parker [1960] has derived the magnetic field configuration in interplanetary space that would result from a steady solar wind flowing radially with uniform velocity from all heliolongitudes. *Ahluwalia and Dessler* [1962] have pointed out that the Archimedes spiral formed by the field lines would corotate with the sun even though the plasma moves radially. In this note we examine conditions in interplanetary space along the solar equatorial plane that are likely to arise when the radial velocity of the solar wind is a function of solar longitude, a most likely possibility judging by localized zones of enhanced coronal temperatures and intensity of 5303°λ which are observed on the sun. Moreover, we consider some broad consequences of the growth and decay of regions of activity and enhanced wind velocity as a function of time. We show that the resulting two-dimensional model has attractive features relevant to the interpretation of several observed cosmic-ray time variations.

When we have a solar region B producing a wind of velocity v_B which differs from the velocity v_A due to the region A, we should expect two boundaries in interplanetary space. With passage of time after the creation of region B, these boundaries extend outward from the sun, tied, however, at all times to the points P and Q, which separate regions A and B on the rotating sun. In Figure 1 we sketch the resulting conditions for $v_A = 300$ km/sec and $v_B = 500$ km/sec after the regions are stabilized (i.e., $dv/dt = 0$ for v_A as well as for v_B). The angular width of region B is taken as 20°. The successive positions of the earth on zero through +5 days after P crosses the earth-sun line are shown in the figure. A step function change of velocity at P and Q is taken to illustrate an extreme case, which is not likely to arise in practice. What must obtain at P and Q are gradients $dv/d\theta$, where we measure solar longitude by the angle θ increasing from east to west on the solar disk as viewed from the earth. The rotation of the sun is also from east to west. It can be seen that the nature of the boundary is quite different, depending on whether $dv/d\theta$ is positive or negative. The creation of a hot region such as B would give a positive gradient at P and a negative one at Q. The reverse would result if B were a cold region. Interplanetary space around the sun may then be divided into four regions: (1) a region α_A, where field line configuration corresponds to the ideal case ($dv/d\theta = 0$) with velocity v_A of wind from A; (2) a region α_B, which corresponds to the ideal case with a wind velocity v_B; (3) a region β, which arises as a result of positive gradient $dv/d\theta$; (4) a region γ, which arises as a result of negative gradient $dv/d\theta$.

The regions α_A and α_B, corresponding to conditions on the sun where $dv/d\theta = 0$, have been extensively considered by Parker. Our main concern here is to understand regions β and γ. If $dv/d\theta$ is positive, as at P, we have slow plasma of velocity v_A following a fast plasma wind with velocity v_B. The distance between the trailing edge of the fast and the leading edge of the slow plasma, of course, increases, as with passage of time both edges move radially outward along each radius vector from the rotating sun. The interface generates in interplanetary space a cavity almost free of plasma and bounded by magnetic lines. In a real case the cavity would represent a region of reduced plasma density with edges that would get progressively more diffuse with increasing radial distance from the sun, owing to the temperature of the plasma.

The expanding cavity offers a mechanism for

[1] On leave of absence from the Physical Research Laboratory, Ahmedabad, India.

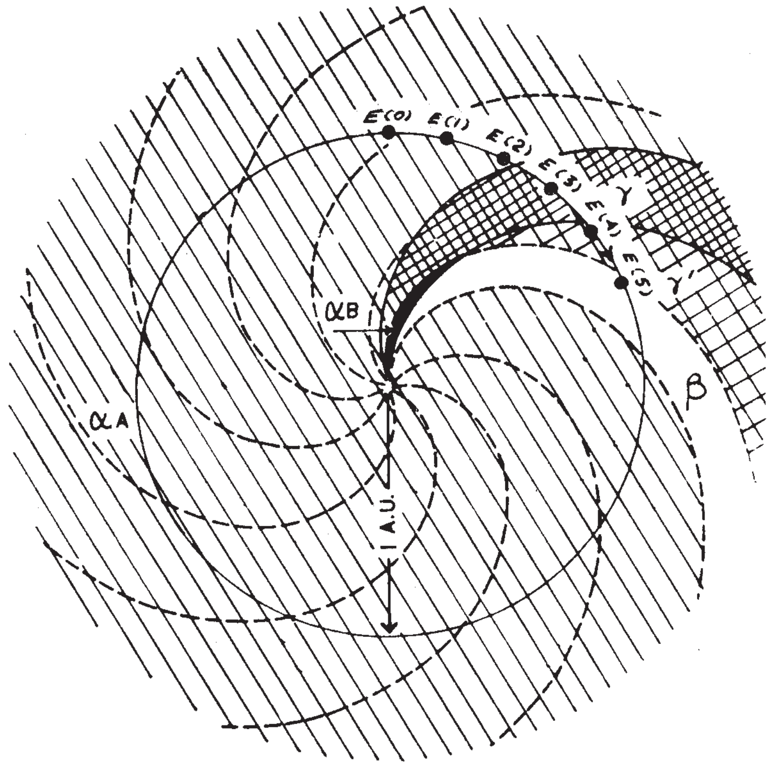

Fig. 1. Regions α_A, α_B, β (cavity), and γ (turbulent) formed in interplanetary space along the solar equatorial plane. The region γ' could be either a part of the cavity or an extension of γ, depending on the interaction of fast with slow plasma.

energy loss of cosmic rays contained in it through the Fermi process. Moreover, the newly created cavity with magnetic field at its edges is deficient in low-energy galactic cosmic rays that can leak into the cavity with passage of time. Thus, a reduced intensity of galactic cosmic rays would be observed at a point in interplanetary space when the cavity sweeps past it. With a decrease in the strength of the magnetic field with increasing distance from the sun, the effectiveness of the cavity in producing variations of cosmic-ray intensity would become negligible beyond a certain distance from the sun. Moreover, if $dv/d\theta$ continues to be positive at P after 27 days, as the sun completes one rotation, the same point in interplanetary space will experience a recurrent decrease. (It is well to realize that this does not involve a static cavity excluding cosmic rays for as long as 27 days. The cavity, being continuously created near the sun and moving radially, is never more than a few days old as it sweeps past the earth.) The sharpness of the decrease would depend on the magnitude of $dv/d\theta$, and there could be decreases that occur slowly as well as decreases that set in rapidly. The recovery of the intensity would depend on the size of the region over which $dv/d\theta$ remains positive. Moreover, increased magnitude of $dv/d\theta$, though it is still positive, would produce a decrease superposed on an earlier one. All the features are in fact observed in variations of cosmic-ray intensity, and it is suggested that long-lasting cosmic-ray storms represent the effects of blast waves as suggested by Parker with a cumulative effect originating from magnetic cavities due to positive velocity gradients whenever the earth is in one of them. The cavities by themselves are responsible for the so-called 27-day variations of galactic intensity.

When a solar region grows or decays and $dv_B/dt \neq 0$, the effect of the cavity could be enhanced. The implications of this would be treated separately. The presence of solar cosmic-ray events within Forbush decreases would result from the production of flares in local hot regions of high density where the magnetic field would be temporarily collapsing. The hot region would earlier have generated a cavity.

There is an important difference between the magnetic cavity proposed here and the magnetic bottle suggested by Gold, even though both provide configurations of magnetic fields in interplanetary space that have some similarities. The cavity occurs as a result of normal temperature gradients that can last over long periods without involving explosive transport of plasma and fields as in a bottle. The cavity, therefore, offers a natural means of furnishing the long time constants and cumulative effects that are seen in many decreases and are difficult to understand if the magetic bottle was to be pinched off near the sun in a period of 3 to 5 days. It is not suggested here that the bottle cannot sometimes occur, but the cavity appears to provide a more plausible model for many observed effects. A good test of the cavity could be provided by observing the geocentric distance of the termination of the geomagnetic field in space along the equatorial plane. According to the present interpretation, the second phase of a cosmic-ray storm should involve a termination at a greater distance than is normally seen.

The boundary at Q where $dv/d\theta$ is negative is more difficult to understand, since, along it, fast plasma runs into slow plasma released earlier along the same radial direction. It seems clear, on general considerations, that along the boundary we would have turbulent regions of magnetic field and irregularities in plasma density. Both these must be responsible for exciting geomagnetic disturbances when the earth is in a region γ generated from areas on the sun where $dv/d\theta$ is negative.[2] On account of the boundary, parts of interplanetary space would be studded with inhomogeneity of plasma and with scattering centers, moving radially outward. The boundaries of this region cannot exceed the limits shown in Figure 1, which correspond to plasma from Q originating with velocity v_A in the one case and velocity v_B in the other.

The observed preponderance of the occurrence of flares on the west disk of the sun associated with some types of solar cosmic-ray events is generally explained through postulating the existence of spiraling magnetic lines of force connecting the points in the western hemisphere of the sun to the earth. The present model does not alter the required spiraling magnetic field configuration in regions α_A and α_B. But, since a flare normally occurs near an active region on the sun, a velocity gradient in the outward solar wind may be expected to be present in its vicinity. For a hot region, over which the solar wind velocity is increased, the conditions could be as shown in Figure 1. For the particular values of velocity chosen, it is seen that a flare could occur up to solar longitude 26°W while the earth is in α_A. For flares occurring at heliolongitudes 26°W to 70°W, the earth is in region γ or γ' as at points $E(3)$, $E(4)$, and $E(5)$ in the figure. There would then be many magnetic scattering centers in the path of the solar cosmic rays reaching the earth, obliterating the initial anisotropy of the radiation. This may be the reason why some solar cosmic-ray events due to flares occurring on the western hemisphere do not exhibit impact zones even in the early stages of the event.

Acknowledgments. I am grateful to A. Dessler and B. Gottlieb for comments on the preparation of the manuscript.

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(Received October 10, 1962.)

[2] Dessler has pointed out that turbulence in the wind can produce geomagnetic disturbance.

INTENSITY OF GREEN CORONAL EMISSION AND THE VELOCITY OF PLASMA WIND

By

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Physical Research Laboratory, Ahmedabad - 9,
India.

1. Solar indices of plasma wind velocity

On the assumption that solar wind velocity $v = f(\lambda)$ where λ is the intensity of the 5303°A coronal emission, a study is made to verify the basic validity of the model of interplanetary magnetic fields arising from longitudinal velocity gradients and to time rate of change of solar wind velocity as suggested by Sarabhai[1,2]. The intensity of the green coronal emission λ is regularly measured on a day to day basis on the sun's east and west limbs by a number of solar observatories. A typical solar chart of Kiepenheuer is shown on the top part of Fig. 1.

For studying sun-earth relationships connected with the solar wind, the plane of the ecliptic should be of major significance. We therefore confine our attention to the mean value of coronal intensity at solar latitudes 0 and $\pm$ 5°. For day n we designate this "equatorial" intensity as λ_n^{oE} and λ_n^{ow} on the east and west limbs respectively.

The region λ_{n-7}^{oE} seen on the east limb is at central meridian on day n and is seen again as λ_{n+7}^{ow} on the west limb. To concentrate attention on individual meridians of the sun which cross central meridian on successive days, we construct a revised chart of the sun which now shows on the east limb the feature λ^{oE}_{n-7} , on the west limb the feature λ^{ow}_{n+7} superposed on the sketch of the disc for the n^{th} day. We call this a time dependent representation (T.D.R) of coronal conditions over meridian at centre on day n. **The bottom** part of Fig. 1 shows a typical T.D.R.

We next define the following for the day n.

$$\bar{\lambda}^{o}_{n} = \lambda^{oE}_{n-7} + \lambda^{ow}_{n+7}$$

$$\Delta \lambda^{o}_{n} = \lambda^{ow}_{n+7} - \lambda^{oE}_{n-7}$$

$$\frac{\partial \lambda^{o}_{n}}{\partial \theta} = \bar{\lambda}^{o}_{n} - \bar{\lambda}^{o}_{n+1}$$

$\frac{\partial \lambda^{o}_{n}}{\partial \theta}$ is a measure of the longitudinal gradient due to long lasting regions of intense coronal intensity. $\Delta \lambda^{o}_{n}$ gives the change of intensity of an individual region in crossing from east to west limb. Thus, in terms of the model proposed by Sarabhai and the assumption $v=f(\lambda)$, we can associate $\Delta\lambda < 0$ with $\frac{dv}{dt} < 0$ and hence the creation of a cavity in interplanetary space. We can, moreover, associate a shock front and a turbulent region with $\frac{\partial \lambda}{\partial \theta} < 0$. In the present paper we proceed to demonstrate the occurrence of the predicted effects in cosmic rays and in geomagnetism.

2. Cosmic ray effects of cavities.

A long lasting Forbush decrease which occured on September 30, 1961 is characterised by initially a rapid recovery of cosmic ray intensity which is however arrested on October 5, 1961. Thereafter it takes another eight days before the intensity returns to the level before the storm. The T.D.R. charts shown in Fig. 2 reveal that the regions at central meridian from September 29 to October 1, 1961 underwent a marked decrease of coronal intensity ($\Delta\lambda \ll 0$) indicative of $\frac{dv}{dt} \ll 0$, a condition which would give rise to a cavity in interplanetary space. When the earth is in the cavity, the intensity of galactic cosmic rays is depressed, but as cosmic ray intensity slowly returns to normal, there is high K_p due to the impact of the enhanced plasma wind on the magnetosphere.

In Fig. 3 we show the conditions on the sun corresponding to the small decrease of cosmic ray intensity which occurred on October 27, 1961, 27 days later. It differs from its predecessor since complete recovery to normal intensity occurs in five days. The absence of a long lasting decrease is associated here with no significant change of coronal intensity of regions crossing central meridian.

The solar coronal indices connected with 33 long lasting Forbush decreases during 1960-1962 have been studied on a statistical basis using Chree analysis. The results are shown in Fig.4.

The onset of a Forbush decrease when the intensity is depressed for more than seven days is taken as epoch. $\bar{\lambda}$ increases through epoch and reaches a maximum value on +5 day indicating that the events are seen on the earth some days after a bright coronal region has crossed central meridian. Moreover, $\Delta\lambda$ is predominantly negative during the period. Since $\Delta\lambda$ is derived from observations separated by 14 days, the position of the region when the decrease of coronal intensity occurred is of course undeterminate. However, we confirm here that long lasting Forbush decreases are associated with regions with $\Delta\lambda << 0$ (i.e. $\frac{dv}{dt} << 0$) which could produce time dependent cavities.

3. <u>Geomagnetic disturbances related to turbulent conditions of interplanetary plasma</u>

The solar coronal indices related to geomagnetically disturbed and quiet days are studied using Chree analysis. The results are shown in Fig. 5. Days with high K_p ($\geqslant$ 25) are associated with c.m.p. of regions with brighter 5303° intensity than days with low K_p ($\leqslant$ 10). Moreover, about a day prior to a high K_p epoch, a bright region crosses central meridian which has $\frac{\partial\lambda}{\partial\theta} << 0$, a condition which would give rise to a turbulent region in interplanetary space with a shock front.

We can demonstrate the same relation starting with epochs based on solar indices as follows:-

1) $\overline{\lambda} \leq 10$ and $\overline{\lambda} \geq 20$

2) $\Delta\lambda \leq -4$ and $\Delta\lambda \geq +4$

3) $\frac{\partial\lambda}{\partial\theta} \leq -4$ and $\frac{\partial\lambda}{\partial\theta} \geq +4$

For reasons which we do not elaborate here, we neglect the first of a pair of successive epochs which occur in a time interval of less than 10 days. Chree analysis of K_p with these epochs is shown in Fig. 6. It demonstrates first, that high K_p is associated with higher $\overline{\lambda}$ than low K_p; second, that high K_p occurs two to three days after c.m.p. of solar regions which could produce turbulent plasma (i.e. when $\Delta\lambda \geq 4$ or $\frac{\partial\lambda}{\partial\theta} \leq -4$); and third, that following $\frac{\partial\lambda}{\partial\theta} \geq +4$ we have low K_p as the earth enters a cavity. The geomagnetic effect of a cavity related to c.m.p. of a solar region with $\Delta\lambda \leq -4$ is similar but less striking than that for regions with $\frac{\partial\lambda}{\partial\theta} \geq +4$.

The self consistency of the results supports the basic suggestions that:

1) Solar wind velocity over regions of high intensity of 5303°A is greater than that over regions of low intensity.

2) Magnetic cavities and turbulent regions are formed in interplanetary space in consequence of the non-uniformity of the solar wind velocity.

3) Cosmic ray intensity measured on the earth and the planetary index of geomagnetic disturbance are to

some extent related to the earth being in one or the other of these regions in interplanetary space.

We are grateful to the Department of Atomic Energy, Government of India for financial assistance.

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Captions for figures

Fig. 1 A typical solar chart of Keipenheuer and the corresponding T.D.R. representation.

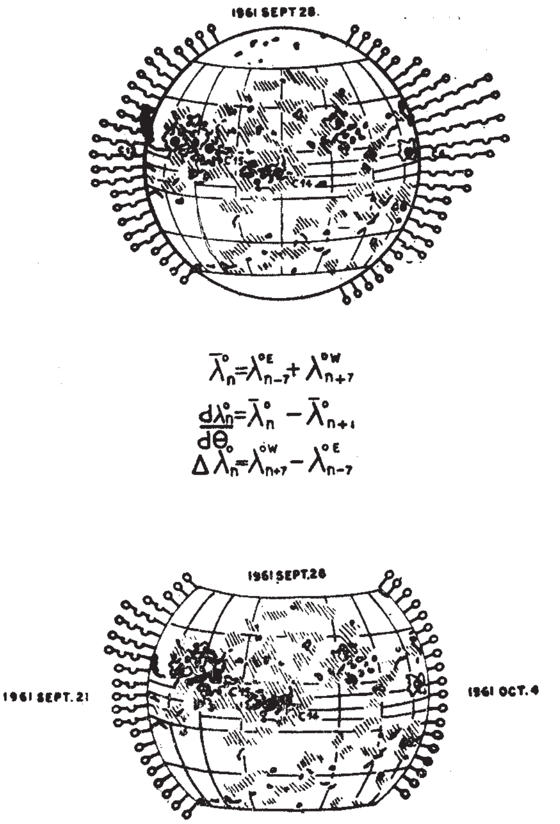
Fig. 2 T.D.R. charts, Deep River neutron intensity and K_p values for the Forbush decrease of September 30, 1961.

Fig. 3 T.D.R. charts, Deep River neutron intensity and K_p values for the Forbush decrease of October 27, 1961.

Fig. 4 Chree analysis results of cosmic ray intensity, $\bar{\lambda}$, $\Delta\lambda$ and K_p for 33 long lasting Forbush decreases during 1960-1962.

Fig. 5 Chree analysis results of $\bar{\lambda}$ and $\frac{\partial\lambda}{\partial\theta}$ for the two sets of epochs $K_p \leqslant 10$ and $K_p \geqslant 25$ for the period 1960-1962.

Fig. 6 Chree analysis results of K_p for $\bar{\lambda} \leqslant 10$, $\bar{\lambda} \geqslant 20$, $\Delta\lambda \leqslant -4$, $\Delta\lambda \geqslant +4$, $\frac{\partial\lambda}{\partial\theta} \leqslant -4$ and $\frac{\partial\lambda}{\partial\theta} \geqslant +4$ epochs during the period 1960-1962.



$$\bar{\lambda}^{\circ}_{n}=\lambda^{\circ E}_{n-7}+\lambda^{\circ W}_{n+7}$$

$$\frac{d\lambda^{\circ}_{n}}{d\theta_{\circ}}=\bar{\lambda}^{\circ}_{n}-\bar{\lambda}^{\circ}_{n+1}$$

$$\Delta\lambda_{n}=\lambda^{\circ W}_{n+7}-\lambda^{\circ E}_{n-7}$$

Fig.1

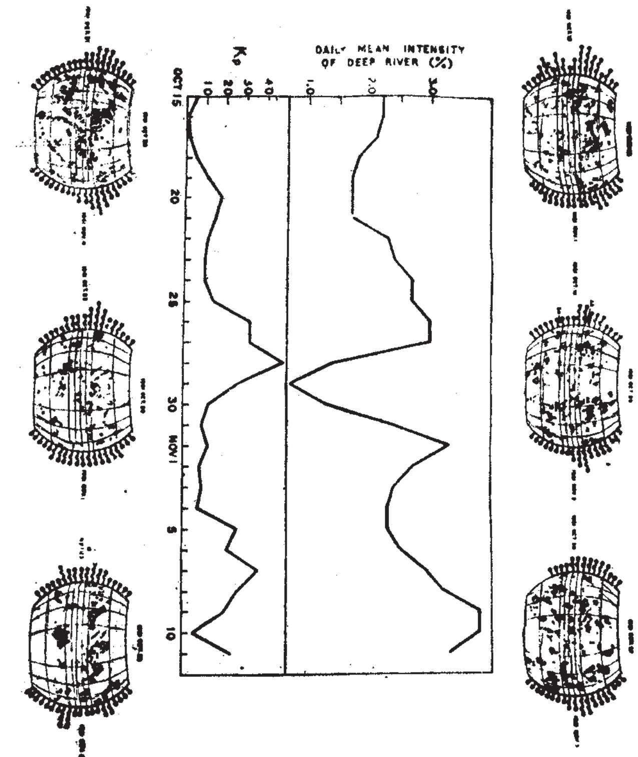


Fig.2

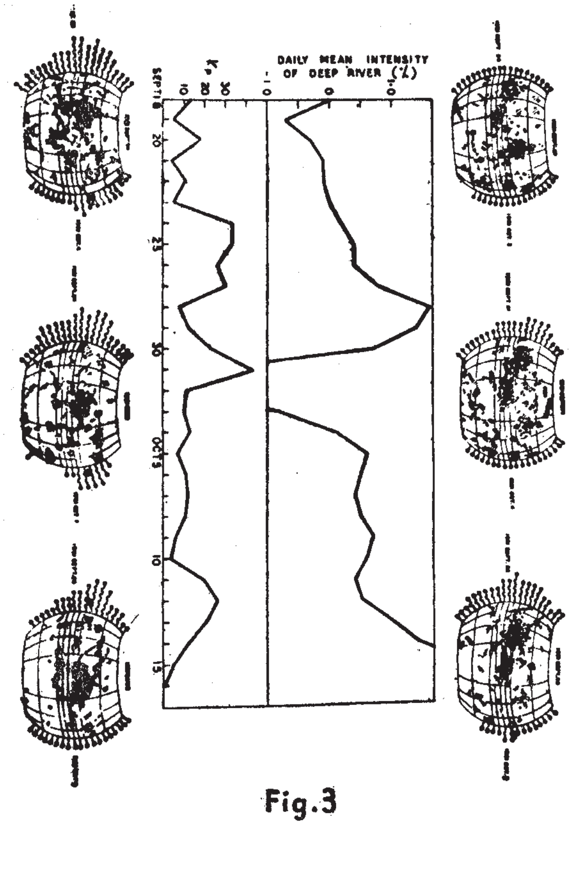
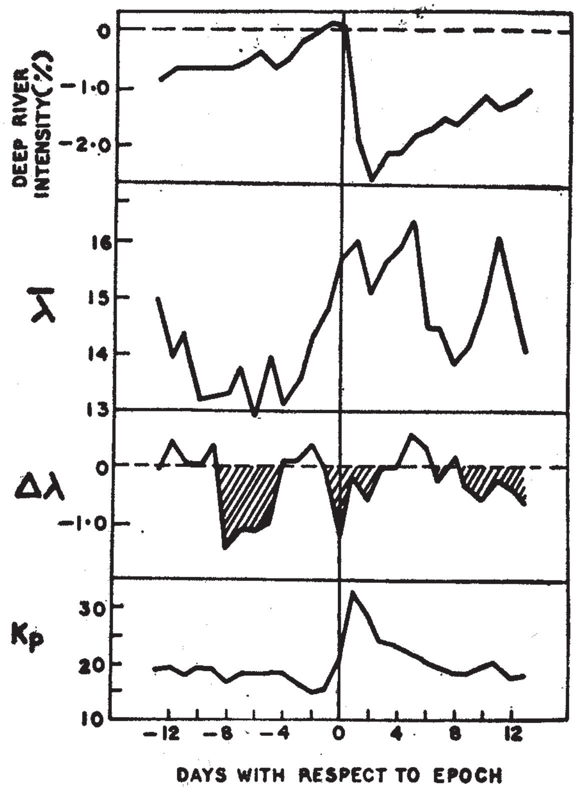
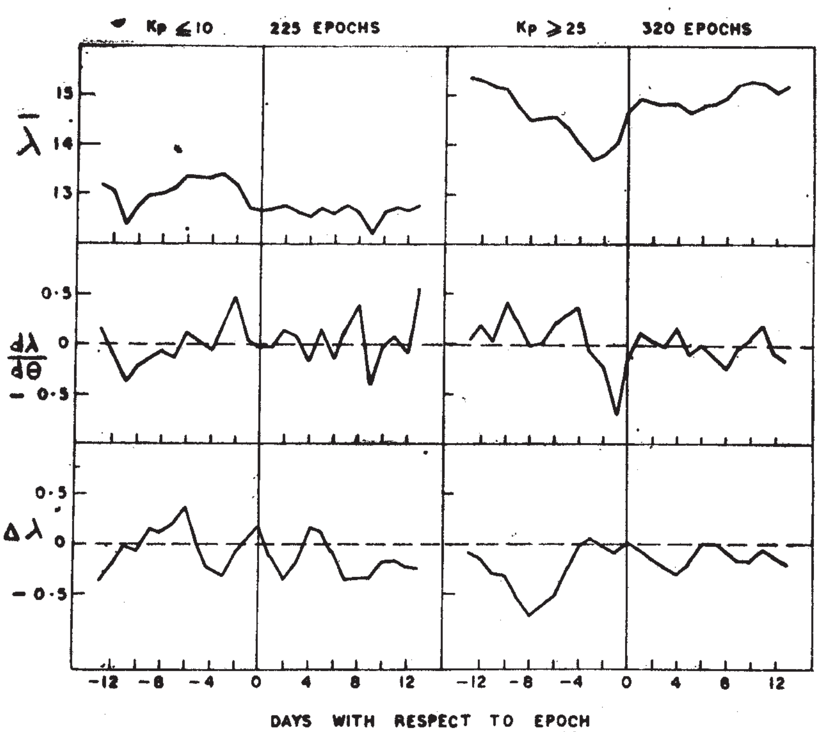


Fig.3



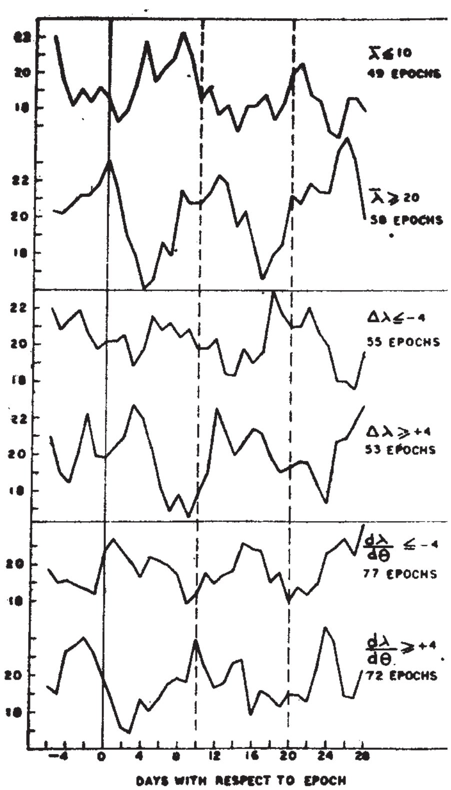
33 LONG LASTING FORBUSH DECREASES

Fig. 4



CHREE ANALYSIS OF $\bar{\lambda}$ $\Delta\lambda$ AND $\frac{d\lambda}{d\theta}$ FOR 1960-62

Fig. 5



Kp CHREE ANALYSIS 1960-62

Fig. 6

MODULATION OF GALACTIC COSMIC RAYS BY INTERPLANETARY PLASMA

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We **derive** by the method of best fit the direction and energy spectrum of the anisotropy outside the influence of the geomagnetic field on individual days during the period 1958 to 1962. We use for this purpose the amplitudes and phases of the first and second harmonics of the daily variation observed by the Huancayo neutron monitor (H_N), the Churchill neutron monitor (C_N) and the Churchill cubical meson telescope (C_C). The method is of general applicability and the error of determination would be reduced as larger number of stations are taken and as short time U.T. variations are small.

The effect on the daily variation of cosmic rays due to deflection in the geomagnetic field and the diffusion in the atmosphere, is a reduction in the amplitudes of the harmonic coefficients and a shift in the time of maximum to earlier hours. The factors by which the amplitudes of the first and second harmonic coefficients are reduced, are α_1 and α_2. The shifts in the time of maxima are τ_1 and τ_2.

From the observed values of the first and second harmonic coefficients of these stations, we calculate the harmonic components of the primary anisotropy assuming a particular value for the exponent of the spectrum of daily variation and different values of E_{min} below which the source strength is zero. The calculation is done by rotating to later hours the observed first and second harmonic factors by τ_1 and τ_2 and increasing their amplitudes by $1/\alpha_1$ and $1/\alpha_2$. In the absence of statistical variation, the calculated parameters of the primary anisotropy from each one of the stations will be identical for the correct spectrum of variation defined by the exponent and E_{min}. If we take into account statistical variation, the quantity

$$S^2 = \sum_{i=1}^{n} \left\{ [(\bar{A}_1 - A_{1i})^2 + (\bar{B}_1 - B_{1i})^2]/\sigma_{1i}^2 + [(\bar{A}_2 - A_{2i})^2 + (\bar{B}_2 - B_{2i})^2]/\sigma_{2i}^2 \right\}$$

becomes a minimum for the optimum spectrum. Here A_{1i}, B_{1i} represent the projections of the diurnal component of the primary anisotropy on the 0 hr. axis and 6 hr. axis respectively. Similarly A_{2i}, B_{2i} denote the components in the 0 hr. direction and 3 hr. direction for the semidiurnal component. $\bar{A}_1$, $\bar{B}_1$ represent the mean values of all the stations and σ_i denotes the standard error.

In processing the data, the long term trend is removed from the pressure corrected bihourly cosmic ray intensity by moving averages of successive 12 bihourly values. The optimum spectrum is determined on each day using an electronic computor.

--3--

We have obtained the best estimates of the spectrum of variation during the year 1958 to 1962 for all days on which data are simultaneously available from the three instruments. The spectra which we have considered in our preliminary study have exponents which can range in value from +.4 to -1.0 in increments of .2. E_{min} has values 0, 6 and 10 BeV. The results are shown in the following table.

The column marked 'positive' indicates percent occurrence of days in each year for which the exponent is +.4. The column marked '0' indicates percent days for which the exponent is +.2, 0, -.2, -.4. The column marked negative indicates percent days for which the exponent is -.6, -.8, -1.0.

The interesting features of the table are (1) percent frequency for zero exponent is always less than for positive and negative exponents, only 10 to 15% of the days have an exponent which is the same as for the galactic spectrum. The result reported by Rao, McCracken and Venkatesan[1] that the exponent is zero and by Pomerantz, Duggal and Nagashima[2] that the exponent is -.5 with E_{min} of 6 BeV arise from using time-averaged data and does not reflect true conditions on a majority of individual days. (2). The frequency of days with positive spectrum increases from 26% in the year 1958 to 56% in 1961 (3). The frequency of days with negative exponent of the spectrum decreases from 1958 to 1961. However, in 1962 a very dramatic change is seen to occur. Almost all days have an exponent which is negative.

A difficulty in the present analysis has been due to data being not available simultaneously for all three instruments for a large number of days in 1961-62. The conclusion which we have reached for the distribution in 1961-62 must be taken, therefore, as tentative for the time being. We are attempting to verify these calculations with data from an independent group of instruments.

An interesting observation is that the value of S^2 which indicates the goodness of fit to an assumed spectrum is smaller for geomagnetically quiet days when K_p is less than 9 than for other days. This would be consistent with a local source of daily variation on geomagnetically disturbed days as suggested by Rao & Sarabhai[3].

The present analysis indicates a new approach to a quantitative determination of the parameters of the anisotropy of galactic intensity on individual days. It fully bears out the results of analysis of Rao and Sarabhai[4], and reveals clearly the error of interpretation that can result from consideration of time-averaged data. Encouraged by the results of the pilot study which is reported here, we are currently engaged in a more rigorous analysis using data from other neutron and meson detectors and with a wider range of assumed characteristics of primary anisotropy.

ACKNOWLEDGEMENT

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% FREQUENCY OF OCCURENCE OF DAYS WITH DIFFERENT SPECTRA

1958, Number of Days 166
Spectrum

E_{min} BeV	Positive	Zero	Negative	
0	3	20	25	48
6	5	1	14	20
10	18	3	10	31
	26	24	49	

1961, Number of Days 73
Spectrum

	Positive	Zero	Negative	
0	9	4	28	41
6	3	3	3	9
10	43	0	7	50
	55	7	38	

1959, Number of Days 178
Spectrum

	Positive	Zero	Negative	
0	6	13	25	44
6	6	3	5	14
10	31	1	11	43
	43	17	41	

1962, Number of Days 40
Spectrum

	Positive	Zero	Negative	
0	0	2.5	77.7	80
6	2.5	0	7.5	10
10	0	7.5	2.5	10
	2.5	10.0	87.5	

1960, Number of Days 208
Spectrum

	Positive	Zero	Negative	
0	7	12	23	42
6	5	1	7	13
10	34	2	9	45
	46	15	39	

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MODULATION OF GALACTIC COSMIC RAYS IN THE SOLAR SYSTEM

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Since Kyoto, there have been advances along several directions in our understanding of cosmic ray intensity in the solar system. These arise from new experimental capabilities and methods of dealing with data, and from fresh insights concerning plasma and magnetic fields in interplanetary space We have measurements of heavy primaries in balloons and in satellites and of cosmic ray intensity outside the boundary of the magnetosphere; high counting rate instruments permitting study of the cosmic ray anisotropy on each day; use of daily variation of meson intensity and the application of quantitative methods to study the anisotropy. Moreover, there is now recognition of the implications of the rotation of the sun and of nonuniformity of solar wind velocity to plasma in interplanetary space.

1. Measurements with balloons, satellites and space probes

We have first the measurements of the spectrum and intensity of heavy primaries. From work of Vogt and Meyers[1] and lately of Fichtel, Guss, Stevenson and Waddington[2] we have evidence that the proton flux in the vicinity of 0.5 GV/c rigidity has decreased with decreasing solar activity whereas the proton flux above 1 GV/c shows an inverse correlation with solar activity. It has been suggested that a solar component with rigidity upto 0.5 GV/c was present in 1960. An alternative to this conclusion would require a modulatio process which acts differently on protons and helium nuclei above and below approximately 1 GV/c.

An interesting experiment has been performed on the Ariel satellite by Elliot and his co-workers[3]. This shows a change of slope of the rigidity spetrcum of primaries with $Z \geqslant 6$ at 8 GV/c, but at the moment the interpretation of the result is not clear.

A major experimental effort has been involved in the measurement of cosmic ray intensity outside the boundary of the magnetosphere in space-craft. This has conclusively demonstrated that there are many solar particle events associated with flares on the sun. F. McDonald and his collaborators[4] have shown that the measured flux is modulated, suggestive of its being carried in packets of plasma of the scale length of approximately 0.02 to 0.05 A.U. Moreover protons of energy greater than 3 MeV appear to be carried in streams of plasma corotating with the sun. A most intere ing result of the study is the observation of velocity dependent travel times of solar protons with appreciable delays which indicate centres of diffusion in the region between the sun and the earth.

2. Study of the quantitative aspects of the anisotropy of cosmic rays

The work which was started by Brunberg[5] and carried forward by Lapointe and Rose[6] as well as by McCracken[7] concerning the cones of acceptance of solar particle radiation has now been extended to the energy range of galactic cosmic rays, and has proved very valuable in understanding the daily variation of cosmic rays observed with instruments which measure secondary components and are situated at different points on the earth. This has led to a quantitative study of the spectrum of variation, the magnitude and the spatial configuration of the anisotropy of galactic intensity. Pomerantz, Duggal and Nagashima[8] and more lately McCracken, Rao and Venkatesan[9] have considered the world-wide distribution of the annual mean diurnal component of the daily variation observed by a net-work of neutron monitor stations. They have come to the conclusion that the spectrum of variation of the anisotropy has an exponent close to zero. However, recent work by Rao and myself[10] using the data of the high counting rate MIT meson detector and the Deep River neutron monitor has shown that real conditions are very different from what this average result suggests at first sight. The high counting rate of the instruments has permitted a quantitative analysis of the anisotropy to be made on a day to day basis. The analysis reveals that even though the time of maximum observed at MIT and at Deep River is very well correlated, the ratio of amplitudes has a wide dispersion. This can only be interpreted on the basis of a day to day change of energy spectrum of variation of the anisotropy. On some days, the ratio is consistent with an exponent of the spectrum which is zero, but on many other days the exponent must have a value close to -1.0. Moreover the magnitude as well as the direction of the anisotropy alter from day to day. The study has demonstrated that on a majority of days, the daily variation of meson intensity corrected only for the barometric effect can be related without serious error to the anisotropy of primary cosmic rays.

3. Changes of energy spectrum of variation of anisotropy of galactic cosmic rays

Several theories have been proposed for explaining anisotropy that could be produced by the motion of plasma and magnetic fields in interplanetary space. The models can be differentiated in terms of the type of change which each produces in the energy spectrum of the galactic cosmic ray intensity. First, we can have a process such as the one suggested by Alfven, Dorman[11] and Nagashima (referred to as ADN), where we have an energy spectrum of variation with an exponent -1.0 which operates for all primary energies above E_{min} (of the order of a few GV). Second, we can have a process such as the one suggested by Ahluwalia and Dessler[12] (referred to as AD), where the exponent is zero for those cosmic rays which partake in a co-rotation with the sun. There is an E_{max} corresponding to several tens of GV in the AD model. For energies above E_{max} conditions are similar to the ADN model.

In a separate communication to be presented at the present Conference by Subramanian and me[13], we have calculated the daily variation as would be observed by various detectors on the surface of the earth due to anisotropy with energy spectrum related to the two different models. We have next considered the neutron intensity at Huancayo, Neutron and meson intensity at Kodaikanal and neutron and meson intensity at Churchill. The use of data from the equatorial stations of Huancayo and Kodaikanal in relation to data from Churchill is very advantageous since, as shown in Figure 1, the time of maximum observed at an equatorial station with respect to the time of maximum observed at a high latitude station is itself a sensitive function of the exponent of the spectrum. For a comparative study of conditions over a period of five years from 1958 to 1962, we have to be content with data from standard IGY instruments with low counting rates. Initially, we consider histograms of the characteristics of the daily variation on individual days in separate years. The data from Churchill and

Huancayo indicate that with decreasing solar activity from 1958 to 1962,

(a) the time of maximum in Figure 2 shifts to earlier hours only at the equatorial station, but not at stations at high latitudes,

(b) the ratio of the peak to peak amplitudes in Figure 3 becomes smaller,

(c) the peak to peak amplitude, in Figure 4, decreases appreciably for Huancayo neutrons, less so for Churchill mesons but remains unchanged for Churchill neutrons, and

(d) the changes indicated above occur most dramatically during 1961 and 1962, while conditions from 1958 to 1961 are pretty uniform.

The evidence clearly indicates that in any one year the anisotropy has a large day to day variability of the spectrum of variation, of its position and of its magnitude. Moreover, with diminishing solar activity, particularly for 1961, the exponent of the spectrum on a large number of days becomes -.8 or -1.0, i.e. the slope increases just as the slope of the galactic spectrum increases with diminishing solar activity. The most probable direction and the magnitude of the anisotropy in all five years are nevertheless approximately constant.

A further analysis has been conducted by Subramanian and me where we consider different models for the energy spectrum of variation and, using a digital computer, the model which fits best on each day the magnitude and the time of maximum of the diurnal and the semidiurnal components of all stations is chosen. The results of this investigation which are reported separately at this Conference fully confirm the conclusions drawn from the analysis of the histograms.

My study with Rao reveals that days with an anisotropy having an exponent -1.0 and a zero exponent occur during the latter part of 1961 in bunches and that they have very distinctive forms of the daily variation associated with them. Indeed through this we derive experimental justification for the hypothesis that interplanetary space can be deemed to be in one or other of a few states broadly specified in terms of plasma and magnetic field conditions which I describe later.

4. <u>The nature of the anisotropy and its physical interpretation</u>

It has been customary in the past for most investigators to consider only the diurnal component of the daily variation and to interpret the time of maximum as corresponding to a direction in which a virtual source could be deemed to lie. Rao and I have, however, drawn attention to the striking fact demonstrated in Figure 5 that the interval between the occurrence of the maximum and occurrence of the minimum on any individual day is not 12 hours, but lies between 7 to 9 hours on a majority of days. The result has now been fully confirmed by more extensive data analysed by Subramanian and me for daily variation observed in Huancayo neutrons, in Churchill mesons and in Churchill neutrons. Figure 6 indicates the histograms of $T_{max} - T_{min}$ for five years for all three detectors. $T_{max} - T_{min} \approx$ 7 to 9 hours is a consistent feature of the primary anisotropy in all years. Thus the results do not fit a simple picture of an anisotropy which can be represented by a virtual source with a virtual sink 180^{o} removed from it in the plane of the ecliptic. Figure 7 illustrates the manner in which we may be able to explain the observations concerning T_{max} and T_{min}. There is clearly the need to have at least two processes which produce anisotropy on most days, giving rise to a virtual source and a sink which are about 120^{o} displaced from each other in the plane of the ecliptic.

Figure 8 indicates the sequence of changes in T_{max} and T_{min} which accompanied the cosmic ray storm of 30th September 1961. The two sequences are similar but displaced in time. We have evidence in our data of a change which was observed in T_{max} several days before the onset of the Forbush decrease and must therefore be interpreted as due to an advancing co-rotating boundary of a shock transition. The change in T_{min} occurs only after the boundary overtakes the earth and produces a cosmic ray storm accompanied by a geomagnetic disturbance. Thus our evidence would indicate that not all cosmic ray storms are due to blast waves in interplanetary plasma moving rapidly outwards after a sudden expansion of the corona.

5. Plasma and magnetic fields in interplanetary space

There have been since Kyoto some significant advances in our understanding of the movements of plasma and magnetic fields in interplanetary space. We have firstly the model of Ahluwalia and Dessler which points out that if solar wind blows outwards in a smooth uniform manner carrying with it magnetic fields in the form of an Archimedes spiral, we would have an anisotropy with a maximum in the direction perpendicular to the garden hose angle. They have suggested that the velocity v_s of the wind could be deduced from the time of maximum of the diurnal variation through the relation

$$v_s = w\ r\ \tan \chi$$

where $12 + \frac{\chi}{15}$ is the time of maximum, w is the angular velocity of the sun and r is the heliocentric distance from the sun. Moreover, they have also suggested that the amplitude of the daily variation would bear a definite relationship with the time of maximum and the velocity of the solar wind.

Some experimental workers have recently attempted to test the validity of these predictions and have comt to the disheartening conclusion that the predictions cannot be confirmed. The real situation is different. Ahluwalia and Dessler have realised that the process would depend on the magnitude of the magnetic field which is carried with the plasma and on the scale length of the tube of force which is involved. They use in fact an upper limit E_{max} for the energy of cosmic ray primaries that could be effected by the process. Only when E_{max} is approximately constant, we can expect to observe a direct relationship between solar wind velocity, the time of the maximum and the amplitude. In real conditions, it is not surprising that variability of E_{max} further complicated by the fact that solar plasma in general does not have ideal uniformity makes impossible a verification of the predicted relationships. However, Rao and I have demonstrated that when conditions of interplanetary space correspond most closely to the ideal case as demonstrated by very low planetary index of geomagnetic disturbance and negligible day to day fluctuations of cosmic ray intensity, we do in fact have an anisotropy which has a spectrum and other characteristics which are consistent with the Ahluwalia and Dessler model.

A second advance has taken place from consideration of the nonuniformity of solar wind velocity due to longitudinal gradients of activity in the solar corona as well as the time rate of change of activity. Subsequent to the first consideration of this problem by me[14], many interesting further aspects have come to be appreciated. I shall briefly summarise the model as we now see it.

A magnetic cavity (termed β region) is formed in interplanetary space either when we have in the solar corona an active zone producing a longitudinal gradient $\frac{\partial V}{\partial \theta} > 0$ or when we have a time dependent activity producing $\frac{\partial V}{\partial t} < 0$. For the sake of differentiating between these two modes of origin, we refer to the cavities as β_θ and β_t respectively. Similarly, we can have turbulent regions (γ_θ) due to a longitudinal gradient or (γ_t) produced by time dependent activity. Parker (private communication) has pointed out that a β_θ cavity, which can be considered to be a stationary hole in a frame of reference fixed to the sun, would produce small cosmic ray effect as compared to a time dependent β_t cavity. The cosmic ray effect in a β_θ cavity arises from a reflection of cosmic ray particles from their mirror points in a rotating trailing spiral which leads to a deceleration. However, as far as the geomagnetic effects are concerned, the two types of cavities act in the same way. When the earth is in **either** of the cavities, we should have low values of K_p.

A γ_t region would be expected to produce a blast wave of the type already considered by Parker, but a γ_θ region would have a shock transition as an envelope of the turbulent region at its leading edge. Both can be expected to produce cosmic ray storms and geomagnetic disturbance as they strike the earth, a γ_t region moving radially outwards and a γ_θ region overtaking the earth from West to East looking along the sun earth direction. Geomagnetic disturbance can also be produced as the earth comes out of a cavity in which cosmic ray intensity is depressed. Thus, we can have high geomagnetic disturbance either with decreasing cosmic ray intensity as during the onset of a storm or with increasing cosmic ray intensity as during the final stage of recovery of a long lasting Forbush decrease.

Pai and I have recently found experimental confirmation of some of the consequences of this model. In a report communicated separately to the Conference, we use evidence derived from solar green coronal intensity observed at the limbs near the equator of the sun and establish relationships of longitudinal gradients and time dependent changes of the intensity with geomagnetic disturbances and long lasting Forbush decreases.

Some interesting new features of interplanetary plasma become obvious if we consider the presence of many zones on the sun with activity which results in nonuniformity of solar wind. In Figure 9 the consequences of two zones of activity have been traced. We have the cavity due to zone A pinched off by the turbulent region from zone B. If there are many such zones along the equator of the sun, we should expect turbulent clouds coasting outwards completely enveloping the solar system beyond a certain distance depending on the average angular distance between zones of activity. At sunspot maximum when the average angular distance is small due to the large number of zones, the shell would contract and it may indeed be less than 1 A.U. from the sun. The 27 day recurrence of geomagnetic disturbance would then be hard to discover even though there might be high degree of geomagnetic disturbance. Similarly, one would not expect during such a period to observe solar cosmic rays guided along connecting magnetic lines of force from the sun to the general vicinity of the earth. It has indeed been pointed out that at the maximum of solar activity, no solar cosmic ray events have been observed.

In general, interplanetary space must be populated by packets of plasma clouds often stringed on a deformed spiral magnetic field. The clouds are formed by the interaction of fast plasma blowing behind slow, producing shears as well as compression during transit through interplanetary space. At sunspot minimum or when α and β regions extend like tongues from the sun, we may expect conditions to be such that connecting lines of force are present in interplanetary space between the sun and the general vicinity of the earth. Experimental support for the model is furnished by:-

(1) the variability of the interplanetary magnetic field measured outside the magnetosphere;

(2) the inhomogeneity of plasma density and the variability of apparent wind velocity measured by plasma probes;

(3) the modulation of solar particle events measured in interplanetary space which suggests their being contained in packets of plasma;

(4) the velocity dependent times of arrival of solar particles which suggest a random walk diffusion in plasma clouds;

(5) the long period fluctuations of geomagnetic field during storms and

(6) the apparent discrepancy in the measured velocity of plasma and the transit time from the sun to the earth.

The experimental evidence seems to indicate a scale length of inhomogeneities of the order of 0.01 to 0.05 A.U. in the region between the sun and the earth.

6. Conclusions

We might, then, summarise that interplanetary space can have the following characteristics:-

(1) It can have packets of turbulent plasma moving radially outwards with a velocity diminished with respect to the initial velocity of the fast wind. Turbulence is set up mainly by the interaction of the fast and slow plasma streams. The clouds would modulate cosmic rays, which come inwards into the solar system, by the Fermi effect. Those packets which pass by the earth would disturb K_p and cosmic rays, measured on the earth.

(2) The packets interrupt the connecting lines of force between the sun and the general vicinity of the earth except when there is uniform solar wind velocity over extended regions or a cavity which clears interplanetary space.

(3) Shock transitions related to long lasting zones of activity producing longitudinal gradients of plasma wind velocity overtake the earth and produce cosmic ray storms and geomagnetic

disturbances just as blast waves produced by the sudden heating of the corona.

(4) α and β regions occur only up to a certain distance from the sun, beyond which through interference with other plasma we have only turbulent γ regions. The distance should vary with sunspot cycle, being closer to the sun at a time of maximum activity near the solar equator.

The modulation of galactic cosmic rays on a day to day basis appears to be consistent with the model which predicts different conditions of magnetic fields and plasma according to the relative position of the earth with respect to the pattern of coronal activity on the sun. Many quantitative aspects of the model still require to be evaluated and tested. So also the possibility of explaining the 11 year cycle of variation of galactic intensity. It should be possible in the near future to confirm through further experimental observations the details related to this model.

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Figure captions

Fig. 1 - The corrections T_1 and T_2 in hours for geomagnetic deflection of trajectories applicable to the time of maximum of the diurnal and the semidiurnal components respectively for various instruments and spectra of variation with different exponents.

Fig. 2 - Yearly histograms of T_{max} observed in the daily variation of Huancayo neutrons (H_N) and Churchill cube (C_C) from 1958 to 1962. The number of days taken for analysis in each year are indicated alongside each histogram.

Fig. 3 - Yearly histograms of the ratio of the amplitudes corresponding to H_N/C_N, and C_C/C_N from 1958 to 1962. The number of days taken for analysis in each year are indicated alongside each histogram.

Fig. 4 - Yearly histograms of peak to peak amplitude for H_N, C_N and C_C from 1958 to 1962. The number of days taken for analysis in each year are indicated alongside each histogram.

Fig. 5 - T_{min} for Deep River and MIT detectors.

Fig. 6 - T_{min}, for H_N, C_N, C_C from 1958 to 1962. The difference is 7 - 9 hours.

Fig. 7 - Schematic representation of positions of virtual positive and negative sources contributing to the anisotropy of galactic cosmic rays due to three alternative conditions, (a) corresponding to a uniform plasma wind, (b) corresponding to an advancing shock transition related to a stationary active zone on the corona and (c) an advancing blast wave due to the explosive heating of the corona.

Fig. 8 - Time series of T_{max}, T_{min} and I, for each day for the period 18 September 1961 to 15 October 1961.

Fig. 9 - On right hand side is shown a cross section of the sun in the equatorial plane. B and C are two zones of enhanced solar wind velocity. On left hand side is shown the resulting configuration in interplanetary space of regions of turbulent plasma (γ_B and γ_C) and cavities (β). The α region corresponds to uniform solar wind velocity.

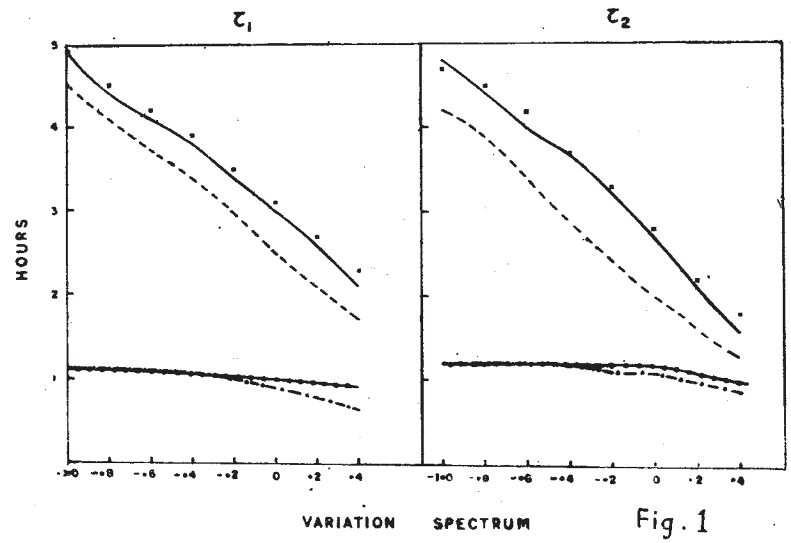
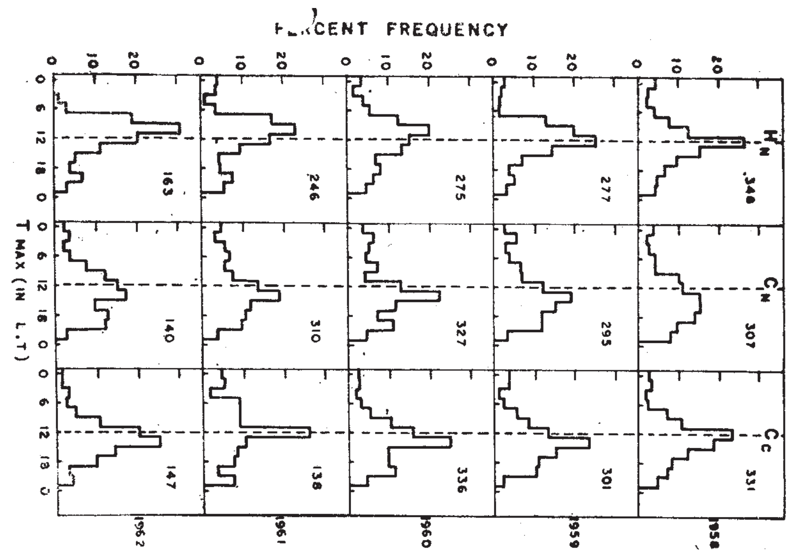


Fig. 1



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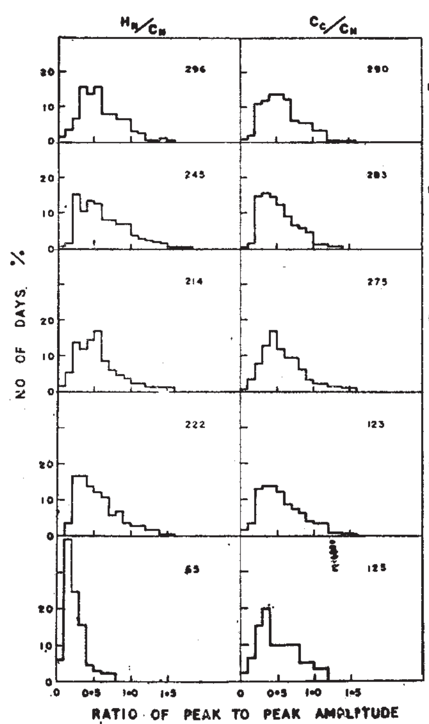

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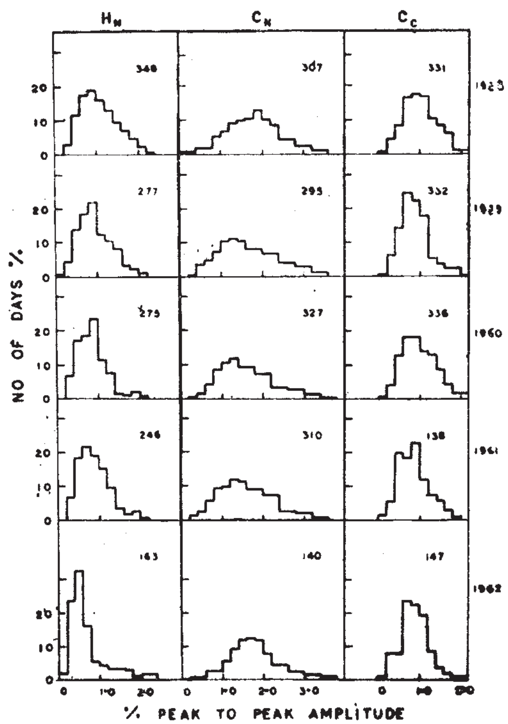

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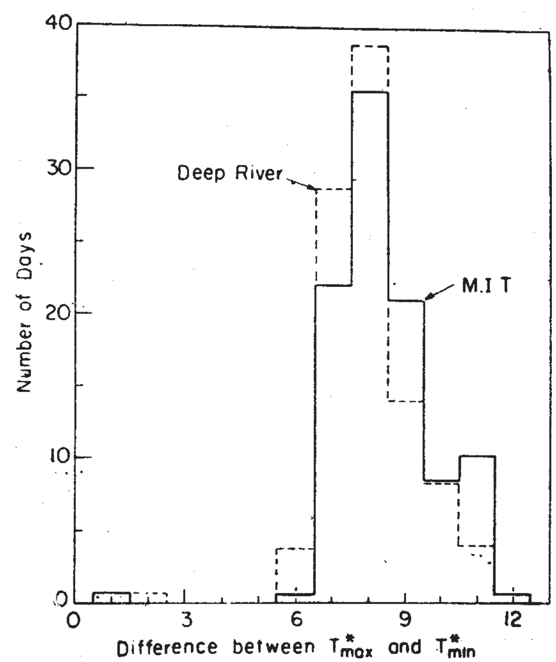

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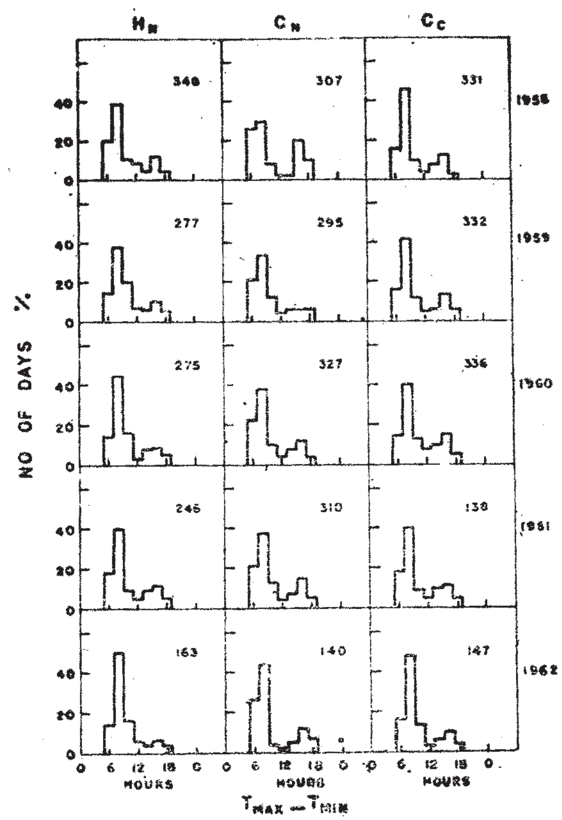

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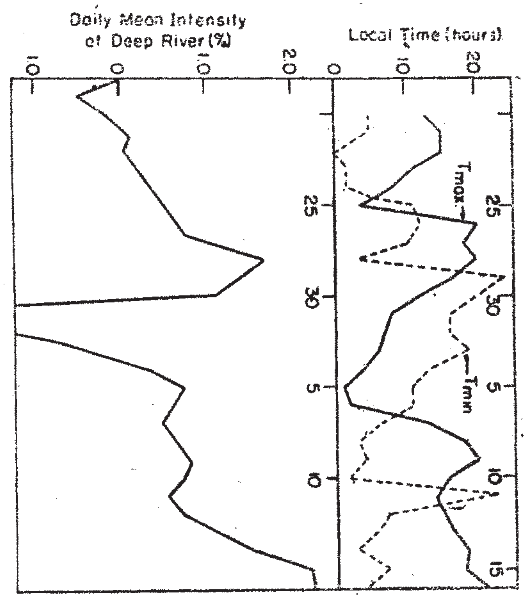

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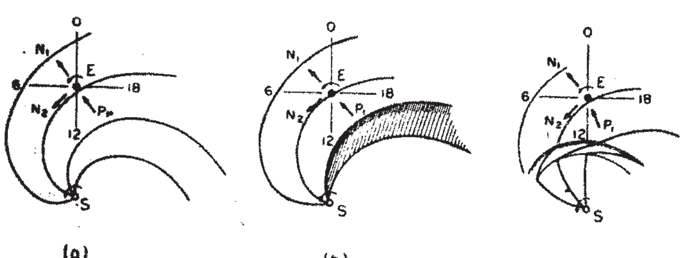

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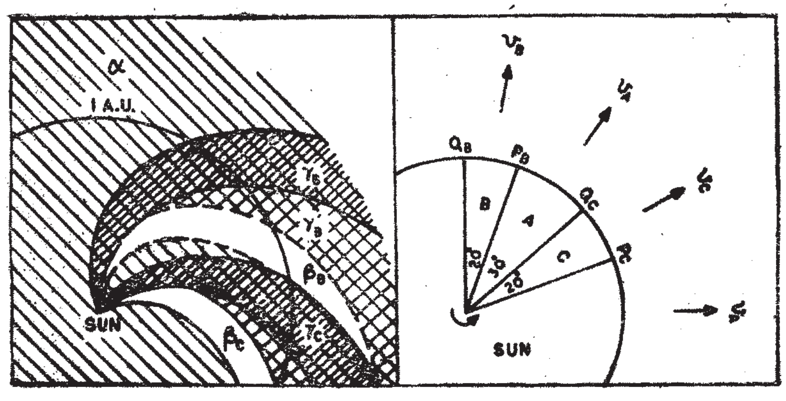

Fig 9

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THE NATURE OF THE DAILY VARIATION OF COSMIC RAY INTENSITY DURING THE PERIOD 1958 - 1962

Vikram A. Sarabhai and G. Subramanian
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We study the frequency distributions of the characteristics of the daily variation of cosmic ray intensity from year to year with diminishing solar activity during the period 1958 to 1962. This study on a day to day basis enables us to follow the changes of the position, the strength and the energy spectrum of variation of the anisotropy.

The daily variation observed on any day can be represented fairly satisfactorily by the first two harmonic components, - the diurnal and the semidiurnal. However, in talking of anisotropy, we are interested in the position of a virtual source and virtual sink as well as the magnitude of the anisotropy. We, therefore, consider in this study not the parameters R_1, ϕ_1, R_2, ϕ_2, of the diurnal and semidiurnal components, but the peak to peak amplitude (A) of the daily variation built-up from the first two harmonic components. We also consider T_{max}, and T_{min}, which are the times of maximum and minimum respectively, of the daily variation of cosmic ray intensity. We use, for this study, the Huancayo neutron monitor (H_N), Churchill neutron monitor (C_N) and the cubical meson telescope at Churchill (C_C). The spectrum of variation can be expressed as $\delta D(E)/D(E) = a\ E^{-\gamma}$ where, depending on the model that is used, we can have different values of the exponent and a high energy cut off E_{max} above which or a low energy cut off E_{min} below which, the source strength will be zero.

In Figure 1, the histograms of peak to peak amplitude are shown. The counting rates of the instruments have a strong effect on the shape of the histograms. C_N with a low counting rate of 625 counts a minute has a broad distribution with a higher average value for peak to peak amplitude than H_N with a high counting rate of 3000 counts a minute. The weighted mean of the histograms at each station for 1961 and 1962 expressed as percent of the weighted mean of 1958 show that H_N reduces to 84 and 47% while C_C reduces to 82 and 81% in 1961 and 1962 respectively. On the other hand C_N reduces to 88% in 1961 and then increases to 103% in 1962. We conclude that H_N shows a reduction in the mean of A from 1958 to 1962 which is more marked than in C_C. C_N does not show any reduction.

In Figure 2, the histograms of T_{max} for the three detectors are shown. The point to be noted is the statistically significant shift by 2 hours to earlier hours of the peak of the histogram of H_N with diminishing solar activity. However, the high latitude detectors do not show this change, and we conclude that there is no change in the average position of the source causing the anisotropy during the years in question. Figure 3 reveals for T_{min} a situation analogous to what we observed for T_{max}, that is, a shift in the position of the peak

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ACKNOWLEDGEMENT

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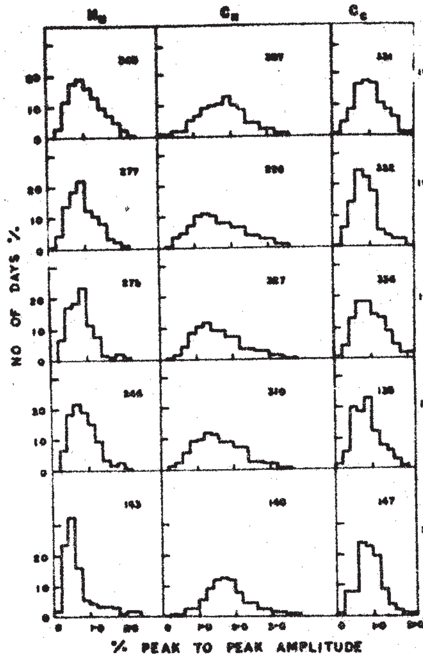
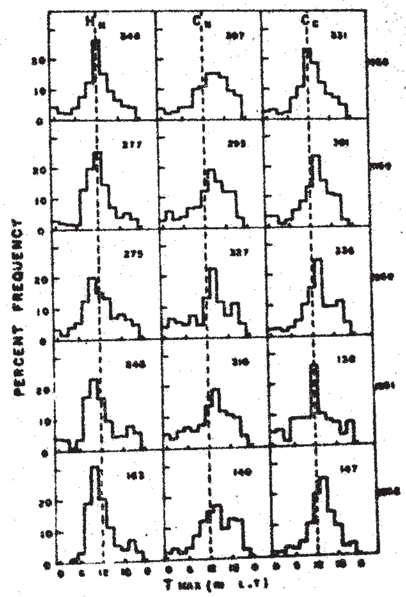


FIG 1



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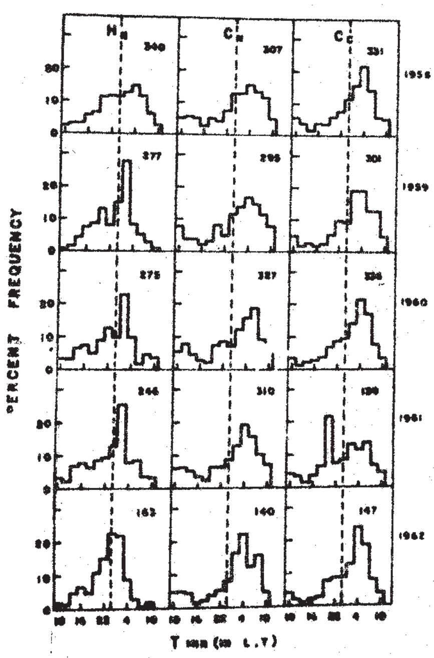

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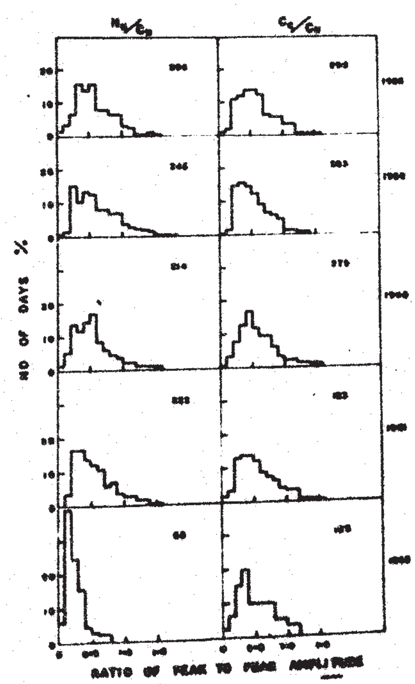

FIG 4

DISCUSSION

SOMOGYI: First I should like to ask you how you have determined the value of the daily peak to peak amplitude.

SUBRAMANIAN: By Fourier analysis, making use of the first and second harmonics.

SOMOGYI: In this case I should like to point out that in many cases the Fourier analysis yields results which have no direct physical meaning. It would be better to apply some more direct method to determine the daily amplitude.

Second, I should like to ask you by which method you have decided whether the shifts of the maxima in the histograms of the daily amplitudes were significant or not.

SARABHAI: It is true that for counting rate detectors the time of maximum can be found out directly without having a recourse to Fourier Analysis.

SUBRAMANIAN: The statistical significance of the shift in the histograms was determined by χ^2 test.

VENKATESAN: What is the physical significance of the T_{max} to T_{min} time in the study?

SARABHAI: The difference between T_{max} and T_{min} will be 12 hrs. only in the case of a source and a sink at 180° from each other. If there are more than one source or sink then a pure diurnal wave will not completely represent the anisotropy.

<u>KANE:</u> Does the time of maximum of daily variation at polar stations show a change from 1958 to 1962?

<u>DUGGAL:</u> We have studied the data of Thule and Resolute from 1958 to 1962 and for both these stations no change in time of maximum has been observed. Even the equaterial station Mina Aguilar does not show any change in time of maximum from 1959 to 1961. The results of Subramanian and Sarabhai cannot be directly compared with those of other authors because the daily variation considered by them contains diurnal as well as semidiurnal components of daily variation.

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PERIODIC FLUCTUATIONS IN THE GEOMAGNETIC FIELD DURING MAGNETIC STORMS

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Abstract—Some of the characteristics of the periodic fluctuations occurring in the horizontal intensity of the Earth's magnetic field during magnetic storms are investigated, using the five minutes values of H at Huancayo, Trivandrum, Alibag, Honolulu and San Juan during the storm of 8 July 1958. The study has been extended to sixteen sudden commencement and twenty gradual commencement storms at Huancayo during 1958 using 5-min values of H at Huancayo. Adopting the method of auto-correlation analysis, we have studied the period of oscillations of the significant fluctuations, and find that most commonly the period is about 40 min. The oscillations occur generally during the initial and main phases of the storm. The fluctuations are in phase at the two equatorial stations of Huancayo and Trivandrum or Huancayo and Alibag. They are therefore simultaneous at stations round the Earth close to the geomagnetic equator. At Honolulu or San Juan, the fluctuations are irregular and are poorly correlated with those at the equatorial stations. The situation at a high latitude station such as Sitka has not been studied.

On the assumption that the periodic fluctuations are due to large scale inhomogeneities in the solar plasma impinging on the magnetosphere, we have calculated the average scale length of the inhomogeneities in the plasma to be 0·02 a.u. This scale length is comparable to the scale length of inhomogeneities derived by McCracken[1] from solar flare cosmic ray events and the scale length indicated in the experimental results by Bryant *et al.*[2] relating to energetic particles measured by Explorer XII.

1. INTRODUCTION

Fluctuations in the geomagnetic field occurring during quiet periods as well as disturbed periods have been studied by many authors. Micropulsations, pulsation trains, continuous pulsations and giant pulsations belong to one category of short period fluctuations, ranging from a fraction of a second to about ten minutes. Magnetic bays which generally appear during the night belong to another category. Fluctuations in the magnetic field with periods of the order of thirty minutes or more (referred to as long period fluctuations in this paper) have not been quantitatively studied, even though Dessler and Parker[3] have observed that during the main phase of the storm large positive and negative excursions with amplitudes of the order of a few hundred gammas and periods up to about half an hour occur in the geomagnetic field. They have suggested that the long time scale associated with the main phase of the storm indicates a spectrum which also contains energy at much lower frequencies (cycles per hour). The large amplitude fluctuations are probably due to changes in the solar wind pressure, to major instabilities in the flow of solar wind past the geomagnetic field, or to a combination of the two effects.

In this paper we attempt to examine some characteristics of large period fluctuations in the horizontal intensity (H) of the Earth's magnetic field during magnetic storms. We are interested in the period of the oscillations, the occurrence of the fluctuations with respect to storm time and local time, and the difference if any between geomagnetic storms with and without sudden commencements. We have also studied the phase and amplitude of the fluctuations at widely-separated stations, so that the dependence of the phenomena on geographic and geomagnetic coordinates and their simultaneity at different meridians may be understood.

2. DATA

The investigation was begun with values of H at four minute intervals read from the magnetograms taken by the India Meteorological Department at Trivandrum and Alibag for the large geomagnetic storm which occurred on 8 July 1958. From these the values of H at 5-min intervals were calculated. For the same storm, the values of H at five minute intervals have been read out from the magnetograms obtained at San Juan and Honolulu by the United States Coast and Geodetic Survey. The analysis covering sixteen sudden commencement storms and twenty gradual commencement storms observed at Huancayo during 1958 has been conducted from values of H for five minute intervals punched on IBM cards kindly supplied to us by Dr. Robert S. Cohen of the Central Radio Propagation Laboratory, Boulder.

TABLE 1. GEOGRAPHIC AND GEOMAGNETIC CO-ORDINATES OF THE MAGNETIC OBSERVATORIES, THE DATA FROM WHICH WERE USED FOR THE ANALYSIS

Station	Geographic		Geomagnetic	
	Latitude	Longitude	Latitude	Longitude
Alibag	18·6°N	72·9°E	9·5°N	143·6°E
Honolulu	21·3°N	158·1°W	21·1°N	266·5°E
Huancayo	12·1°S	75·4°W	0·6°S	353·8°E
San Juan	18·4°N	66·1°W	29·9°N	3·2°E
Trivandrum	8·4°N	76·9°E	1·1°S	147·5°E

Table 1 gives the coordinates of the stations considered for the study. From the standpoint of geographical co-ordinates, Trivandrum and Huancayo may be considered equatorial stations while Alibag, Honolulu and San Juan are at the edge of the equatorial belt. However, from the standpoint of geomagnetic co-ordinates, Alibag, Huancayo and Trivandrum can all be considered equatorial stations while Honolulu and San Juan are significantly removed from the geomagnetic equator.

In Table 2(a), the onset time of the storm, the sudden commencement amplitude in H, the range in H and the classification of the storm are given for the 16 *SC* storms considered. In Table 2(b), the onset time of 20 gradual commencement storms and the range of H are given. The sudden commencement storm amplitude as well as the range varies largely from storm to storm. Even gradual commencement storms show very large range at Huancayo.

In Fig. 1, we have plotted the five minute values of H for six sudden commencement storms at Huancayo. The morphology of a storm with its long period fluctuations varies greatly from storm to storm. There are some storms where the long period fluctuations are very pronounced and occur throughout the initial and main phases as for example the storm of 8 July 1958 shown in Fig. 1. There are others, such as the storm on 21 July 1958 where the fluctuations are large only in the initial phase or as in the storm of 14 March 1958, in the main phase. Very high sudden commencement amplitude and rapid decrease in H are shown during some storms, like the one on 31 May 1958. The storm on 11 February 1958 is a typical severe sudden commencement storm where the *SC*-amplitude as well as the range is very high. Long period fluctuations are observed almost throughout the storm.

In Fig. 2, six gradual commencement storms are shown. Gradual commencement storms usually last longer than the sudden commencement storms and some, such as the storm of 3 March 1958, exhibit long period fluctuations of high amplitude.

TABLE 2(a). DETAILS OF THE SUDDEN COMMENCEMENT STORMS AT HUANCAYO STUDIED FOR PERIODIC FLUCTUATIONS

Greenwich date of the storm	Storm time: GMT of beginning h	m	GMT of ending d	h	*SSC* amplitude γ	*C* Figure of activity	Range in *H* at Huancayo γ
11 February 1958	01	25	12	13	167	s	990
14 March 1958	12	12	14	22	139	ms	364
26 April 1958	12	47	26	20	34	ms	280
31 May 1958	16	53	1	21	245	ms	656
7 June 1958	00	46	7	20	25	ms	285
28 June 1958	07	12	29	21	21	ms	532
8 July 1958	07	47	9	15	97	s	805
21 July 1958	16	36	22	14	178	ms	470
17 August 1958	06	22	18	21	90	ms	542
24 August 1958	01	39	24	19	76	ms	369
3 September 1958	08	43	3	22	22	ms	419
25 September 1958	04	07	26	05	32	ms	302
30 September 1958	10	03	30	23	21	ms	325
22 October 1958	03	15	22	20	44	ms	315
24 October 1958	07	30	24	24	32	ms	312
27 October 1958	15	23	27	22	83	ms	420

SSC = storm sudden commencement. ms = moderately severe.
s = severe. m = moderate.

TABLE 2(b). DETAILS OF THE 20 GRADUAL COMMENCEMENT STORMS STUDIED AT HUANCAYO FOR PERIODIC FLUCTUATIONS

Greenwich date of the storm	Storm time: GMT of beginning h	m	GMT of ending d	h	*C* Figure of activity	Range in *H* at Huancayo γ
20 January 1958	14	20	21	22	ms	379
4 February 1958	13	05	4	21	ms	340
16 February 1958	11	20	17	22	ms	391
3 March 1958	09	30	4	04	ms	442
13 March 1958	09	37	13	20	ms	212
17 March 1958	07	51	17	21	ms	187
18 March 1958	12	00	18	22	ms	315
25 March 1958	12	03	26	02	ms	404
2 April 1958	06	52	2	21	m	333
3 April 1958	05	29	5	04	m	373
16 April 1958	06	16	18	05	ms	361
13 May 1958	10	45	14	19	ms	290
26 May 1958	02	00	26	19	ms	223
29 May 1958	00	40	30	02	m	220
21 June 1958	02	00	22	22	ms	339
18 July 1958	02	20	18	20	ms	289
27 August 1958	02	35	27	18	m	291
4 September 1958	10	20	5	19	s	632
16 September 1958	09	30	16	22	ms	416
28 October 1958	06	50	28	21	ms	358

s = severe. ms = moderately severe. m = moderate.

3. METHOD OF ANALYSIS

Scaled values of H at 5-min intervals for Huancayo are given for 00, 05, 10, 15, . . . 50, 55 minutes for each hour of the day. If the onset of the magnetic storm does not correspond to any multiple of 5 min in the hour, then the five minute value which just follows the onset time is taken as the value corresponding to 0000 storm time. Hence there is in some cases a shift of up to 4 min in the storm time.

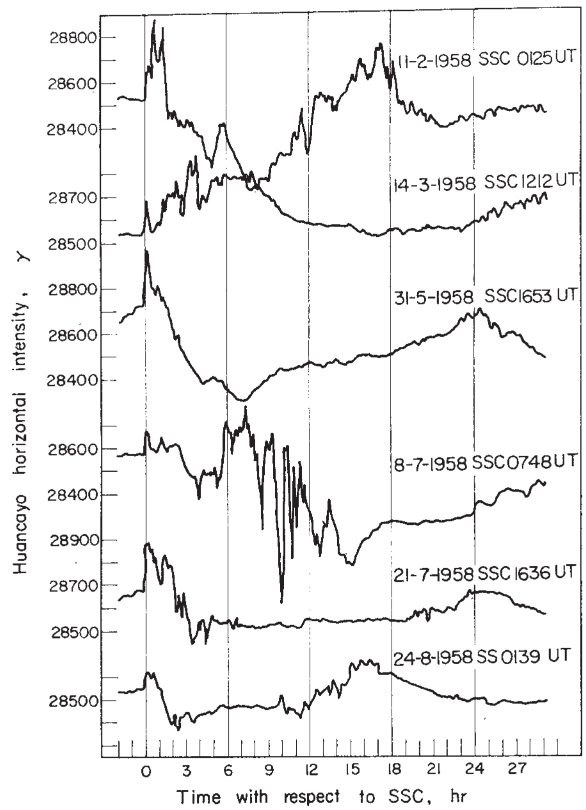

FIG. 1. FIVE-MINUTES VALUES OF H AT HUANCAYO PLOTTED IN STORM TIME FOR STORMS ON 11 FEBRUARY 1958, 14 MARCH 1958, 31 MAY 1958, 8 JULY 1958, 21 JULY 1958 AND 24 AUGUST 1958. THESE ARE SOME OF THE SUDDEN COMMENCEMENT STORMS.

During magnetic storms, the variations in H that we get at any station consist of the following:

(a) The solar quiet day variation in H designated as S_q.

(b) The storm time variation D_{st}. In the storm time variation we have the general trend of change in H.

Since our object was to study the periodic fluctuations in the geomagnetic field during magnetic storms, the following procedure was adopted for the analysis of the data. The mean five minute values for the five international quiet days for each month of 1958 were found out. These represent the S_q variation. Similarly for the month of July 1958, the S_q variation was also derived for the other four stations. The five minute values of S_q for the month were next subtracted from the values corresponding to the storm days to free the storm time variation from the influence of the local time effect.

In Fig. 3 we have plotted the storm time variation for the storm on 8 July 1958 for five stations. The plot begins about two hours before *SSC* and extends for about 25 hr after *SSC*. It is quite clear from this figure that, neglecting periodic fluctuations, the D_{st} variation is similar at all the five stations. Huancayo shows fluctuations with very high amplitude ($\sim$300–400γ), which are not seen so clearly at other stations. This has been described as a special feature of Huancayo magnetograms by many workers (Chapman and Bartels, 1940).

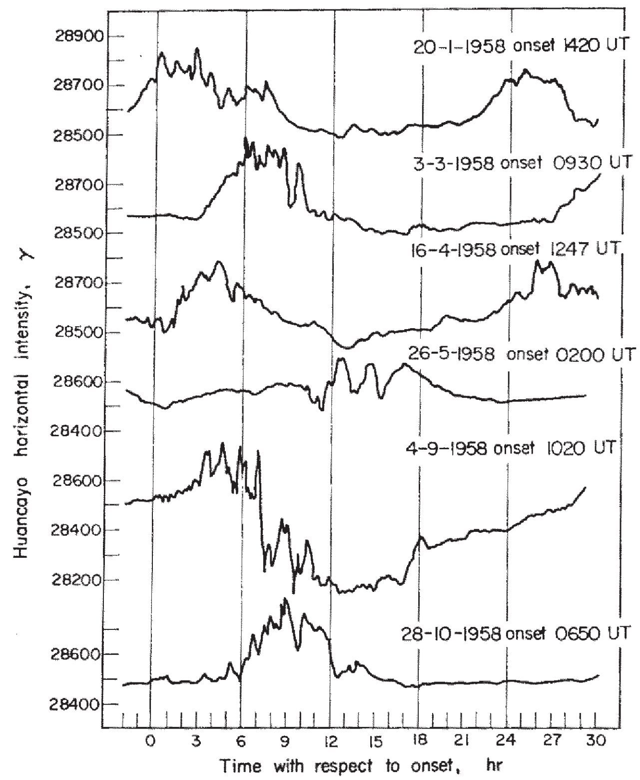

FIG. 2. FIVE-MINUTES VALUES OF H AT HUANCAYO PLOTTED IN STORM TIME FOR SIX GRADUAL COMMENCEMENT STORMS ON 20 JANUARY 1958, 3 MARCH 1958, 16 APRIL 1958, 26 MAY 1958, 4 SEPTEMBER 1958, AND 28 OCTOBER 1958.

In order to study periodic fluctuations, it is appropriate to first eliminate the main D_{st} variation during each storm. The trend of the D_{st} variation is therefore calculated by taking moving averages over ten successive 5-min values of H. This is continued up to 25 hr from the commencement of the storm. The D_{st} variation is then subtracted from each 5-min value of H to prepare the data for the study of the periodic fluctuation.

The first value that we get for our study is for 0025 storm time. Starting with this value, we consider successive five minute values X_1 to X_{72}, the last corresponding to storm time 0620. This group of 72 values extending over a period of six hours is referred to as the first set. The second set consists of the values X_{73} to X_{144}, the third set X_{145} to X_{216}, and the fourth set X_{217} to X_{288}. After 24 hr storm time, the magnetograms generally exhibit a smooth variation, even though the value of H may still be depressed. Further data is uninteresting for the determination of periodic fluctuations.

The study of the periodic fluctuations is undertaken by performing autocorrelation of each set with the following set. In the autocorrelation analysis the first correlation is between the n-values of X from X_1 to X_n with the same values X_1 to X_n. The correlation coefficient is therefore $+1{\cdot}00$. The next correlation is between X_1 to X_n and X_2 to X_{n+1} and so on for 72 values consisting of the first and second sets. Similarly, we get 72 autocorrelation coefficients for the second and third sets and for the third and fourth sets. The

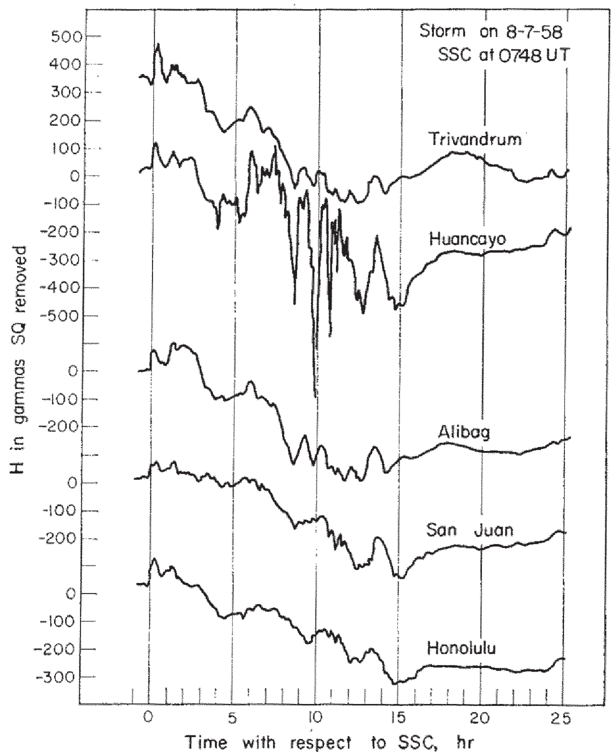

FIG. 3. FIVE-MINUTES VALUES OF H after S_q REMOVAL AT HUANCAYO, ALIBAG, TRIVANDUM, HONOLULU AND SAN JUAN FOR THE MAGNETIC STORM ON 8 JULY, 1958.

autocorrelation coefficients for the storm on 8 July 1958, for the different stations are plotted in Fig. 4. Such plots were also made for the other 35 storms studied at Huancayo.

4. PERIODIC FLUCTUATIONS DURING MAGNETIC STORMS

An examination of the plots of autocorrelation coefficients shows that there is definite periodicity in their values. Many correlation coefficients are as high as $\pm 0{\cdot}5$ while the maximum error in the correlation coefficients is about $\pm 0{\cdot}1$. The significance of the correlation coefficients during storms has been verified by the completion of a similar autocorrelation analysis during a randomly selected period of 24 hr when no geomagnetic storm was in progress. The autocorrelation coefficients obtained in this case were all less than $\pm 0{\cdot}1$ after the initial three or four values in each set.

The most frequently occurring period of fluctuation during storms was determined in the following manner. Since the maximum standard error in the autocorrelation coefficients was $\pm 0{\cdot}1$, periods with monotonic changes in the plot of correlation coefficients with

Основываясь на предположении, что периодические флуктуации происходят вследствие крупных неоднородностей в солнечной плазме, влияющих на магнитосферу, мы вычислили, что среднемасштабная длина неоднородностей в плазме равняется 0,02A. Эта масштабная длина сравнима с масштабной длиной неоднородностей, установленной МакКракеном на основании явлений космических лучей хромосферной вспышки, а также масштабной длины, указанной в экспериментальных результатах Брайанта и др., относящихся к энергетическим частицам, измеренных Эксплорером XII.

PROBING INTERPLANETARY SPACE WITH COSMIC RAYS

by

VIKRAM A. SARABHAI

The sun is the driving force of weather and of all life on earth. It has been perceived by man through the ages as one of the most constant objects of nature. Against this constancy man has found it difficult to understand the changing environment on earth, years of drought and floods, hurricanes and storms. He has invoked the divine to reconcile himself to the caprices of nature. But to the scientist, there are clearly many missing links in our understanding of the relationship between the sun and the earth. He may have fathomed quite early some of these, were he not tied for long to the solid earth under the blanket of the atmosphere which provides a window admitting only a narrow band of the radiation from the sun which brings energy to the earth. It so happens that the sunlight which he normally perceives is remarkably constant.

We know that the bright sphere which we observe as the sun is itself enveloped by its corona at a temperature of more than a million degrees. This is normally invisible except when the bright disc is eclipsed by the moon or when viewed through special instruments. Apart from visible light, the sun emits electromagnetic radiation in the form of radio waves, infra-red radiation, ultra violet radiation and X-rays and we know, moreover, that the corona continuously expands producing a solar wind which fills interplanetary space with rarefied plasma consisting mostly of protons and electrons. Observed closely in filtered light, the sun's disc has a fascinating microstructure of bright and grey areas and of filaments. Complex patterns of local magnetic fields are often associated with this structure. The frequency of dark sunspots and other symptoms of local activity change over a period of about 11 years with the solar cycle; and so does the intensity of a significant part of the solar radiation coming to the earth, particularly of some components outside the visible region. Occasionally there is a catastrophic event involving a bright flash of light observed on the disc. These flares are followed by the emission of a burst of fast particles with energy millions of times greater than the highest energy of radiation from natural radioactive sources.

Perhaps one reason for the slow progress of our understanding of sun-earth relationships is because we exist on the thin surface shell of the earth with very special conditions of temperature and density, where there is little effect of electrodynamic forces on fluid motion. But conditions in the interior of the earth, the outer atmosphere, interplanetary and interstellar space and in stars are such that electromagnetism and hydrodynamics are intimately linked with each other. While we have come to recognise the crucial importance of hydromagnetics in astrophysical problems, much experimental and theoretical work requires to be done before we can hope to have a better understanding of how nature functions on a cosmical scale. Interplanetary space, where a plasma wind from the sun stretches out with it a frozen magnetic field, is a wonderful laboratory for this kind of studies. We do not yet know how to duplicate these conditions for controlled experimentation.

Space-craft travelling at great distances from the earth directly sample plasma and magnetic fields and measure those components of solar radiation which are normally blanketed by the atmosphere. Such studies provide valuable information on the microstructure of conditions in interplanetary space. Observations of comet tails and the disturbances produced in the earth's magnetic field by plasma from the sun provide indirect information of plasma conditions on a larger scale. There is, however, yet another indirect method which furnishes unique information over an even larger region of space in the solar system, extending to several million kilometres from the earth. This is by using cosmic rays as probes for studying interplanetary electromagnetic conditions.

Cosmic rays were discovered almost half a century ago, but theories concerning their origin in the universe are still largely speculative. We know that much of the radiation consists of very energetic protons and a smaller proportion of heavier nuclei, which have originated mainly in our own galaxy and have, on the average, spent about 2.5 million years in interstellar space. The energies of individual particles are truly staggering, sometimes exceeding a billion times what we can currently achieve in our most energetic particle accelerators, which itself is more than a thousand times the energy found in natural radioactivity. Through interaction with magnetic fields in intersetellar space, the cosmic rays which approach the solar system are almost completely isotropic and have lost all sense of their original direction. Thus they appear to come with equal intensity from all directions. However, within the solar system they encounter magnetic fields associated with plasma from the sun. In consequence, they lose their isotropy and undergo significant changes in energy and total number density.

For the past twenty years, I have been interested in studying the minute changes, often as small as a few parts in a thousand, which are observed in the intensity of galacti cosmic rays on earth due to the modulation that occurs within the solar system. Our group at the Physical Research Laboratory, Ahmedabad, operates instruments which continuously monitor cosmic ray intensity at Ahmedabad, Trivandrum, Kodaikanal and Gulmarg in India and at the Laboratory at Chacaltaya in Bolivia, which is at an elevation of 5200 metres above sea level, very close to the geomagnetic equator passing through South America. I have also been actively connected with a very high counting rate instrument at the Massachusetts Institute of Technology. We are particularly fortunate to work near the equator where we observe changes in cosmic rays arriving along the plane of the ecliptic which contains the sun and the earth.

The systematic character of daily meteorological changes in the tropics has moreover enabled us to disentangle effects due to changes within the atmosphere from those in interplanetary space. We observed fairly early that, with respect to the sun, galactic cosmic rays were not arriving uniformly from all directions. Indeed the daily variation of cosmic rays, corrected for meteorological effects, was demonstrated to be due to the anisotropy of galactic cosmic rays as it is scanned by an instrument fixed to the spinning earth. Almost ten years ago we were able to show that the anisotropy itself changed with the 11-year and the 22-year cycle of solar activity. We noted that conditions in interplanetary space altered from day to day almost like weather on the surface of the earth, and while one could sometimes talk of average conditions over an extended period of time, it was indeed necessary to study the phenomena with accuracy on a day-to-day basis in order to understand the physical processes that were operative.

It is difficult to describe in detail the insights which we have gained in our study of solar activity and the physics of interplanetary space without involving terms which only the specialist may be expected to be familiar with. I think I will spare mutual embarrassment by presenting at this time only a general description of the area in which I work and of its broad significance to scientific knowledge. Like any other field of modern science, insight into the nature of cosmic ray variations has grown through work by many groups in the world - in Europe, in Asia, in Australia and in the Americas. The particular contribution to this international endeavour of our group at the Physical Research Laboratory, Ahmedabad, has been in identifying the electromagnetic states of interplanetary space in terms of measurements made with galactic cosmic rays and disturbances in the geomagnetic field. We feel that it is important in studying the solar anisotropy of cosmic rays to look at the direction in which there is an excess as well as the direction in which there is an apparent deficiency of intensity. This permits us to observe the effects of advancing magnetic field discontinuities travelling in interplanetary space, sometimes from the sun outwards, but more often appearing to corotate with the spinning sun. We have recently demonstrated that, during the period of low solar activity early in 1964, there was a deficiency of cosmic rays from a direction towards the sun along the frozen magnetic field stretched out by the plasma wind. We believe that we are observing here a mechanism whereby galactic cosmic rays penetrating into the solar system along the magnetic lines get scattered by the field irregularities near the sun.

Last year, I proposed that local regions of excitation in the solar corona as shown by the varying intensity of the green coronal emission line should imply a non-uniform velocity of solar plasma wind from different regions of the sun. As the sun spins on its own axis, the non-uniformity of wind velocity should have certain broad implications to plasma conditions in interplanetary space. There should be regions where fast plasma blows behind slow plasma and creates shock tra-nsitions and turbulent conditions. There should also be regions where slow plasma follows fast and in consequence, cavities which have low densities and low magnetic fields should be produced. As the earth enters various structures in interplanetary space due to the non-uniformity of solar wind velocity, it should experience characteristic geomagnetic disturbances and cosmic ray effects. The model offers a plausible mechanism for the 27 day recurrent effects seen in geomagnetism and cosmic ray variations. Moreover, it suggests a mechanism in which cosmic ray intensity may be depressed for several days as in some long-lasting Forbush decreases and an explanation for geomagnetic disturbances which are sometimes associated with decreases and at other times with increases of galactic cosmic ray intensity.

We have recently verified some of the predictions of the model of interplanetary conditions on the basis of a non-uniformity of solar wind velocity with ground-based observations and studies in spacecraft. An analysis of the anisotropy in interplanetary space from 1958, when the sun was at its height of activity, to 1963, when the sun was relatively quiet, has demonstrated the progressive change of the type of modulation which occurs with changing conditions in interplanetary space. We are far from having solved the jigsaw puzzle, but we recognise that in doing so we shall have to pool theoretical predictions and model building, experimental observations of solar activity and measurements made in spacecraft as well as observations of the variations of cosmic rays and of the geomagnetic field. From an analysis of ground-based magnetometer measurements of fluctuations of the strength of the earth's magnetic field following magnetic storms, we have, for instance, estimated the dimensions of the irregularities in plasma wind which correspond fairly closely to estimates made from other considerations.

I am deeply grateful for the honour done in the recognition of my modest contribution through the Shanti Swarup Bhatnagar Memorial Award. I have had the privilege of having work with me, initially as doctoral students and then as colleagues, a series of eager and dedicated young men with originality, who have shared the excitement of discovery with me. The story which I have related today is their story as well. For those who are interested in the detailed scientific aspect of our work, I list what I believe to be some of our most significant published contributions.

Shri Jawaharlal Nehru will be remembered as a head of a State in the atomic age who recognised, perhaps more than any other statesman, the importance of science to modern society. I wish to take this opportunity to pay my respectful homage for all that Panditji did to encourage many, such as me, in our effort to pursue science.

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Characteristics of anisotropy of galactic cosmic rays during the solar cycle

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Abstract. Applying the method of best fit to the daily variation of cosmic ray intensity observed by neutron monitors at Huancayo, Churchill, Mawson and Mt. Norikura and cubical meson telescopes at Mawson and Churchill, the authors determine for each day from 1958 to 1963 the amplitude, the directions in space of maximum and minimum intensity and the energy spectrum of variation of the anisotropy of galactic cosmic rays. Out of 36 combinations of assumed values for x and E_{min}, in the relations $\delta D(E)/D(E) = aE^x$ and $\delta D(E)/D(E) = 0$ for $E \leqslant E_{min}$, the authors find that four combinations account for more than 70 per cent of the total days considered. They are:

Type of spectrum	Exponent x	E_{min} (GeV)
A	−1	2-6
B	−1	15
C	+0.2, +0.4	2
D	1	15

Azimuthal streaming of galactic cosmic rays by itself is insufficient to account for the anisotropy on most days. The direction of maximum of the anisotropy usually lies between 1200 and 1800 hours. The deficiency of the cosmic ray intensity along the direction of the spiralling magnetic field line is observed particularly prominently in type A and B days. With declining solar activity, the frequency of days having a variation spectrum of type D decreases, while the frequency of days of type A increases. It is suggested that this is indicative of a weakening of the strength of the field and/or a reduction of the scale length of magnetic field irregularities in sectors of interplanetary space distinguished by the two types of energy spectrum of anisotropy.

1. Introduction

Evidence has steadily accumulated over the past few years that the anisotropy of galactic cosmic rays varies from day to day (Rao and Sarabhai 1964, Sarabhai and Subramanian 1963 a, Sarabhai 1963). This is seen in its peak to peak amplitude A^*, directions in space of maximum intensity T^*_{max} and of minimum intensity T^*_{min} as well as its spectrum of variation defined by the exponent x, E_{min} and E_{max} in the equation

$$\begin{aligned} \delta D(E)/D(E) &= aE^x \text{ for } && E_{min} \leqslant E \leqslant E_{max} \\ &= 0 \quad \text{when} && E < E_{min} \\ & \quad\quad \text{or} && E > E_{max}. \end{aligned} \tag{1}$$

We present here an extension of our earlier studies using data, during the period 1958 to 1963, from six stations indicated in table 1. They have been analysed to identify types of energy spectra of anisotropy that occur on individual days. The characteristics of the anisotropy of each type and its frequency of occurrence are studied in relation to changes with the cycle of solar activity.

2. Energy spectrum of the variation of the anisotropy of galactic cosmic rays

In determining the energy spectrum we consider 36 combinations of x and E_{min} to describe the energy dependence of the anisotropy. The values are shown in table 2 where x ranges from +1.0 to −1.0, E_{min} ranges from 2 to 15 GeV, while E_{max} has a constant value of 600 GeV. For each combination of x and E_{min} the effect of an anisotropy on the amplitude and phase of the diurnal and semi-diurnal components, as would be observed by different detectors, is calculated by the method of variational coefficients (Rao et al. 1965). The asymptotic directions

Table 1

Characteristics of the cosmic ray detectors

Detector	Source of data	Mean energy (GeV) x = −1	Mean asymptotic latitude (degrees) x = 0	x = −1	Standard error† (%)
Churchill meson	D. C. Rose	55	48	39	0.30
Mawson meson	A. G. Fenton	55	−48	−42	0.15
Huancayo neutron	J. A. Simpson	34	~ 0	~ 0	0.18
Mt. Norikura neutron	Y. Miyazaki	25	~ 0	~ 0	0.20
Churchill neutron	D. C. Rose	12	38	29	0.50
Mawson neutron	A. G. Fenton	12	−40	−26	0.25

† Standard error in bi-hourly counting rate according to the Poisson distribution.

The authors are grateful to the various research workers who have kindly supplied us their data.

Table 2

Frequency of occurrence of days having different variation energy spectra

E_{min} (GeV) \ x	−1.0	−0.8	−0.6	−0.4	−0.2	0	+0.2	+0.4	+1.0
2	2.1 (A)	0.9	1.7	1.0	1.6	0.6	2.4 (C)	8.4 (C)	0.8
6	21.4 (A)	1.7	1.2	0.9	0.6	1.1	0.3	0.3	1.5
10	2.2	0.4	0.2	0.4	0.1	0.1	0.2	0.4	0.6
15	10.9 (B)	4.9 (B)	0.5	0.5	0.4	0.5	4.7	0.6	22.7 D

needed for the calculation were obtained from McCracken et al. (1962, MIT Tech. Rep.) and Brunberg and Dattner (1953). The multiplicity values are taken from Quenby and Webber (1959).

For station i for a particular combination of x and E_{min}, defining a variation spectrum k of the anisotropy, the attenuation factor α_{jik} by which the amplitude of the jth harmonic is reduced with respect to its free space value and the effective bending angle τ_{jik} in the geomagnetic field are calculated. For the observed diurnal and semi-diurnal components (a_j, b_j), the free space values (denoted by *) are determined using the formulae:

$$X_{jik} = \alpha_{jik} \cos \tau_{jik}$$
$$Y_{jik} = \alpha_{jik} \sin \tau_{jik}$$
$$a^*_{jik} = \frac{a_{ji} \cdot X_{jik} - b_{ji} \cdot Y_{jik}}{\alpha^2_{jik}} \tag{2}$$
$$b^*_{jik} = \frac{a_{ji} \cdot Y_{jik} + b_{ji} \cdot X_{jik}}{\alpha^2_{jik}} .$$

A measure of the goodness of fit of calculated values for an assumed k with observed values from different detectors is given by

$$S_k^2 = \sum_{i=1}^{N} \sum_{j=1}^{2} \frac{(a^*_{jik} - \overline{a^*_{jk}})^2 + (b^*_{jik} - \overline{b^*_{jk}})^2}{\sigma^2_{jik}} \tag{3a}$$

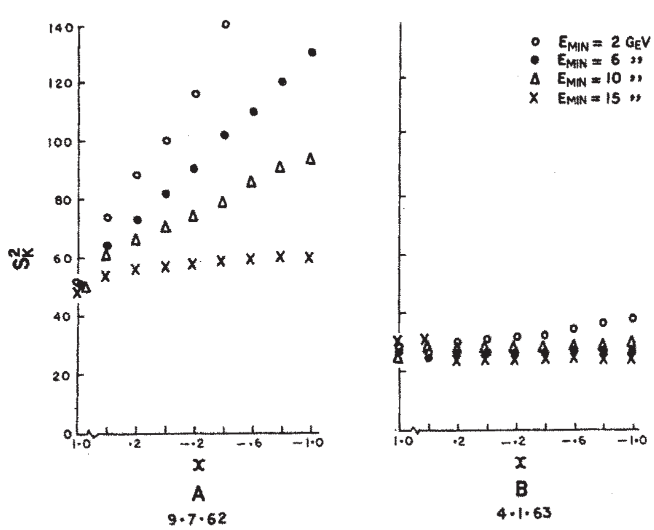

Fig. 1 S^2 values are plotted for various values of x and E_{min} for two typical days. For 1A, the variation spectrum can be resolved; for 1B, resolution is impossible.

where the bar denotes values averaged over all stations. The denominator represents the variance of the corresponding term in the numerator and is given by

$$\sigma^2_{jik} = \frac{(N^2 - 2N)\, \alpha^2_{jik} \cdot \sigma^2_{ji} + \sum_{i=1}^{N} \alpha^2_{jik} \cdot \sigma^2_{ji}}{N^2} . \tag{3b}$$

The spectrum which gives the minimum value of S_k^2 is considered to fit the data best.

The degree of resolution that can be achieved between the alternate spectra on conducting the analysis on an individual day can be judged by an examination of figures 1 A, B, where the value of S_k^2 is indicated for various values of x and E_{min}. Resolution is good as indicated in figure 1 A on 25% of the days but is poor as in figure 1 B on about 27% of days. Determination of spectra with the present data is therefore possible for roughly 70% of the days. When resolution is poor, a hypothesis that a local source or a universal time variation may be involved would be equally compatible as an anisotropy in interplanetary space to account for the observed daily variation at the six stations.

Once the spectrum of variation is identified, $\overline{a^*_{jk}}, \overline{b^*_{jk}}$ as well as A^*, T^*_{max} and T^*_{min} are calculated.

3. Four types of energy spectra of variation

In table 2 we present the percentage frequency of occurrence of each of the 36 types of the spectrum of variation. Four groups marked A, B, C and D account for 70% of the total d: considered. All days do not have the same exponent for the spectrum of variation. The occurrence of the positive exponent on 23% of the days indicates that the anisotropy is often relatively less pronounced for primaries of energy up to 15-20 GeV than for cosmic rays in a higher energy band.

The characteristics of the four groups are indicated in table 3. In figure 2 are shown histograms of T^*_{max} and T^*_{min} for the four types of spectra for all days in the period 1958-63. We conclude:

(a) That T^*_{max} and T^*_{min} of the anisotropy have greater variability on days having a positive exponent (D) than on days having negative or zero exponents (A, B or C).

(b) The days with positive spectrum D have their most probable time of occurrence of T^*_{max} earlier than days with types A and B. This means that the direction of maximum of the anisotropy for $E > 15$ GeV is nearer to the Sun-Earth line than the direction of anisotropy when low energy particles are also included.

(c) T^*_{min} in the garden-hose direction occurs most prominently on days having negative exponent (A and B).

(d) The semi-diurnal component indicated by $T_{max} - T_{min} \approx$ 6-8 hours is most prominent for a positive exponent (D).

Table 3

Characteristics of the four types of anisotropy

Group	x	E_{min} (GeV)	E_{max} (GeV)	Percentage frequencies (1958-1963)	Most probable value of A^*	T^*_{max}	T^*_{min}	ratio of $T^*_{max} - T^*_{min}$ $\frac{6\text{-}8}{10\text{-}12}$
A	−1	2	600	21.0	1.28 ±0.25	16.6 ± 0.6	6.6 ±0.6	2.6
B	−1	15	600	15.6	1.07 ±0.30	16.7 ± 0.7	8.7 ±0.7	5.6
C	0.4 ~ 0.2	2	600	10.7	1.17 ±0.30	14.8 ± 0.8	6.5 ±0.5	4.0
D	+1	15	600	22.6	1.08 ±0.25	15.9 ± 0.9	5.0 ±1.0	12.5

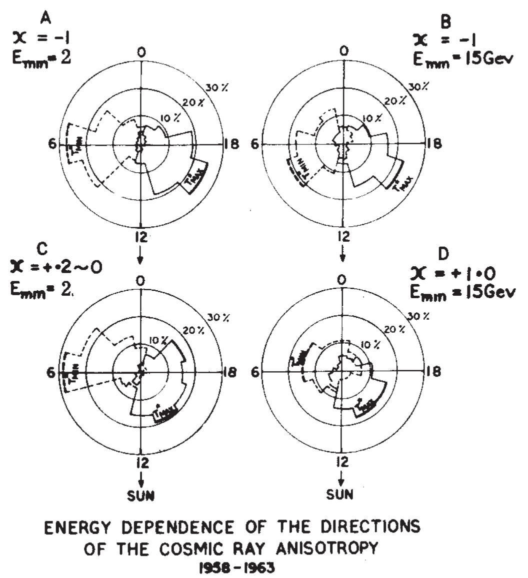

Fig. 2 Polar histograms of T^*_{max}, T^*_{min} are shown for the four types of spectra A, B, C and D.

4. Changes of the anisotropy with solar activity

We present in table 4 characteristics of the anisotropy separately for the years 1958-1960 relating to maximum solar activity and for the years 1961-1963.

The noteworthy changes with declining activity are:

(a) The frequency of occurrence of the type A spectrum increases markedly from 21% to 31%, while the frequency of positive exponent (D) declines from 27% to 19%.

(b) The strength of the anisotropy remains relatively constant. The slight indication of a decrease of amplitude is not established at an adequate level of significance.

(c) Type A shows no change in any of the characteristics during the solar cycle. Type B shows no change in T^*_{max}.

Discussion

Parker (1964) and Axford (1965) have recently described processes by which an azimuthal streaming of cosmic rays could occur in the inner solar system with relatively smooth field lines bounded by a shell containing magnetic field irregularities. The streaming would give rise to an anisotropy of galactic cosmic rays in interplanetary space which would be diurnal in character. Its source strength would fall off as cos λ with asymptotic latitude. Its energy spectrum of variation

Table 4

Changes in the characteristics of the anisotropy with solar activity

Spectrum	x	−1	−1	0	+1
	E_{min} (GeV)	2	15	2	15
	Type	A	B	C	D
Frequency	a	20.8	14.8	9.0	26.1
	b	31.1	16.4	12.3	19.4
Normalized amplitude A^*	a	1.28 ± 0.25	1.11 ± 0.30	1.06 ± 0.30	1.07 ± 0.25
	b	1.28 ± 0.25	1.04 ± 0.30	1.28 ± 0.30	1.08 ± 0.25
T^*_{max}	a	16.6 ± 0.6	16.7 ± 0.7	17.8 ± 0.8	14.8 ± 0.8
	b	16.6 ± 0.6	16.6 ± 0.7	14.7 ± 0.7	16.8 ± 0.8
T^*_{min}	a	6.6 ± 0.6	8.6 ± 0.6	6.4 ± 0.4	7.0 ± 1.0
	b	6.5 ± 0.5	6.7 ± 0.7	5.6 ± 0.6	4.4 ± 0.9

a, for the period 1958-1960; b, for the period 1961-1963.

would have an exponent $x = 0$, $E_{min} = 0$ and some finite value (~100 GeV) for E_{max}.

There are a number of experimental facts which demonstrate that on individual days the anisotropy has many other features besides what one may expect from the purely azimuthal drift of galactic cosmic rays. The most important of these are:

(a) Except on about 10% of days corresponding to type C, the variation spectrum has an exponent which is significantly different from 0.

(b) Except in type C during solar maximum, T^*_{max} is not along the 1800 direction. Generally T^*_{max} occurs between 1200 h and 1800 h. There is thus an additional component, most pronounced for D type, which could be due to a radially outward drift arising from lack of spherical symmetry in the distribution of magnetic field irregularities and solar wind velocity. Alternatively the component may arise when the deficiency along the garden-hose direction is harmonically analysed (Sarabhai and Subramanian to be published).

(c) $T_{max} - T_{min} \simeq$ 6-8 hours occurs more frequently than $T_{max} - T_{min} \simeq$ 10-12 hours. This is most pronounced for type D.

Our results therefore support the contention of Rao and Sarabhai (1964) that on most days one has to look for a process in addition to azimuthal streaming to explain the anisotropy of galactic cosmic rays in interplanetary space. The direction of T_{min} in types A and B suggests that a possible candidate for the additional process could be a deficiency of cosmic ray intensity through scattering at magnetic field irregularities along spiralling magnetic lines.

For days on which the anisotropy is weak for energies up to 15 GeV (types B and D) we must conclude that isotropic diffusion must occur in interplanetary space in the neighbourhood of the Earth for primaries up to E_{min}. This would indicate the presence of a large number of magnetic field irregularities of appropriate dimension.

The decrease in the percentage frequency of type D and increase of type A with declining solar activity gives revealing information concerning the change of electromagnetic conditions of interplanetary space. Whichever way we may interpret this change in the frequency, in terms of a decrease of E_{max} (Sarabhai and Subramanian 1963 b, Jacklyn and Humble 1965, preprint) or a decrease of E_{min}, we come to the conclusion that with decreasing solar activity the strength and/or the scale length of the irregularities of the interplanetary magnetic field decrease in sectors of interplanetary space distinguished by the two types of energy spectrum of anisotropy.

A basic assumption which is made in this analysis is that there is an anisotropy in space which can be described by diurnal and semidiurnal components both having the same energy spectrum and latitude dependence of variation. Further it is assumed that the direction of the source is the same for cosmic rays of all energies. These assumptions are only partially true in the light of evidence which indicates that on each day there is in general a modulation of cosmic ray intensity as well as a deficiency along the garden-hose direction and the two processes can have different energy spectra of variation (Sarabhai and Subramanian, to be published, Sarabhai et al. 1965) An extension of the present work using techniques attempting to differentiate the effects of the two processes responsible for the anisotropy is in progress.

Acknowledgments

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THE PROCEEDINGS OF THE NINTH INTERNATIONAL CONFERENCE ON COSMIC RAYS

LONDON, 1965

Modulation II

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1. Introduction

Professor McCracken has presented a very lucid account of some first order effects in the modulation of galactic cosmic rays. Experimental facts concerning them are now fairly well established and these are in general agreement with what one may expect on the basis of the latest versions of models which have been proposed for the electromagnetic conditions in interplanetary space with a plasma wind due to the continuous expansion of the solar corona, as proposed by Parker. I will confine myself mainly to other effects, which in some cases are of second order, where neither the experimental position nor the theoretical interpretation can be considered to be as secure. They are nevertheless of great importance since I believe they are related to zones of activity on the spinning Sun and to conditions of interplanetary space outside the plane of the ecliptic.

In this Conference, which is held during a year of minimum olar activity, we have listened to papers which deal mostly with the 11-year modulation, the 27-day variation and the solar anisotropy of galactic cosmic rays. As may be expected, there are fewer papers on Forbush decreases or solar flare events. A major emphasis in recent studies has been in relating ground-based observations to measurements in satellites and deep space probes. There have been attempts at a theoretical understanding of the effects of solar wind on cosmic rays, of cosmic rays on solar wind, the topology of electromagnetic conditions in the solar system, the diffusion of cosmic rays and the size of the modulating region surrounding the Sun in interstellar space.

2. 11-year modulation

A most interesting problem arises from the observation that the cosmic ray intensity at a given level of solar activity is different during the increasing and decreasing phases of activity in the solar cycle. This has sometimes been referred to as the 'hysteresis' effect in the 11-year modulation. While the Minnesota group (Winckler et al. MOD 2) questions its existence, there is, in my opinion, good evidence to demonstrate that the effect is real. Neher et al. (MOD 1) confirm the hysteresis effect but make the important observation that if the relationship between sunspot number Z and cosmic ray intensity I is examined at different values of Z at sunspot maxima in successive solar cycles, there is more or less a linear relationship between Z and I. This illustrates in a striking way that the heliolatitude of solar activity has an important bearing on the magnitude of the cosmic ray effect which is observed on the Earth. The interpretation fits well with the model proposed by Sarabhai and Subramanian (MOD 6, 1966) for the diffusion of galactic cosmic rays in the solar system. According to them the 11-year modulation is generally most effective not along the solar equatorial plane but in two zones on either side of it corresponding in heliolatitude to the zones of maximum solar activity at any particular period of the solar cycle. The intensity measured at the Earth is then dependent on diffusion along the ecliptic plane as well as on transverse diffusion from regions adjoining it which drift to lower heliolatitudes with advancing phase of the solar cycle.

A second interesting question relates to the size of the modulating region around the Sun at different periods of the solar cycle. This is connected with the distance at which solar plasma wind becomes subsonic. Experimentally, it has been related to the radial gradient of galactic cosmic ray intensity and is also inferred from the delay in the cosmic ray maximum with respect to the minimum of solar activity in the 11-year modulation. I. V. Dorman and L. I. Dorman (Invited Paper) have discussed this extensively. There is, firstly, a difference of opinion amongst groups concerning the time delay. Some (Winckler et al. MOD 2) claim that it is as large as 9 to 12 months, while others put it at about 3 to 4 months. Balasubrahmanyan et al. (SPEC 39) have presented a striking comparison of evidence on this matter from cosmic ray measurements made at ground level with measurements made with balloons and in satellites. The experimental evidence seems to indicate a delay of 3 to 5 months.

The gradient of the cosmic rays and the position of the shock transition have been discussed by Axford (MOD 7) and by Quenby (MOD 9). If the termination of the region of modulation is at 6 to 12 astronomical units from the Sun, there would be difficulty in associating its boundary with the position of the shock transition where the solar wind would become subsonic. A shock transition at a larger distance beyond 30 A.U. would be more reasonable. If indeed the 11-year modulation is related not only to conditions in the plane of the ecliptic but also to regions of interplanetary space at different heliolatitudes (Sarabhai and Subramanian 1966), estimation of the size of the modulating region from the time delay would hardly be justified. In any case one should relate cosmic rays to some other index of solar activity, such as coronal excitation, which is probably more relevant to the solar wind than the sunspot number.

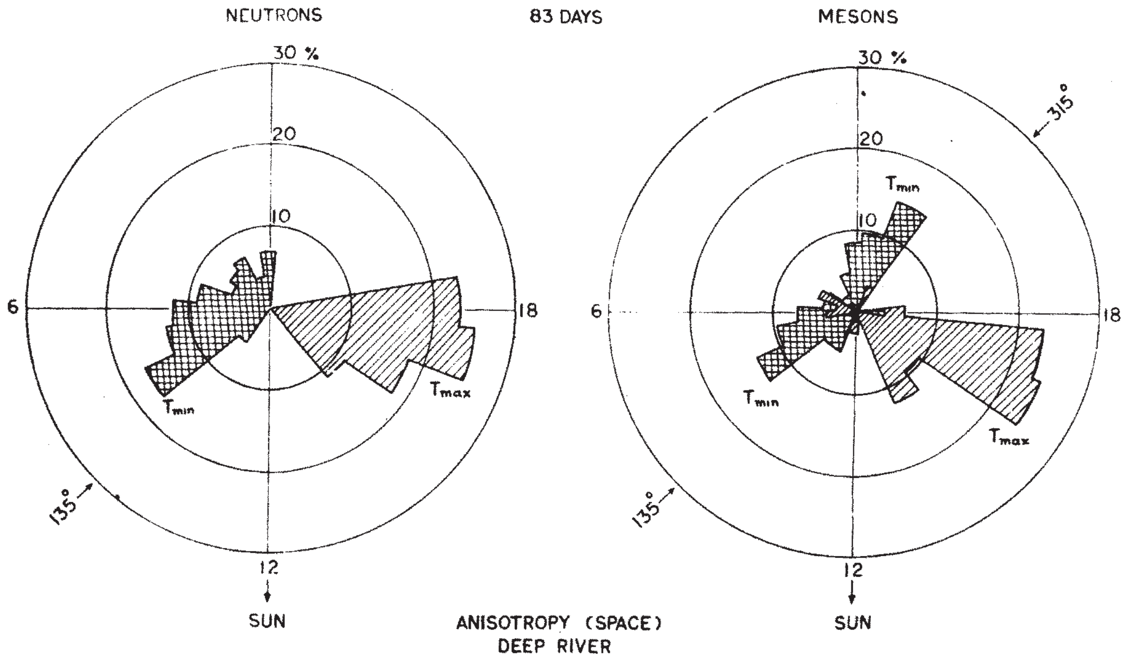
A third crucial question concerns the extent to which cosmic ray intensity at solar minimum at 1 A.U. is depressed with respect to interstellar intensity of galactic cosmic rays. Hildebrand and Silberberg (ACCEL 8) estimate from the ratio L/M of light and medium nuclei that the intensity is significantly depressed even at solar minimum. Studies on the energy spectrum of the primary intensity also support this conclusion.

Rose and Katzman (MOD 12) have drawn attention to a most curious effect which no one quite understands, but which at the present time cannot be explained away as spurious. They point out that in the intensity at Resolute and Ottawa, two stations which are beyond the knee of the latitude effect, the 11-year variations exhibit differences which repeat cyclically each year after 1960 during the current solar cycle.

3. The energy spectrum of variation

It has been noted earlier that the spectrum of variation observed for the 11-year modulation varies from period to period and for Forbush decreases from event to event. Rao and Sarabhai (1964) pointed out that this occurs also for the anisotropy on a day to day basis and this is confirmed by other workers at this Conference (McCracken and Rao MOD 20, Murakami and Kudo MOD 21). A most interesting recent example (figure) of the energy dependent characteristics of the anisotropy comes from a study by Sarabhai et al. (1965 a), which shows that the direction of deficiency responsible for the minimum in the daily variation of meson intensity can flip over from the garden hose to the anti-garden hose direction in space on different days. This occurs for primary cosmic rays in the energy range 10-50 GeV while for 2-10 GeV the minimum is mainly in the garden hose direction towards the Sun. Kitamura (MOD 17) has observed that even on the same day, the daily variation as observed at mountain and sea level stations has times of maxima which are inconsistent with a simple spectrum of variation due to a unique modulating process.

There is now good evidence (Sarabhai and Subramanian MOD 6, MOD 18, 1966) to indicate a modulation in particular directions which, on some days, is more effective at intermediate energies from 10 to 30 GeV than at lower energies.



Orientation histograms of T_{max} and T_{min} for cosmic ray anisotropy in space on individual days from 27th November 1963 to 17th February 1964 (a) from the daily variation of Deep River neutron intensity and (b) from the daily variation of Deep River meson intensity. (Primary data of J. F. Steljes and H. Carmichael.)

4. The anisotropy of cosmic rays

Using the technique of complex demodulation to analyse data for the harmonic components of the daily variation, Ables et al. (MOD 19) have confirmed in unambiguous terms the existence of a persistent semi-diurnal variation with maxima occurring in directions approximately perpendicular to the garden hose direction in interplanetary space. This is consistent with a deficiency along the garden hose or the anti-garden hose direction, which has been pointed out earlier. It is clear then from the work of Sarabhai et al., of Rao and McCracken and of Kitamura that we have at least two processes to consider when we observe the anisotropy on any particular day. The energy spectrum of the two processes is different and, while one of them appears to correspond to an azimuthal drift, the other is in the form of a deficiency along the garden hose or anti-garden hose direction and/or a semi-diurnal modulation oriented perpendicular to the spiralling magnetic lines.

This is in contrast to evidence presented by McCracken and Rao (MOD 20) which shows that the monthly average of the diurnal component corresponds very well to azimuthal streaming in the solar system. One is forced to the conclusion that the additional anisotropy which is observed on a day to day basis is largely related to the sector structure of activity on the Sun which is carried forward with the plasma wind. Averaging data over essentially a complete period of solar rotation appears to suppress the additional effect.

Parker (1964) and Axford (1965) have described a mechanism which should cause an azimuthal streaming of galactic cosmic rays in the solar system. Sarabhai et al. (1965 b) have suggested scattering at field irregularities along spiralling magnetic lines to explain the deficiency which shows up as an additional feature in the anisotropy of galactic cosmic rays. Since effectiveness of scattering depends on the gyroradius of cosmic rays as well as the scale length of irregularities, the process can show up selectively at certain energies, say from 10-30 GeV, without affecting primaries of lower energies to the same extent. If this interpretation is valid, the observation of the sink gives an insight into some features of the configuration of magnetic field irregularities in the solar system and of the 11-year modulation of galactic cosmic rays outside the plane of the ecliptic.

5. Topology of electromagnetic conditions in interplanetary space

Purely from the manner in which solar activity is distributed along belts of latitude and concentrated in regions at certain longitudes on the spinning Sun, broad inferences can be made (Sarabhai and Subramanian 1966) of a plausible topology of interplanetary conditions which are relevant to the modulation of cosmic rays in the solar system through diffusion, acceleration or deceleration.

Of interest to us are magnetic field configurations and their movements. Magnetic field irregularities, in addition, provide a mechanism for transverse diffusion of cosmic rays across field lines. Sarabhai and Subramanian (MOD 6, MOD 18, 19(have suggested a sector structure consisting of co-rotating shock transitions alternating with regions of low and high transverse diffusion. Blast waves advancing radially from the Sun could occur whenever there is a sudden heating of the corona. This sector structure should be enveloped in a shell extending outwards from a distance of 3-10 A.U., where diffusion of cosmic rays would be nearly isotropic on account of a large number of magnetic field irregularities. The shell of isotropic diffusion would finally terminate at a shock transition where solar wind velocity would become subsonic. While much work has been done concerning the streaming of cosmic rays within the solar system, there is need for a quantitative consideration of scattering in permitting transverse diffusion which is most likely connected with many of the effects observed in modulation which have been described in the presen talk.

In conclusion, I would like to express my regret at not having been able, within the period at my disposal, to adequately refe to the many interesting papers which have been presented at this Conference.

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Discussion

S. E. FORBUSH. I think the phase lag between the maximum of cosmic ray intensity and sunspots should not be taken seriously, nor likewise any deduction based upon it.

Over two and a half solar cycles we find no significant lag between the ten-year wave for cosmic ray intensity at the equator and that for the ten-year wave in the newly derived field of the so-called equatorial ring current which results somehow from the flux of solar plasma upon the Earth's magnetosphere.

Galactic cosmic rays in the solar system

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Abstract. In consideration of the zonal distribution of activity on the Sun, a new model is proposed for the diffusion of galactic cosmic rays in the solar system. It is suggested that the processes responsible for the 11-year modulation produce conditions such that the density of galactic cosmic rays on both sides of the solar equatorial plane is depressed with respect to the density along the plane. Thus at 1 A.U. there is generally both a radial gradient of intensity as well as a gradient normal to the equatorial plane. Magnetic field irregularities along the spiralling field lines permit the Earth to sample the cosmic ray intensity characteristic of interplanetary space at high heliolatitudes. Cosmic ray intensity measured on the Earth can then be related to the intensity N_θ due to diffusion along the field lines at each heliolatitude θ and to a factor η_θ which determines, in the neighbourhood of the Earth, the effectiveness of transverse diffusion from higher heliolatitudes. N_θ is connected with processes occurring at large distances from the Sun with a long time constant of the order of months, while η_θ is connected with the distribution of magnetic field irregularities in the interplanetary space in the neighbourhood of the Earth. The model appears promising for understanding a number of observed cosmic ray effects such as the deficiency of cosmic ray intensity along the garden-hose direction, the day to day changes of the energy spectrum of anisotropy, the 27-day variations and some aspects of the 11-year modulation.

1. Introduction

Cosmic ray physicists have generally tended to consider rather an over-simplified picture of activity on the Sun while trying to understand the time variations and the changing anisotropy of galactic cosmic rays observed on the Earth. The approach has proved inadequate to explain many effects, particularly those with time constants from a few hours to some weeks. In the present communication we summarize some insights we receive from taking into account features which have been experimentally studied by astronomers observing the Sun. This leads us to a three-dimensional model of the diffusion of galactic cosmic rays into the solar system and an expression to describe the time variations of cosmic ray intensity.

2. Zonal and meridional distribution of solar activity

We have recently (Sarabhai and Subramanian, to be published) drawn attention to the implications to cosmic ray intensity in the solar system of the well-known zonal character of activity on the Sun. In figure 1 we show the change of mean

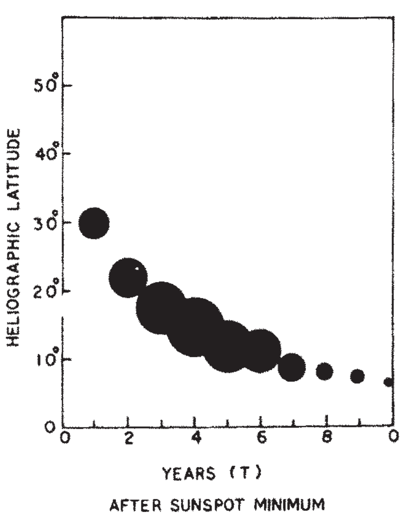

Fig. 1 Diagram showing average heliolatitude and relative sunspot number (proportional to the size of each dot) during a typical solar cycle (Sarabhai and Subramanian, to be published).

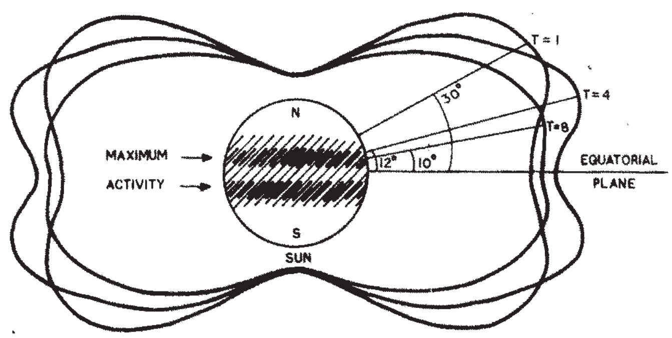

Fig. 2 Hypothetical contours of equal galactic cosmic ray intensity in interplanetary space in a meridional plane of the Sun. Notice that the contour intersects the equatorial plane closer to the Sun at the beginning (T = 1) and during the declining phase (T = 8) of the solar cycle than at T = 4 corresponding to the maximum of solar activity (Sarabhai and Subramanian, to be published).

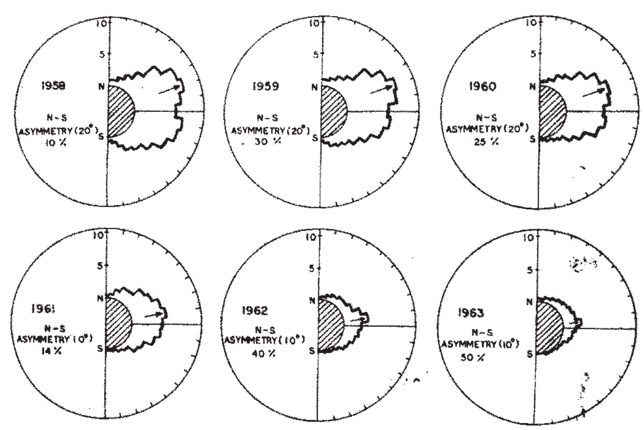

Fig. 3 North-South asymmetry of 5303° coronal emission derived from daily charts of solar activity prepared by Kiepenheuer (Patel et al., to be published).

latitude of sunspots in successive years T after sunspot minimum. The size of each dot is proportional to the annual mean sunspot number. In figure 2 we show hypothetical contours of equal cosmic ray density which would arise through the reduction of number density and mean energy of galactic cosmic rays diffusing inwards as they encounter magnetic field irregularities carried outwards with the solar wind. Note that the radial gradient of cosmic ray density connected with the 11-year cycle is itself a function of heliolatitude. In consequence there is also a gradient of density normal to the equatorial plane. The interesting feature of the model is that at a given distance from the Sun the cosmic ray density on either side of the equatorial plane is lower than in the plane itself. This is only ideally true for, as seen in figure 3 (Patel et al., to be published), the intensity of coronal 5303° emission $\bar{\lambda}$ during the years 1959 to 1963 has a North-South asymmetry in addition to a zonal structure.

$$\text{Asymmetry} = \frac{2(\bar{\lambda}_N^{\theta} - \bar{\lambda}_S^{\theta})}{\bar{\lambda}_N^{\theta} + \bar{\lambda}_S^{\theta}} \times 100\%\,.$$

If the solar wind velocity $v = f(\bar{\lambda})$, as has been suggested elsewhere (Sarabhai and Pai 1963), the velocity as well as the non-uniformity would be greatest at the heliolatitude where $\bar{\lambda}$ is maximum. Thus the density contours in figure 2 would not always be symmetrical on the two sides of the equatorial plane. We should in future consider the possible implications of this to cosmic ray diffusion as well as to the interplanetary magnetic field.

3. Cosmic ray variations

To describe the diffusion of cosmic rays and scattering at magnetic field irregularities, we can consider $\epsilon = K_{\perp}/K_{\parallel}$ where $K_{\perp}, K_{\parallel}$ are the diffusion coefficients perpendicular and along the interplanetary magnetic field respectively (Parker 1964, EFINS Rep.). $\epsilon = 1$ corresponds to isotropic diffusion and $\epsilon \ll 1$ to anistropic diffusion largely along the field. When a fast solar wind blows behind a slow one as a consequence of the sudden expansion of the corona (Parker 1961) or the non-uniformity of solar wind velocity (Sarabhai 1963 a, b), magnetic field irregularities occur. ϵ is therefore a function of (θ, ψ, t, T), where θ and ψ define position in interplanetary space in terms of heliolatitude and longitude and t is time.

We show in figure 4 the distribution in the solar equatorial plane of segments with low, medium and high ϵ due to a hypothetical meridional distribution of activity on the Sun. The segments as well as shock transitions co-rotate with the Sun, but the pattern is contained in a shell where $\epsilon \simeq 1$ owing to the interaction of solar wind from two active regions (Sarabhai 1963 b). When the Earth is in a segment where $\epsilon \ll 1$, it samples an intensity arriving mainly along the equatorial plane. However, if there are scattering centres such as P (figure 5) transverse diffusion between regions at different heliolatitudes becomes possible. The process of scattering, being dependent on the gyroradius of the particle, the scale length of the field irregularity and the average distance between the irregularities, is also related to the pitch angle and the rigidity. Thus the effect of scattering centres is to produce cosmic ray decreases which are either isotropic or show up as deficiencies along the garden-hose or the anti-garden-hose directions, as have indeed been observed (Sarabhai et al. 1965, a, b).

Analytically we can express the intensity at (θ, ψ, t) at $r = 1$ A.U. by

$$N(\psi, t, T) = \int_{\theta} \eta(\theta, \psi, t)\, N_{r=1}(\theta, T)\, d\theta$$

where $N(r, \theta, T)$ is the number density of galactic cosmic rays at point (r, θ) in the solar system T years after a solar activity minimum. In this expression, η represents the effectiveness of scattering centres at time t along the spiralling line passing through (r, θ, ψ) for scattering cosmic rays from heliolatitude θ into the plane of the ecliptic. Variations of galactic cosmic rays with a time constant ranging from a few hours to many days are largely to be attributed to changes in η, apart from the effects of blast waves or shock transitions which produce sudden changes, as in Forbush decreases.

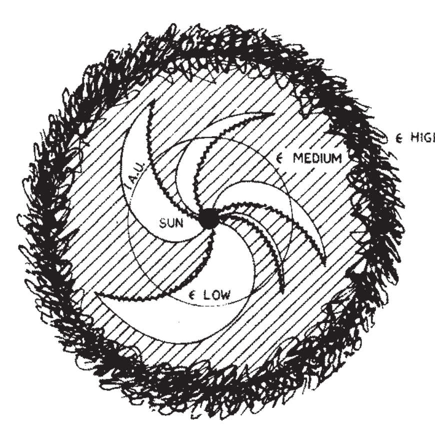

Fig. 4 Diagram showing structuring of interplanetary space into sectors enveloped within a shell due to non-uniformity of solar wind velocity. The sectors consist of shock transitions, regions of magnetic field irregularities and cavities with relatively smooth field lines (Sarabhai and Subramanian, to be published).

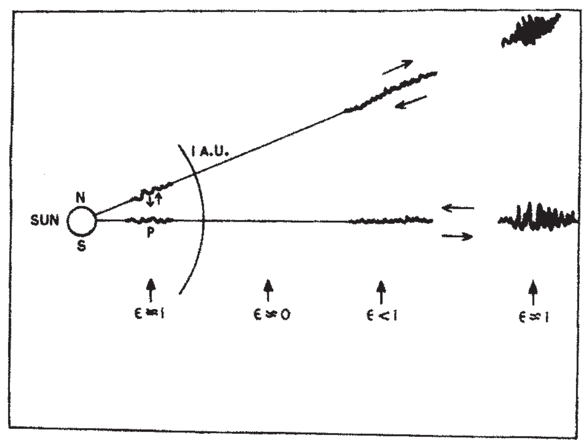

Fig. 5 An idealized diagram illustrating some features in a solar meridional plane of the diffusion of galactic cosmic rays (E < 50 GeV) into the solar system. Interplanetary space has typically four types of regions: (i) where (as at P) $\epsilon \simeq 1$ due to magnetic field irregularities, (ii) where $\epsilon \ll 1$, (iii) where $\epsilon < 1$ and (iv) where $\epsilon \simeq 1$ at a large distance (~ 10 A. U).

4. Conclusion

The important features of the model proposed here are:

(a) There is a gradient of cosmic ray density normal to the equatorial plane in addition to the radial gradient.

(b) Cosmic ray time variations are related to large scale diffusion as well as to local regions of magnetic field irregularities where transverse diffusion occurs between regions at different heliolatitudes.

(c) The topology of regions of low, medium and high ϵ in interplanetary space is related to changes of solar activity over active regions and to longitudinal gradients of solar wind velocity.

The model is likely to help us to understand the following observations:

(a) The time of maximum and the time of minimum in the anisotropy being separated by 8 to 9 hours (Rao and Sarabhai 1964) with a sink along the direction of the spiralling magnetic field (Sarabhai et al. 1965 a, b).

(b) The change of energy spectrum of the variation of anisotropy from day to day (Rao and Sarabhai 1964).

(c) The 27-day changes of cosmic ray intensity which have been shown to be decreases (van Heerden and Thambyahpillai 1955).

(d) The observation that the cosmic ray intensity at a given level of sunspot activity is different in the ascending and the descending phases of the solar cycle of activity (Simpson 1963).

Acknowledgments

The authors are grateful to Professor E. N. Parker, Professor S. Olbert, Professor K. G. McCracken, Professor W. I. Axford and Dr. G. L. Pai for helpful discussions.

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Discussion

K. G. McCRACKEN. Just before sunspot minimum, you point out that the contours of cosmic ray density are furthest from the Sun at a heliographic latitude of 7° to 10°, and that this results in a 'sink' down the Archimedes spiral (towards the Sun). The heliographic equator, and the ecliptic, are inclined at an angle of 7°, hence twice a year the Earth is at a heliographic latitude of 7°. At this time your model predicts a 'source' down the Archimedes spiral, hence $T_{max} - T_{min}$, and the shape of the daily intensity variation, should exhibit semi-annual variations. Are such variations seen?

V. SARABHAI. We have not yet looked for this effect in the anisotropy. However, it does seem that during 1962, when the disturbing influence of cosmic ray storms was not great, the isotropic intensity had a semi-annual wave as would arise in the suggested model.

G. SUBRAMANIAN. There is some evidence for a semi-annual wave in the cosmic ray mean intensity measured by high latitude neutron detectors (Climax, Chicago, Manson, Sulphur Mountain, Deep River) during the period 1962-1963. The depressions of intensity are seen during March-April and September which seem to be in agreement with the epochs expected from the model proposed above.

U. R. RAO. I would like to make two comments. Firstly, with regard to Dr. McCracken's question, the time difference between T_{max} and T_{min} can vary from about 7 to 11 hours, even though on a large number of days it is only 8 hours. Secondly, I do not think it is possible to explain the variability of the spectrum of diurnal variations on a day to day basis (which can assume any exponent between +1.0 and −2.0) using Dr. Sarabhai's model.

Sector Structure of Solar Activity and the Electromagnetic conditions of Interplanetary Space.

By

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Ahmedabad.

ABSTRACT

The sector structure of the interplanetary magnetic field as revealed by the IMP 1 satellite is compared with a derived index of the coronal 5303 Å emission intensity at c.m.p. at the solar equator. It is observed that sectors where the magnetic field lines point outwards from the sun are associated with highly excited regions where the solar wind velocity is enhanced.

The correlated changes in K_p and cosmic ray intensity show that high K_p is caused by at least two different types of interplanetary conditions. In one case where high K_p is associated with decreases of cosmic ray intensity, coronal conditions indicate the development of a shock transition due to fast wind blowing behind slow. In the other condition when high K_p occurs with recovery of cosmic ray intensity, the earth emerges out of a "cavity' which develops due to slow plasma following fast plasma.

1. Introduction

Attempts have been made by Pai and Sarabhai[1] to relate the velocity v of solar wind to a derived index of solar coronal 5303°A intensity near the equator at CMP on the sun. It has been demonstrated from studies of geomagnetic disturbances and cosmic ray variation that large v corresponds to high value of intensity λ and conversely. In the present communication we examine the implications of this suggestion for the period 27th November 1963 to 17th February 1964 during which the sector structure of the interplanetary magnetic field has been investigated by Wilcox et al[2]. As in the earlier communication we use for the solar coronal intensity an index $\bar{\lambda}_n$ given by

$$\bar{\lambda}_n = \lambda^{\circ E}_{n-7} + \lambda^{\circ W}_{n+7}$$

where n is the day of CMP, $\lambda^{\circ E}_{n-7}$ is the coronal intensity on the east limb seven days earlier and $\lambda^{\circ W}_{n+7}$ is the coronal intensity on the west limb seven days later.

2. Coronal intensity and sector structure of interplanetary magnetic field.

The IMP 1 satellite which measured the interplanetary magnetic field for 3 solar rotations (1784 - 86) revealed a quasi-stationary corotating sector structure. The observed direction of the interplanetary magnetic field was consistent with the Archimedian spiral structure as predicted by Parker, but the sense of the field changed from time to time. There were 3 sectors each of width 2/7 of the total circumference, where the interplanetary magnetic field was alternately directed either away or towards the Sun and one sector of width 1/7 where the field was directed towards the Sun. In Figure (1) we have super-imposed the 27-day pattern of $\overline{\lambda}$ (0°) averaged over the same 3 solar rotations over this sector structure. The comparison of $\overline{\lambda}$ values with the sense of the interplanetary field shows that the sectors where the field is away from the Sun correspond to enhanced coronal emission, while the low or normal coronal intensity corresponds to field towards the Sun.

3. <u>Correlated changes of cosmic ray intensity and K_p.</u>

It is interesting to examine the changes in ΣK_p and cosmic ray intensity during these 3 solar rotations. Figure 2 shows the 27-day patterns of $\overline{\lambda}$ (0°), ΣK_p and Deep River neutron intensity. The important features to take note of are the following:-

(1) ΣK_p shows high peaks in all the sectors, irrespective of whether the field is away or towards the sun.

(2) Cosmic ray neutron intensity at Deep River is initially decreasing in both the sectors where the field is away from the Sun but is increasing in the large sector where the field is towa[illegible] the

(3) The comparison between ΣK_p and cosmic ray intensity shows that only two high ΣK_p peaks can be associated with low cosmic ray intensity, while the other peak of high K_p is associated with increasing cosmic ray intensity.

4. Conclusions

We confirm an earlier observation of Sarabhai et al[3] that high K_p is caused by at least two different types of conditions in interplanetary space. In one case, where high K_p coincides with decreases of cosmic ray intensity, coronal conditions indicate the development of a shock transition due to fast plasma blowing behind slow. In the other case high K_p occurs with recovery of cosmic ray intensity. This is consistent with the suggestion that it is due to the earth emerging from a region of low plasma density into one of high plasma density, a condition which should occur when a cavity is formed due to slow plasma following fast plasma.

The most interesting observation which emerges from a comparison of the IMP 1 data with coronal intensity is that the field lines pointing outwards are associated with highly excited regions, where the solar wind velocity is enhanced. It is obviously inappropriate to generalise from evidence of three rotations that the indicated relationship is, in fact, characteristic of solar activity and the direction of the field line. However, the relationship is sufficiently intriguing to merit further study by comparison of the data concerning interplanetary magnetic field from later experiments in outer space.

5. Acknowledgement

The authors are thankful to the Department of Atomic Energy of the Government of India for financial support.

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Caption for the Figures

Fig. 1 - 27-day pattern of $\bar{\lambda}$ (0^{o}) superimposed over the sector structure of the interplanetary magnetic field. The arrows indicate the direction of the interplanetary magnetic field.

Fig. 2 - 27-day patterns of $\bar{\lambda}$ (0^{o}), ΣK_p and cosmic ray neutron intensity at Deep River averaged over 3 solar rotations (1784 - 86). The + and - signs indicate the sectors where the magnetic field is directed away and towards the Sun respectively.

27- DAY PATTERN OF $\bar{\lambda}$ (0°) SUPERIMPOSED OVER THE SECTOR STRUCTURE

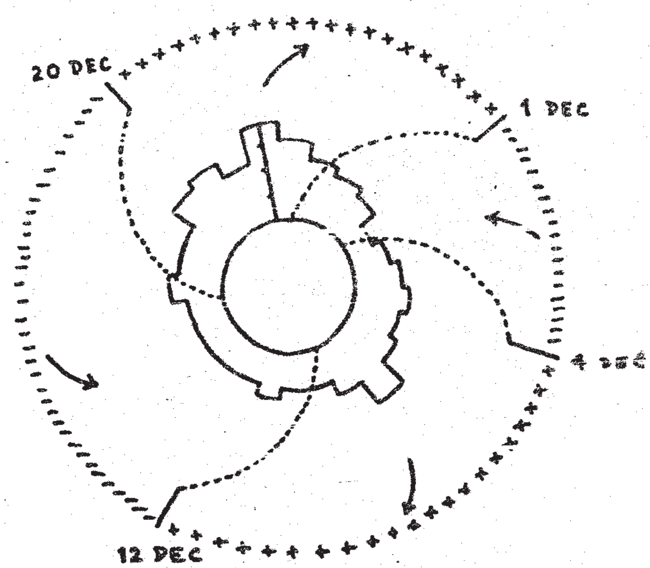

Fig. 1

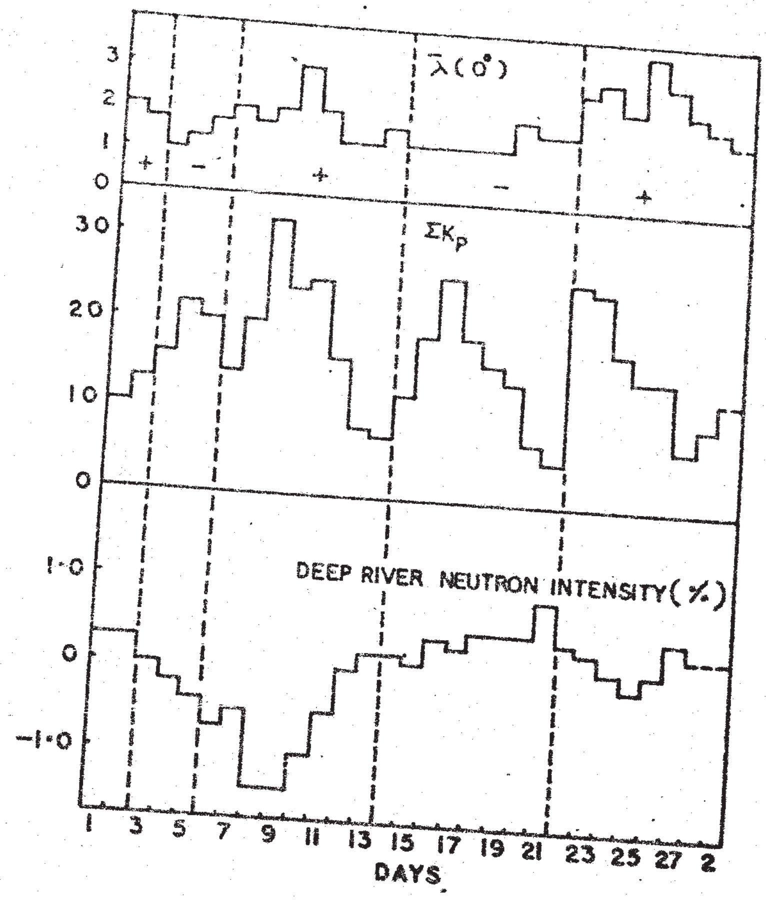

Fig. 2

Changes In The Characteristics Of The Anisotropy Of Galactic Cosmic Rays With Solar Activity.

By

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and
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Abstract

Results are obtained from a more rigorous study of the cosmic ray anisotropy than that presented by Sarabhai and Subramanian at the 9th International Conference on Cosmic Rays, London 1965. This is accomplished by considering only those days on which good resolution is possible in the determination of the spectrum of variation. Two groups are obtained; for the first, the exponent χ ranges from 0 to -1.0, while E_{min} has a value 2 GeV and for the other χ ranges from +1.0 to -1.0 while E_{min} = 15 GeV.

With declining solar activity the number of days in Group I (E_{min} = 2 GeV) increases by 10 per cent and in Group II (E_{min} = 15 GeV) decreases by the same amount, in conformity with our earlier results. Other characteristics of the anisotropy remain unchanged with solar activity. The semidiurnal component is more predominant in Group II than in Group I.

Using the days in Group I and Group II as epochs a Chree analysis is done on solar (λ 5303°), Geomagnetic (ΣK_p) and cosmic ray data (Deep River neutron intensity). The results indicate that on days corresponding to Group I electromagnetic conditions of interplanetary plasma are similar to what one would expect in a 'Cavity' when slow plasma trails behind fast plasma. Days in Group II correspond to conditions in the shock front

1. Introduction

Sarabhai and Subramanian[1] have earlier applied the method of best fit to daily variation of cosmic ray intensity, observed by neutron monitors at Huancayo, Churchill, Mawson and Mt.Norikura and cubical meson telescopes at Mawson and Churchill to determine for each day from 1958 to 1963 the amplitude, the directions in space of maximum and minimum intensity and the energy spectrum of variation of the anisotropy of galactic cosmic rays. Out of 36 combinations of assumed values for x and E_{min}, in the relations $\delta D(E)/D(E) = aE^x$ and $\delta D(E)/D(E) = 0$ for $E < E_{min}$, the authors find that 4 combinations account for more than 70 per cent of the total days considered. They are:

Type of spectrum	Exponent x	E_{min} (GeV)
A	-1	2 - 6
B	-1	15
C	+0.2, +0.4	2
D	1	15

In the present paper, we consider implications of the degree of resolution which is possible in our determination of spectrum of variation under varying conditions.

2. Two types of spectra of variation of anisotropy on individual days

Though in a technical sense there is only one spectrum of variation that fits the data best on any particular day, the selection is not really unambiguous with respect to certain other spectra on account of the lack of resolution within tolerance limits imposed by experimental conditions. Limitations of space do not permit a detailed description of the criteria by which the tolerance limits are chosen. While the methocology will be described in detail elsewhere, it is important to note that as a result of looking deeper into this question, we are able to unambiguously identify 2 rather than 4 types of spectra. Spectrum A remains by itself. However, when E_{min} = 2 GeV, other spectra with exponents -0.8, -0.6, -0.4 and -0.2, are almost equally consistent with the data as the exponent -1.0. Thus, in the present paper, we refer to days belonging to Group I when they have spectrum of variation with E_{min} = 2 GeV and an exponent ranging from -0.2 to -1.0. The second group which appears unambiguously consists of days having E_{min} = 15 GeV, but with exponent which could be any value from -1.0 to +1.0. Days having this spectrum, i.e. with E_{min} = 15 GeV are referred to as Group II days. With the net-work of stations which we have used for the present analysis, there is poor resolution in determination of the energy spectrum on 54% of the total days for which data are available.

3. Characteristics of the anisotropy on days with unambiguously identified spectrum of variation

Through an examination of the histograms of characteristics of the daily variation on individual days in the two groups, we come

(a) As shown in table I, the semi-diurnal component is significantly more predominant in Group II than in Group I. This is reflected in the ratio, as shown in the last column of table I, of the number of days on which $T_{max} - T_{min} = 10$, 12 or 14 hours ~~and~~ to the number of days on which it is 6 and 8 hours. Moreover, Group II days occur about 1½ times more frequently than Group I days.

(b) The frequency of occurrence of Group I days increases from 24.3 per cent to 34.6 per cent with declining solar activity from 1958 to 1963. Simultaneously the frequency of Group II days decreases from 50.7 per cent to 40.2 per cent. The percentage is taken with respect to days on which the spectrum determination is significant, which form 46% of the days on which data are available.

(c) From a comparison of coronal 5303 derived index at central meridian passage (Pai and Sarabhai[2]) as well as of K_p, it is observed that Group I days occur during a condition of interplanetary space referred to as "cavity" when slow plasma follows fast, geomagnetic disturbance is low and cosmic ray intensity is recovering. On the other hand, Group II days occur under conditions when fast plasma blows behind slow and K_p is relatively more disturbed (Sarabhai[3]).

4. Conclusions

The present analysis is consistent with the broad picture of change of interplanetary conditions with 11-year cycle and its effects on cosmic ray intensity as visualised by Sarabhai and Subramanian[4]. The Group I days are associated with the earth being in a cavity, where the field lines have relatively few magnetic field irregularities. In consequence, there is little diffusion transverse to the plane of the ecliptic and the effect of azimuthal drift[5,6] of cosmic rays is seen down to the lowest energies detectable with the instrument. Moreover, because of the relative absence of magnetic field irregularities, there is hardly any transverse scattering which can give rise to a deficiency of cosmic ray intensity along the garden hose direction as suggested by Sarabhai, Pai and Wada[7] and the semi-diurnal component is therefore unimportant. The per cent days in Group I increases with decreasing solar activity due to the decrease of the number of active regions making it possible for cavities to extend to larger distances from the sun than would otherwise be the case.

The Group II days are characterised by E_{min} = 15 GeV. The smearing out of the anisotropy in the lower energy range $E < E_{min}$, must be due to magnetic field irregularities in the inner solar system. The same irregularities would contribute to a T_{min} in the garden hose direction giving rise to a significant semi-diurnal component which is also observed. The magnetic field irregularities would also contribute to geomagnetic disturbance (Dessler and Fejer[8]). Finally, it is to be expected that Group II days would decrease in relative frequency with decrease of solar activity.

5. Acknowledgement

The authors are grateful to the Department of Atomic Energy, Government of India for financial assistance.

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Table I

Characteristics of the Anisotropy on days with unambiguously identified spectrum of variation

Group	X	E_{min} GeV	E_{max} GeV	% frequency (1958-63)	Most probable values of			Ratio of $T_{max} - T_{min}$ $\frac{10+12+14}{6+8}$
					A mean	T Max	T Min	
I	1.0 -1.0	2	600	29.2	1.4(1.2)	17.0 ± 1.06	6.9 ±0.9	0.64
II	+1.0 -1.0	15	600	45.3	1.33(0.7)	15.7 ± 1.7	7.5 ±1.5	0.18

Root mean square deviations are shown in the brackets.

DISCUSSION

RAO: In your chree analysis, you have averaged a number of epochs. The dispersion of values from event to event can be very large. The average behaviour of various parameters say decrease of cosmic ray intensity may be a result of two large decreases out of the various events. I suggest that instead of averaging over epochs, if you average a few similar stations for the same epoch, you will achieve good statistical accuracy and at the same time avoid the above criticism.

An Explanation of the Semidiurnal Anisotropy of Galactic Cosmic Rays

By

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Physical Research Laboratory, Ahmedabad.

ABSTRACT

Sarabhai and Subramanian have suggested that at most periods of the solar cycle density at a given radial distance from the sun would be less along the solar equatorial plane than on either side of it. It is pointed out in the present communication that a cosmic ray telescope scanning the solar equatorial plane would observe along the direction of the spiralling magnetic field intensity corresponding to the density in the equatorial plane. However, when viewing along a direction perpendicular to the spiralling field the same telescope would observe intensity corresponding to higher cosmic ray density at a distance of the order of a gyroradius above or below the equatorial plane. This would give rise to a semidiurnal anisotropy at a detector on the spinning earth, the direction of maximum of the anisotropy being perpendicular to the magnetic field. Because of the dependence of the effect on the gyroradius stronger anisotropy should be observed for higher energy particles. The dependence of the anisotropy on the asymptotic latitude of viewing is also such that the semidiurnal anisotropy should be more pronounced at equatorial stations.

1. Introduction

A semidiurnal variation in cosmic ray intensity has long been observed but owing to its small magnitude and variability a consistent picture of the anisotropy was not available (Nicolson and Sarabhai[1], Sekido and Yoshida[2], Rao and Sarabhai[3], Katzman and Venkatesan[4], Ahluwalia[5]). Recently, Sarabhai et al[6] have conclusively demonstrated that a deficiency of cosmic rays is often observed along the garden hose direction towards the sun. On harmonically analysing, this would appear as a semidiurnal component with maximum perpendicular to the garden hose direction. Applying the technique of numerical filtering to the data of neutron monitors, Ables et al[7] conclude that a semidiurnal anisotropy persists throughout the period 1954-64. The direction of maximum of the anisotropy is found to be perpendicular to the average spiral interplanetary magnetic field lines and the average magnitude of the anisotropy is about .1%.

Models of interplanetary space assuming spherically symmetrical helio-centric modulation have been proposed by Parker[8], Axford[9] and Krymskiy[10] to explain satisfactorily the average characteristics of the diurnal anisotropy of cosmic ray intensity. It is the purpose of this present paper to draw attention to the possibility of explaining the observed semidiurnal component using the model of the diffusion of galactic cosmic rays in interplanetary space recently proposed by Sarabhai and Subramanian[11].

2. The distribution of Cosmic Ray Intensity in Interplanetary Space.

In the vicinity of the earth recent measurements of interplanetary magnetic field by Ness et al[12] indicate that the field lines are often relatively undisturbed. When this is so, the gradient of cosmic ray density along the tubes of force will be much smaller than across different tubes. Moreover, on account of the dependence of solar activity on heliolatitude, the cosmic ray density associated with tubes of force at different heliolatitudes would differ.

In figure 1 is shown the distribution of coronal brightness as indicated by the green coronal emission λ 5303°, obtained at each 10° of heliolatitude from solar maps supplied by Kiepenheuer. The distribution during the year of maximum solar activity, 1958, is compared with that of 1963 when the solar activity was approaching its minimum. The radius vector at any latitude corresponds to the annual mean value of the coronal index at that latitude. At all times the coronal excitation is far from spherically symmetric, the equatorial regions being brighter than polar regions. The deviation from spherical symmetry is more pronounced during years of sunspot minimum, 1962-63, than during years of higher solar activity 1958-59. Moreover, during the last solar cycle there was a N-S asymmetry, the brightness at any heliolatitude of the northern hemisphere of the sun being more than the activity at a corresponding latitude of the southern hemisphere. Following Sarabhai and Subramanian's model, the implications of the observed distribution of coronal activity are as follows:-

(a) During sunspot maximum, there are two minima of cosmic ray density at heliolatitudes 10 to 20° north and south of the equatorial plane.

(b) Approaching sunspot minimum, there is only one minimum of cosmic ray density between 5 and 10° north heliolatitude.

3. <u>Semidiurnal anisotropy</u>

In figure 2, the interplanetary magnetic field, is assumed to be uniform and OY representing its direction is away from the observer, perpendicular to the plane of the paper. The cosmic ray density increases in the directions oz, oz' perpendicular to the magnetic field and is constant along the plane OYX. The density of cosmic rays can be expressed as a function N(z) of the position of the guiding center of the particles. Consider particles of rigidity R (GV/C.) and gyroradius $\rho_\perp$, when the pitch angle is 90°. The density measured while looking along the directions OY, OY' is N(0), since the gyrocenters of particles which arrive along these directions are situated at the plane z=0. On the other hand, when the direction of viewing is ox, or ox', the gyrocenter of the particle is situated at $z = \rho_\perp$ or $-\rho_\perp$ and the density observed will be $N(+\rho_\perp)$ or $N(-\rho_\perp)$. Thus maximum flux is measured twice during each rotation while viewing along directions perpendicular to the lines of force. A semi-diurnal variation arises when observed by a detector fixed to the spinning earth as shown in figure 2b, where the plane of minimum density corresponds to the ecliptic plane, the direction of magnetic field corresponds to ox and oz is normal to the ecliptic.

For a cosmic ray telescope which is scanning a latitude λ of the celestial sphere, using trigonometrical relationships, it can be shown:

$$Z = \rho_\perp \cos\lambda \; \mathrm{Sin}\, \omega\,(t - to) \quad \ldots \quad (1)$$

where ω is the angular velocity of the rotation of the earth and t is the time. The magnitude of the anisotropy is given by

$$A = \frac{N\ (Z) - N\ (0)}{N\ (0)} \quad \ldots \quad (2)$$

4. Discussion

A quantitative discussion is possible only when the cosmic ray density distribution perpendicular to the ecliptic plane is known. For the sake of illustration, when the increase of cosmic ray intensity with Z is a function symmetric about Z = Zo, we express the dependence by

$$N\ (Z) = N\ (Zo)\ (\ 1 + C_1\ (Z-Zo)^2\ )\ \text{or}\ N(Zo)\ (1-C_2\ \mathrm{Cos}\ (Z-Zo) \quad \ldots . (3)$$

from which the variation with time of cosmic ray intensity is given by

$$I(t) = b\left[\rho_\perp^2 \cos^2\lambda \cos 2\omega(t-t_0) - 2Z_0\, \rho_\perp \cos\lambda \sin\omega(t-t_0) + Z_0^2\right]$$

The first term on the right hand side of equation (4) represents a semidiurnal anisotropy. It is clear that

(1) the magnitude of the anisotropy falls off as $\cos^2\lambda$ in contrast to $\cos\lambda$ for diurnal anisotropy,

(2) the dependence of the anisotropy on the energy of primary particles is given by $6\rho_{\perp}^2$ and a positive exponent for the spectrum of variation is likely, and

(3) during the period of maximum of the solar activity the semidiurnal component should be absent for low rigidity particles $P \leqslant P\ min = (300\ H_o\ L)$ as the cosmic ray density perpendicular to the equatorial plane vanishes up to a certain distance L.

This is in accordance with the experimental data of equatorial stations which show higher amplitudes of the anisotropy in spite of their wide cones of acceptance. The magnitude of the semidiurnal anisotropy will be much more variable than the diurnal component due to change in χ, the upper limiting energy, E_{max}, and the lower limiting energy for modulation, E_{min}. Blast waves causing decreases of cosmic ray intensity in a large region around the earth, and irregularities due to the nonuniformity of solar wind velocity can be expected to wipe out any density gradients perpendicular to the equatorial plane. Therefore, on days with high K_p semidiurnal anisotropy should be less. This agrees with the finding of Sekido & Yoshida[2].

The basic assumption regarding the cosmic ray density gradients perpendicular to the solar equatorial plane in interplanetary space is not yet experimentally verified. Further only an average picture of semidiurnal anisotropy is explained here. However, the model is a promising candidate to explain the direction of maximum of the anisotropy, its energy spectrum and latitude dependence.

5. Acknowledgement

The authors are grateful to Dr.U.R.Rao and Mr.P.N.Pathak for stimulating discussions. Support to this investigation from the Department of Atomic Energy, Government of India, is gratefully acknowledged.

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Figure Captions

Fig. 1 - The index of green coronal emission 5303°, obtained at each 10° of heliolatitude from the solar maps of Fraunhofer Institute during the year of maximum solar activity, 1958, is compared with 1963 which is very near the minimum of solar activity. The radius vector at any latitude corresponds to the annual mean value of the coronal index at that latitude.

The values of the coronal index for the year 1963 have been multiplied by 3. Note-worthy features of the coronal activity are the pronounced deviation from spherical symmetry and the increased north-south asymmetry during the year 1963 as compared to 1958.

Fig. 2 - (a) The direction of the interplanetary magnetic field OY and the plane OXY at which cosmic ray intensity is minimum are shown. The centers of gyration of particles which arrive along OX, OX' are at distances $\rho_{\perp}$ and $-\rho_{\perp}$ respectively, where $\rho_{\perp}$ is the gyroradius when the pitch angle is 90°.

(b) A semidiurnal anisotropy will be observed with its direction of maximum perpendicular to the interplanetary magnetic field as the earth spins.

DISCUSSION

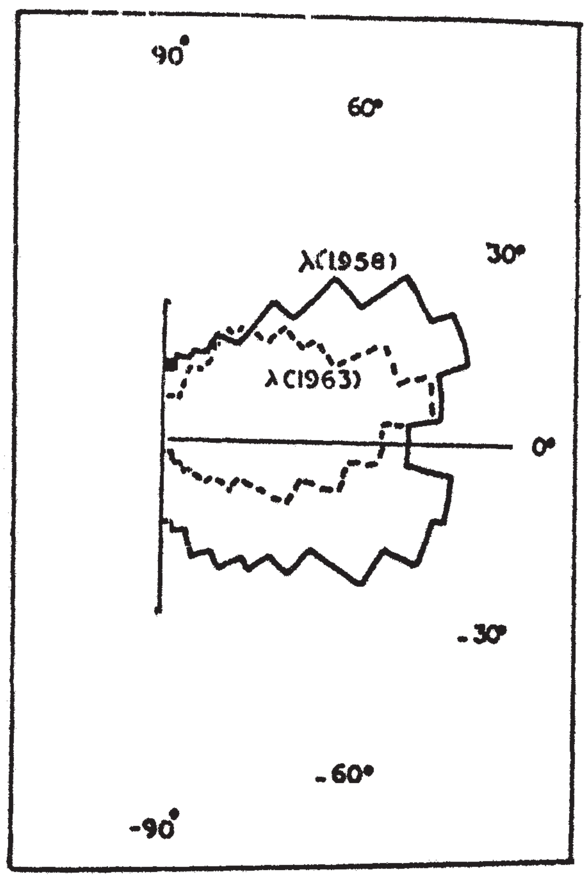
DAMLE: If the asymmetry of distribution of coronal intensity gives rise to the diurnal variation, then it looks from the slide shown that during IGY (1958) there should be no diurnal variation.

SUBRAMANIAN: The diurnal variation caused by a cosmic ray density gradient perpendicular to the magnetic line of force will reverse its direction when the magnetic field reverses its direction. This diurnal component is then different from the steady diurnal component caused by streaming of cosmic ray particles at 1800 hour direction, which has almost constant amplitude during the present solar cycle.

KUNTE: Whether difference between 1958 & 1963 intensities as shown by you, arise only due to solar activity or some other reasons?

SUBRAMANIAN: It is only due to solar activity decrease in 1965 from 1958.

LATITUDE DEPENDENCE OF THE INTENSITY OF 5303 CORONAL EMISSION



FIG·I

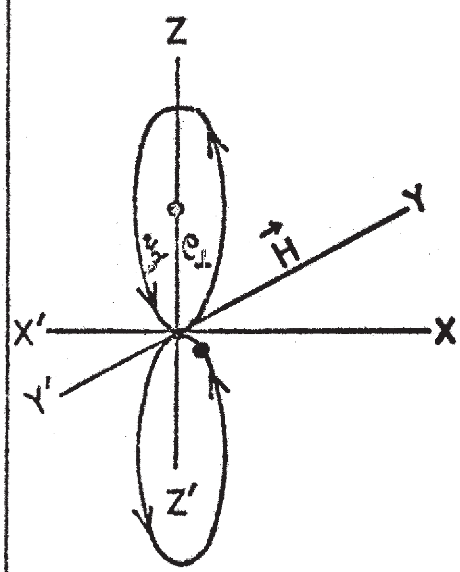


FIG. 2A

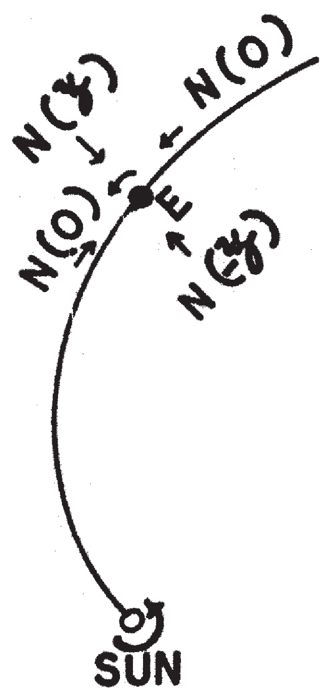


FIG. 2B

Paper g.9 presented on Monday, the 17th May 1965
in session g - COSPAR Symposium held in May 1965
in Mar del Plata, Argentina.

INTERPLANETARY MAGNETIC FIELD AND THE ANISOTROPY OF GALACTIC COSMIC RAYS

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and

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1. Cosmic ray anisotropy related to direction of interplanetary magnetic field.

The anisotropy of galactic cosmic rays derived from the daily variation of the intensity measured by the Deep River Neutron Monitor*** on each day from November 27, 1963 to February 17, 1964 has recently been studied by us[1]. During the same period, the interplanetary magnetic field was also measured[2] on IMP-1 satellite. Figure 1(a) shows the orientation histogram of the anisotropy, expressed in terms of the directions with respect to the earth-sun line of maximum intensity T_{max} and of minimum intensity T_{min} outside the influence of the geomagnetic field. We have here direct evidence for the first time that on a majority of days there is a virtual sink of galactic cosmic rays towards the sun along the spiralling interplanetary magnetic field.

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** On leave of absence from the Institute of Physical and Chemical Research, Tokyo, Japan.

*** We are grateful to M.Steljes and H.Carmichael for supplying us the Deep River data.

Further analysis of unpublished data from the Deep River high counting rate meson detector, kindly supplied by Steljes and Carmichael, has now been conducted. We derive T_{max} and T_{min} from the dailv variation of meson intensity using an identical procedure to the one adopted for the intensity of the super neutron monitor. The directions of anisotropy observed by the meson detector are shown in the orientation histogram in figure 1(b). A comparison of the two histograms reveals a similarity for T_{max}, but a marked difference for T_{min}. Even though the asymptotic cones of acceptance of the two detectors sample almost identical regions of space, the detectors have quite different response characteristics to the primary energy spectrum. We therefore conclude that the experimental results demonstrate that the direction of T_{min} is energy dependent. While for low energy galactic cosmic ray primaries (1 - 10 GeV) T_{min} is generally along the garden hose direction towards the sun, for high energy primaries (10 - 50 GeV) T_{min} can occur either along the garden hose direction or along the anti-garden hose direction.

2. Effect of scattering centres along spiralling magnetic lines

In our earlier communication[1] we have suggested that the sink along the garden hose direction is probably related to the scattering by magnetic field irregularities of cosmic rays as they penetrate into the solar system along the spiralling lines of force and mirror at some point close to the sun. Particles which are scattered out would reappear as isotropic intensity, but the net addition in the direction in question cannot equal the depletion as the particles scattered towards the sun and guided along the garden hose direction have a probability of getting absorbed in the sun's atmosphere.

The discovery of the direction of T_{min} for high energy primaries on many days along the anti-garden hose direction has recently led Sarabhai and Subramanian[3] to suggest an additional mechanism, besides the absorption of scattered intensity in the sun, as a possible cause for the deficiency. They suggest a model (figure 2) which postulates that due to a higher degree of irregularity of solar wind velocity on both sides of the solar equatorial plane corresponding to the two zones of activity, the galactic cosmic ray intensity in the solar system at helio-latitudes 5 to 25^{o} in the north and south must be depressed with respect to the intensity along the equatorial plane and at higher helio-latitudes. In the absence of magnetic scattering centres along spiralling magnetic lines in the vicinity of the earth, a detector mainly samples intensity of galactic cosmic rays diffusing along the equatorial plane. However, when scattering centres are present in the region close to the earth, significant transverse diffusion is possible permitting the detector to partly measure reduced intensity characteristic of higher helio-latitudes. Thus, whenever there are fresh scattering centres in the region close to the earth, one would observe decreases of cosmic ray intensity. The decrease is on the average anisotropic with maximum effect along the spiralling magnetic field.

Magnetic field irregularities could be produced by the interaction of fast solar wind with slow[4], or due to the sudden expansion of the corona causing a blast wave[5], or through plasma instability. The observation that for high energy primaries T_{min} can flip over from garden hose to the anti-garden hose direction must mean that irregularities of large scale length with an appropriate strength of magnetic field can be produced in the earth-sun region or beyond. However, irregularities of small scale length occur principally in the earth-sun region.

3. Conclusion

The full implications of the model of Sarabhai and Subramanian are being presented elsewhere. There is now an attractive explanation for the flipping over of the direction in which the deficiency is observed in the anisotropy. We have also the basis for an integrated theory of time variations of galactic cosmic ray intensity, of their energy spectrum and of their solar anisotropy.

The underlying ideas presented here are capable of being tested experimentally through the observation of the energy spectrum of galactic cosmic rays in the region 1 to 30 GeV by detectors, in space-craft outside the magnetosphere, looking along and away from the garden hose direction. A consequence of the present model would be that through the occurrence of magnetic field irregularities along the spiralling lines of force, deficiency of intensity would appear selectively at certain regions of the energy spectrum corresponding to the matching of the scale length of the irregularity with the Larmor radius of cosmic rays in the magnetic field in question. Thus one has the means of studying the size distribution of field irregularities in the sun-earth region and for some distance beyond the orbit of the earth.

4. Acknowledgement

The authors are grateful to Professor K.G.McCracken and Professor S.Olbert for stimulating discussions. One of the authors (V.Sarabhai) is grateful to the Department of Atomic Energy, Government of India, for financial assistance. Also this work is supported in part through funds provided by the U.S. Atomic Energy Commission under Contract No.(30-1) 2098 and this is gratefully acknowledged.

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LEGEND

Figure 1 - Orientation histograms of T_{max} and T_{min} for cosmic ray anisotropy in space on individual days from 27 November 1963 to 17 February 1964.

(a) From the daily variation of Deep River neutron intensity.

(b) From the daily variation of Deep River meson intensity.

Primary data of Steljes and Carmichael.

Figure 2 - Diagramatical representation of contour of equal density of galactic cosmic rays on a solar meridianal plane following the model of Sarabhai and Subramanian.

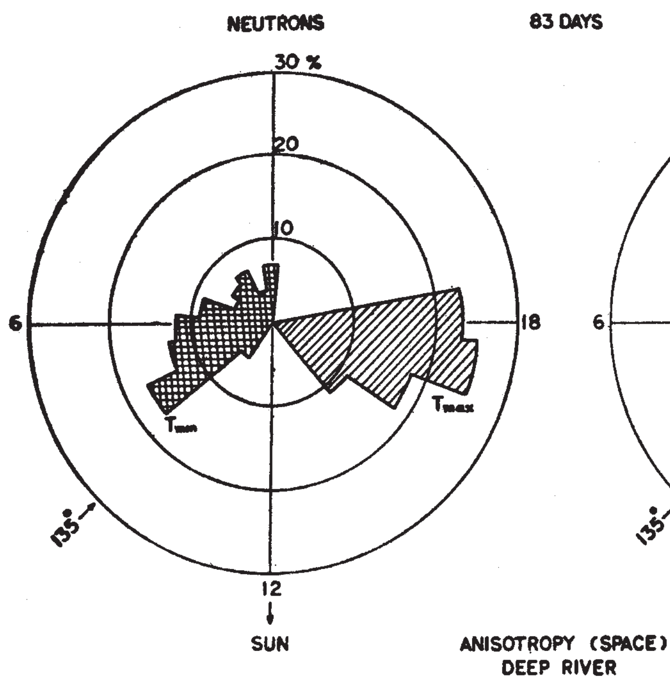
NEUTRONS
83 DAYS
MESONS
30 %
20
10
6
18
12
SUN
T_{min}
T_{max}
135°
36°
ANISOTROPY (SPACE)
DEEP RIVER

Fig. 1

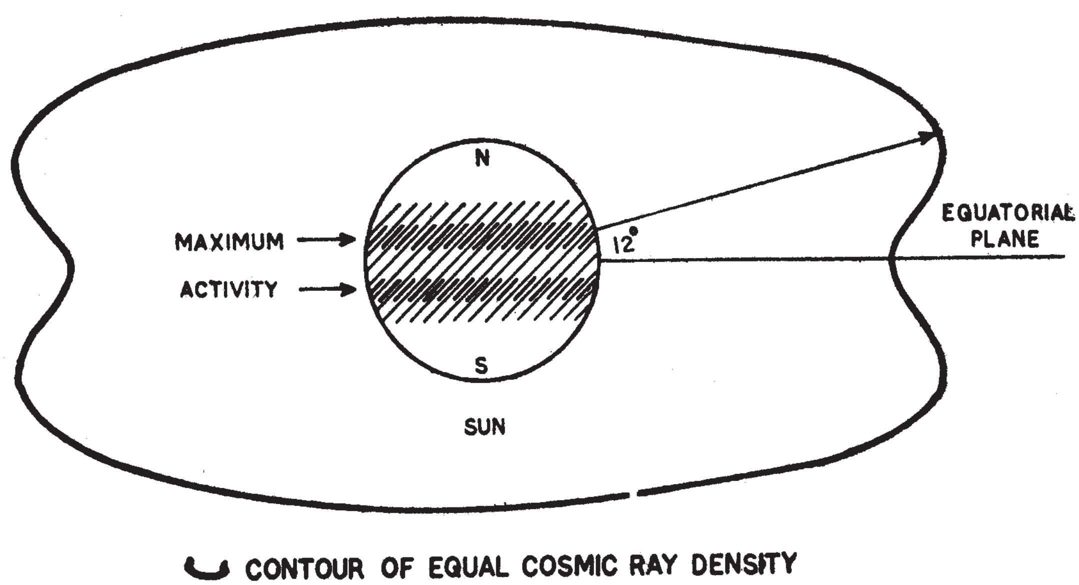
N
S
SUN
MAXIMUM
ACTIVITY
12°
EQUATORIAL
PLANE
CONTOUR OF EQUAL COSMIC RAY DENSITY

Fig. 2

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Geomagnetic Disturbance, Plasma Wind and Solar Activity

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Geomagnetic Disturbance, Plasma Wind and Solar Activity

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Abstract

The authors demonstrate by analysing data for 1960, 1961 and 1962 that daily planetary index of geomagnetic disturbance $K_p \geqslant 25$ occurs about as often with decreases $\left(\frac{dI}{dt}<0\right)$ as with increases $\left(\frac{dI}{dt}>0\right)$ of daily mean intensity of galactic cosmic rays measured on the earth.

They have studied the association of these two types of $K_p \geqslant 25$ epochs and of International Quiet Days with the central meridian passage of long lasting zones of activity in the corona at the solar equator.

The authors suggest that high K_p is caused by two distinct types of interplanetary conditions, (a) the passage of a corotating shock front or a radially advancing blast wave, and (b) the emergence of the earth from a cavity as proposed by Sarabhai considering the consequences of nonuniformity of solar wind velocity.

The occurrence of an International Quiet Day is related to c.m.p. of the intermediate point of declining intensity on the trailing edge of a bright coronal zone which should produce a cavity (a region of reduced plasma density and weak magnetic field) where slow plasma does not catch up with fast plasma in front of it.

1. Introduction

K_p is recognised as a geomagnetic indicator of a corpuscular emission from the sun. However, the qualitative and quantitative relationships between the parameters which would define the solar corpuscular emission, such as the density, the composition and the velocity of the stream and the magnitude of K_p, have been the subject of much discussion. Any attempt to understand the physical processes which are operative should take cognizance of the following facts:

(a) That the solar wind as suggested by Parker is related to the excitation of the corona. Marked local regions of high excitation are seen in the intensity of 5303 Å coronal emission. Marked variations in solar wind velocity have been demonstrated in plasma measurements made in interplanetary space. It has been demonstrated by *Snyder et al.* (1963) that during the exploration by Mariner II, there was a high correlation between the velocity v of the solar wind and K_p.

(b) If solar wind velocity varies one should expect interplanetary conditions to be rather different from the idealised model proposed by Parker, according to which the solar magnetic field would would be stretched out in the form of an Archimedes spiral by the radially flowing wind.

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Sarabhai (1963 a, 1963 b) has pointed out some consequences of the nonuniformity of solar wind velocity. The important features to take note of are:

(i) Whenever local conditions in the corona are such that there is longitudinal gradient of solar wind velocity involving, due to the spinning of the sun, fast plasma blowing behind slow, a shock transition would be propagated in the interplanetary plasma. The envelope of the transition as the sun spins would appear as a corotating shock front which would form the leading edge of a region of turbulent plasma in interplanetary space.

(ii) When a longitudinal gradient of activity on the sun is such that slow plasma blows behind fast, a "cavity" would develop in interplanetary space. This would have reduced density of plasma.

(iii) Even as the sudden expansion of the corona produces a blast wave as suggested by Parker, a sudden contraction would produce a time dependent "cavity".

(iv) A "cavity" usually terminates due to a second region of activity giving rise to a fresh shock transition and a turbulent region in interplanetary space.

If the model arising from the nonuniformity of solar wind velocity has any validity, one should expect a disturbance of the magnetosphere leading to high values of K_p whenever a shock transition or a blast wave overtakes the earth or the earth is subject to increased

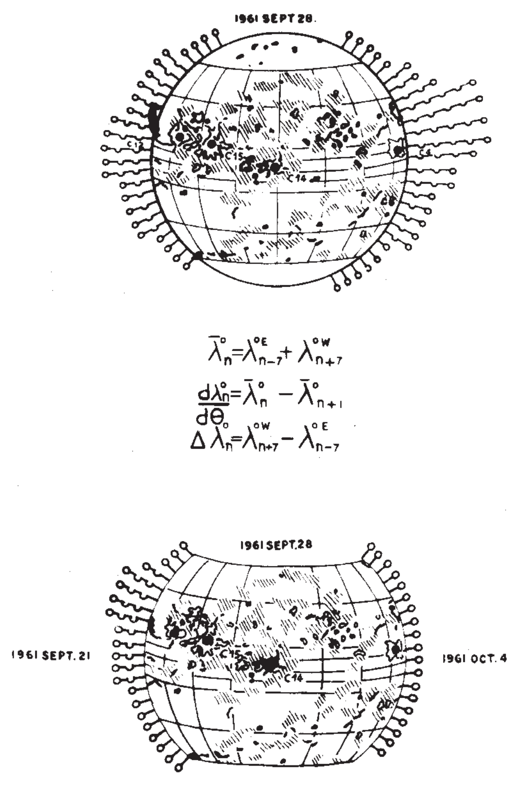

Fig. 1 A typical solar chart of Kiepenheuer and corresponding time dependent representation.

pressure of solar wind as it emerges from a cavity into a region of high velocity and density of plasma wind. Moreover, the magnetosphere should experience less pressure in a cavity and uniform pressure when the earth is in a region of smooth flowing solar wind relatively free from velocity gradients. Following Dessler and Parker's early suggestion that steady solar wind by itself would not generate high K_p, we can associate low K_p with earth being in both these types of interplanetary conditions.

Pai and Sarabhai (1963) have secured some confirmation for the validity of this model by deriving a new index of the intensity of the 5303 Å coronal emission near the solar equator as shown in Figure 1. The indices

$$\bar{\lambda}^0{}_n = \lambda^{0E}{}_{n-7} + \lambda^{0W}{}_{n+7},\ \frac{\partial \lambda^0{}_n}{\partial \theta_0} = \bar{\lambda}^0{}_n - \bar{\lambda}^0{}_{n+1} \text{ and } \Delta\lambda^0{}_n = \lambda^{0W}{}_{n+7} - \lambda^{0E}{}_{n-7}$$

have been derived from Kiepenheuer's charts of daily solar activity and relate to projected conditions of the excitation of 5303 Å on the solar corona over the region at central meridian. This projection is most valid for long lasting regions of solar activity and is least relevant when conditions vary significantly during transit of the region from east to west limb; i.e. when $\Delta\lambda$ has a large value. Correlating these indices with the occurrence of High K_p and long-lasting Forbush decreases of galactic cosmic rays observed on the earth, the authors conclude that the observations are consistent with the proposed model and an assumption that solar wind velocity over regions of high intensity of 5303 Å is greater than that over regions of low intensity.

We present here a continuation of the study of Pai and Sarabhai which throws further light on the interpretation of K_p.

2. Coronal Emission Associated with Geomagnetically Disturbed and Quiet Days

Rao and Sarabhai (1964) observed that associated with a long-lasting Forbush decrease which occurred on 30th September 1961, K_p was high not only at the onset of the decrease but during the final phase of recovery of cosmic ray intensity almost two weeks later. Indeed the association of K_p maxima sometimes with decreases and at other times with increasses of intensity of galactic cosmic rays is quite general and is not a special feature of the event of 30th September 1961.

Analysing data for 1960, 1961 and 1962, we find that $K_p \geqslant 25$ occurs about as often with decreases $\left(\frac{dI}{dt} \leqslant -0.5\%\right)$ as with increases $\left(\frac{dI}{dt} \geqslant +0.2\%\right)$ of daily mean intensity of galactic cosmic rays measured on the earth. We have studied the association of these two types of $K_p \geqslant 25$ epochs and of international quiet days with the central meridian passage of long-lasting zones of activity in the corona at the solar equator using the derived indices described earlier. The results are shown in Figure 2 using the Chree method of superposed epochs. The time series of $\frac{\partial \lambda}{\partial \theta}$ and $\bar{\lambda}$ are plotted separately. A negative value of $\frac{\partial \lambda}{\partial \theta}$ indicates that the leading edge of a long-lasting zone of intense 5303 Å emission is at central meridian. A positive value of $\frac{\partial \lambda}{\partial \theta}$ indicates that a trailing edge of a bright zone is at central meridian.

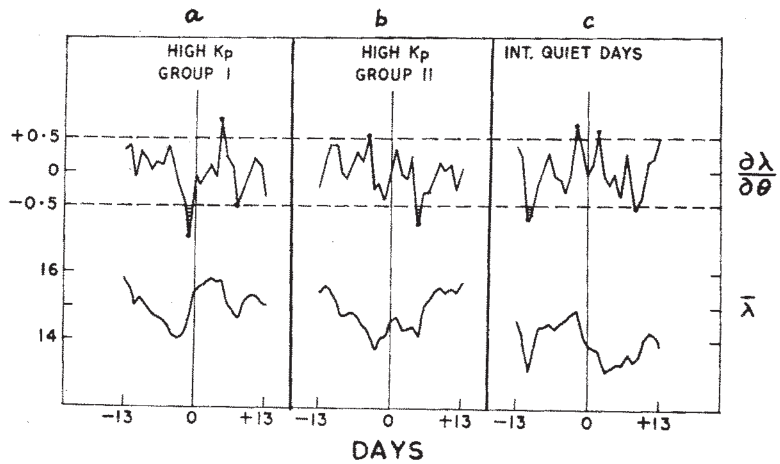

Fig. 2 Chree analysis results of $\frac{\partial\lambda}{\partial\theta}$ and $\bar{\lambda}$ for the three types of epochs for the period 1960, 1961 and 1962. The total number of epochs in group I is 135, in group II it is 160 and a total of 180 in international quiet days.

In Figure 2a, the epochs (Type I) correspond to the occurrence of a geomagnetically disturbed day ($K_p \geqslant 25$) associated with a decrease of the daily mean intensity measured by the Deep River neutron monitor on the day in question or one day preceding or following it. It is required that $\frac{dI}{dt}=(I_{n+1}-I_n)$ should be $\leqslant -0.5\%$, where I_n is the daily mean intensity on nth day. It is seen that the occurrence of Type I geomagnetically disturbed days is related to the c.m.p. one day earlier of the leading edge of a bright zone of 5303 Å emission. This should produce a corotating shock transition in interplanetary plasma due to fast wind pushing slow plasma in front of it.

In Figure 2b, the epochs (Type II) correspond to the occurrence of a geomagnetically disturbed day ($K_p \geqslant 25$) associated with an increase of the daily mean intensity measured by the Deep River neutron monitor on the day in question or one day preceding or following it. It is required that $\frac{dI}{dt}=(I_{n+1}-I_n)$ should be $\geqslant +0.2\%$. The occurrence of Type II geomagnetically disturbed days is related to the c.m.p. 3–4 days earlier of the trailing edge of a bright coronal zone. Thus, the event is associated with the earth emerging from a cavity and experiencing increased pressure of the solar wind.

In Figure 2c, the epochs correspond to international quiet days during the years 1960, 1961 and 1962. These are the five days for each month when K_p has the smallest value. The occurrence of an international quiet day is related to c.m.p. of the intermediate point of declining intensity on the trailing edge of a bright coronal zone which should produce a cavity (a region of reduced plasma density and weak magnetic field) where slow plasma does not catch up with fast plasma in front of it.

3. Interpretation of K_p

We suggest that high K_p is caused by two distinct types of interplanetary conditions,

(a) the passage of a corotating shock front or a radially advancing blast wave, and (b) the emergence of the earth from a cavity as proposed by Sarabhai considering the consequences of nonuniformity of solar wind velocity. These conclusions are consistent with the findings of Mariner II where high K_p is associated with high v and low K_p with low v. However, we wish to emphasise that the correlation between K_p and v reported by Snyder et al. is not to be interpreted as indicating $K_p \propto v$. Indeed the correlarion between K_p and v is insignificant (0.29 ± 0.12) for conditions on about half the total number of days when K_p is between 10 and 25. The proposition that steady solar wind does not by itself generate geomagnetic disturbance finds support in the observation of *Rao and Sarabhai* (1964) of a comparatively constant anisotropy of galactic cosmic rays when K_p is low and the isotropic intensity of galactic cosmic rays does not change from day to day.

Acknowledgement

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GALACTIC COSMIC RAYS IN THE SOLAR SYSTEM

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ABSTRACT

The authors postulate a model for the diffusion of galactic cosmic rays in the solar system based on the zonal character of solar activity. In this model there are two zones on either side of the solar equatorial plane where the density of galactic cosmic rays at any given distance from the Sun is lower than the corresponding density in the equatorial plane or at high heliolatitudes. It is suggested that the time variations of cosmic rays up to 50 GeV should be related to a factor which is dependent on the diffusion of galactic cosmic rays along the spiraling magnetic lines and another factor which is related to diffusion normal to the equatorial plane due to magnetic-field irregularities in interplanetary space, particularly in the neighborhood of Earth. It is also suggested that the deficiency of cosmic rays observed along the garden-hose direction from the Sun and sometimes for high-energy cosmic rays from the anti-garden-hose direction must be attributed not only to scattering of particles into the Sun but also to transverse diffusion across the radial gradients of intensity which are not the same at different heliolatitudes.

The authors demonstrate how regions of magnetic-field irregularities are related to non-uniformity of solar-wind velocity over local zones of activity on the Sun. The properties of interplanetary space relevant to cosmic-ray diffusion can be described in terms of the value of $\epsilon = K_{\perp}/K_{||}$. Interplanetary space has a structure with sectors where diffusion is isotropic ($\epsilon = 1$) alternating with sectors where diffusion is largely anisotropic ($\epsilon \ll 1$). The sectors are contained in an envelope where diffusion becomes increasingly isotropic.

The authors suggest that the following cosmic-ray effects can be understood in terms of the model: (1) the deficiency (sink) observed in the anisotropy of galactic cosmic rays along the spiraling magnetic lines of force; (2) the 27-day variations and the day-to-day changes of cosmic-ray intensity; (3) events such as some Forbush decreases, where the intensity decreases sharply but recovers only slowly; (4) the occurrence of days on which the energy spectrum of variation of anisotropy has a positive exponent; (5) the observation that cosmic-ray intensity at a given level of solar activity is more depressed during the declining phase than during the rising phase of activity of the Sun.

The authors suggest an experimental verification of the principal ideas contained in the model through the measurement of the differential energy spectrum of galactic cosmic-ray intensity arriving along the spiraling magnetic lines outside the magnetosphere.

I. INTRODUCTION

Sarabhai, Pai, and Wada (1965*a*, *b*) have recently demonstrated that, during the early part of International Quiet Sun Year, there was often a deficiency of galactic cosmic-ray intensity in interplanetary space along the garden-hose direction from the Sun. An example of this is shown in Figure 1, where the daily variations of the cosmic-ray intensity measured by the Deep River meson detector and by the superneutron monitor on February 28, 1964, are plotted. Following the suggestion of Rao and Sarabhai (1964), they refer to the deficiency and its orientation in space with respect to the Sun-Earth line as due to a virtual sink in the direction T_{min}, and the maximum of intensity as due to a virtual source in the direction T_{max}.

The significance of T_{max} and T_{min} can be grasped by an examination of Figure 2. We show the types of basic daily variations that would be observed when a directional telescope fixed to the spinning Earth, having an asymptotic cone pointing toward the equatorial plane, scans three types of anisotropy of galactic cosmic rays in interplanetary space. The types of anisotropy are related to different physical processes as follows.

Type A: Diurnal modulation.—The anisotropy is created by a streaming of galactic cosmic rays in interplanetary space (Dorman 1963; Parker 1964*a;* Axford 1965). A telescope on Earth observes a maximum displaced 180° from the minimum in the plane of the ecliptic ($T_{max} - T_{min} \approx 12$ hours). The daily variation is mainly sinusoidal in

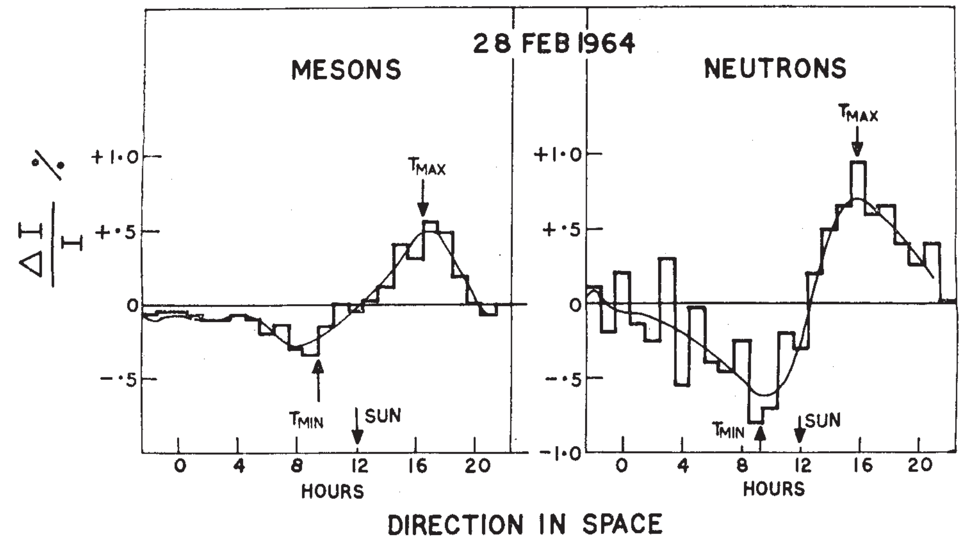

FIG. 1.—The daily variation of cosmic-ray meson and neutron intensity on February 28, 1964, recorded at Deep River by J. F. Steljes and H. Carmichael.

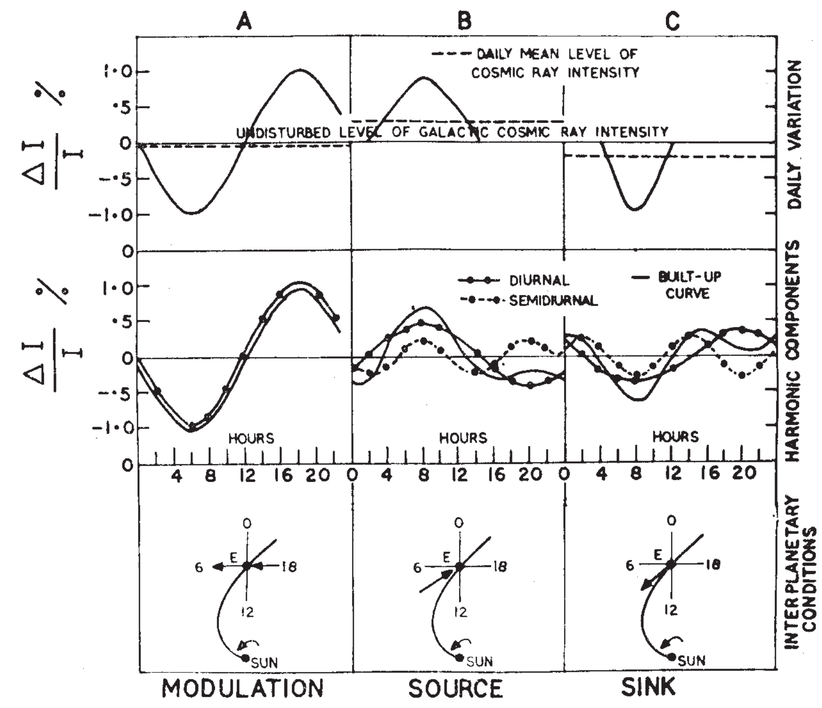

FIG. 2.—The daily variation, its harmonic components and schematic representation of direction of anisotropy in interplanetary space due to (*A*) a modulation corresponding to an azimuthal drift, (*B*) a single source along the garden-hose direction, and (*C*) a single sink along the garden-hose direction. Note the change in level of daily mean cosmic-ray intensity with respect to the undisturbed galactic intensity in each case. Also note the semidiurnal component for the source and the sink.

form. The daily mean intensity is unaltered by the modulation, which may be considered as due to a virtual source equal and opposite to a virtual sink.

Type B: Source.—The anisotropy resulting from a solar proton event is of this type. The intensity is not affected except when the cone of acceptance of the detector looks toward the direction of arrival of particles from the source. Both the diurnal and the semidiurnal components are generated when the profile is harmonically analyzed.

Type C: Sink.—This type is associated with a deficiency such as could occur when cosmic-ray protons of particular pitch angles guided along spiraling magnetic lines of force are scattered by magnetic-field irregularities and are absorbed in the Sun's atmosphere. The deficiency of cosmic-ray intensity is observed only when the cone of acceptance of the detector points toward the direction of the sink. The profile, when harmonically analyzed, gives rise to diurnal and semidiurnal components.

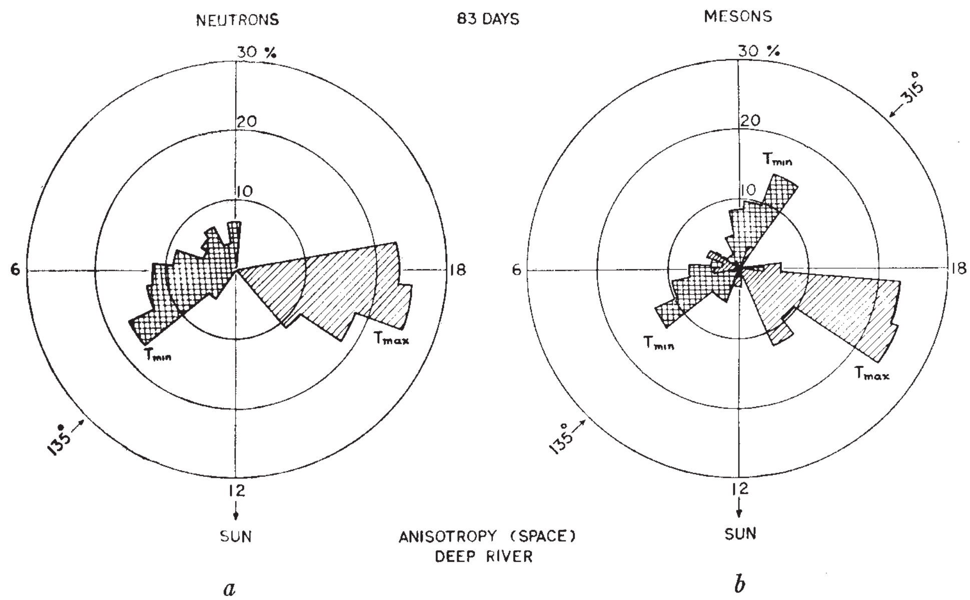

FIG. 3.—Orientation histograms of T_{max} and T_{min} for cosmic-ray anisotropy in space on individual days from November 27, 1963, to February 17, 1964: (*a*) from the daily variation of Deep River neutron intensity; (*b*) from the daily variation of Deep River meson intensity. Primary data of J. F. Steljes and H. Carmichael.

It is noteworthy that a diurnal component is present in all three types. Thus, from the diurnal component of the observed daily variation by itself, we have no way of differentiating between the three processes. On the other hand, when we consider T_{max} (due to a virtual source) and T_{min} (due to a virtual sink) and find that $T_{max} - T_{min} \approx$ 8–10 hours, we can conclude that there is at least one other process besides streaming which is responsible for the observed anisotropy. Since solar proton events are rare, the main processes to be considered for interpreting solar anisotropy of galactic cosmic rays are diurnal modulation and a sink.

Fresh analysis by Sarabhai, Pai, and Wada (1965*a*) of the anisotropy derived from the daily variation of intensity measured by the Deep River high-counting-rate meson monitor[1] has shown (Fig. 3, *a* and *b*) that the direction of minimum intensity often flips over from garden-hose direction to anti-garden-hose direction. Thus the direction of the sink is energy-dependent and, while for low-energy primaries (2 to 10 GeV for protons)

[1] Data have been kindly supplied by J. F. Steljes and H. Carmichael.

it appears only along the garden-hose direction, for high-energy primaries of 10 to 50 GeV it can be either along the garden-hose or the anti-garden-hose direction. It is the purpose of this communication to point out important conclusions concerning the diffusion of galactic cosmic rays in the solar system that could be drawn from the experimental demonstration of deficiency of cosmic-ray intensity along the spiraling magnetic lines in interplanetary space.

II. DIFFUSION OF COSMIC RAYS IN THE SOLAR SYSTEM

In attempting to understand how sinks may be observed in the solar anisotropy of cosmic rays, we are led to a general consideration of the diffusion of galactic intensity in the solar system. There are, of course, many previous studies of this latter problem,

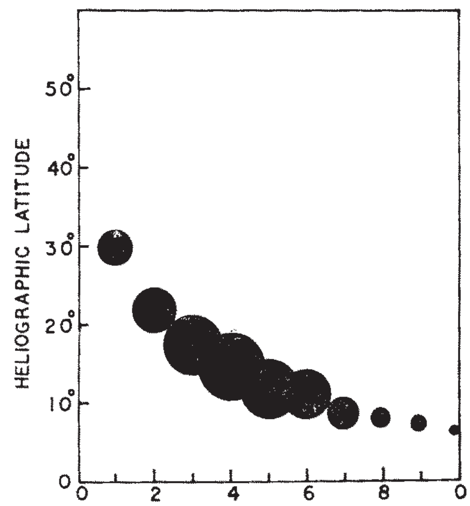

FIG. 4.—Diagram showing average heliolatitude and relative sunspot number (proportional to the size of each dot) during a typical solar cycle.

mainly with the object of explaining the 11-year modulation of cosmic rays. None, however, considers the following factors which determine the topology of physical characteristics relevant to the diffusion of cosmic rays as it may really occur: (*a*) activity on the Sun is concentrated in zones north and south of the solar equator; (*b*) the zones of activity appear in each new solar cycle at high heliolatitudes (30°–35°) but drift toward the equator as the cycle progresses; (*c*) centers of activity are non-uniformly distributed over the longitude on the spinning Sun.

We shall consider here features of a plausible model which takes account of these factors. We suppose, as in earlier explanations, that the decrease of cosmic-ray intensity in the 11-year modulation arises from a change in number density as well as in the mean energy of galactic cosmic rays diffusing inward, as they encounter irregularities coasting outward with the solar wind. Figure 4 shows the change of the mean heliolatitude of sunspots and the annual mean sunspot number during the solar cycle 1954–1965. Figure 5 shows hypothetical contours of equal cosmic-ray intensity at commencement of a solar cycle ($T = 1$), maximum ($T = 4$), and about 3 years before minimum ($T = 8$).

The interesting feature to note is that, at almost all periods of the solar cycle, except perhaps at the very minimum of solar activity, the solar system has two zones on either side of the equatorial plane where the density of cosmic rays at any given distance from the Sun is lower than the corresponding density in the equatorial plane. Moreover, since the depression of intensity is due to irregularities in the flow of solar wind associated with sunspot activity, we should expect that at latitudes higher than 50°–60° the full interstellar intensity would be able to penetrate quite close to the Sun.

III. MODULATION OF COSMIC RAYS MEASURED ON THE EARTH

We sketch in Figure 6, *a*, an idealized view of the manner in which galactic cosmic rays could arrive at the Earth, after diffusing into the solar system along spiraling lines of force lying in the solar equatorial plane, which terminate at some large distance about 30–50 a.u. from the Sun. We neglect here the 7°.5 inclination of the solar equatorial plane

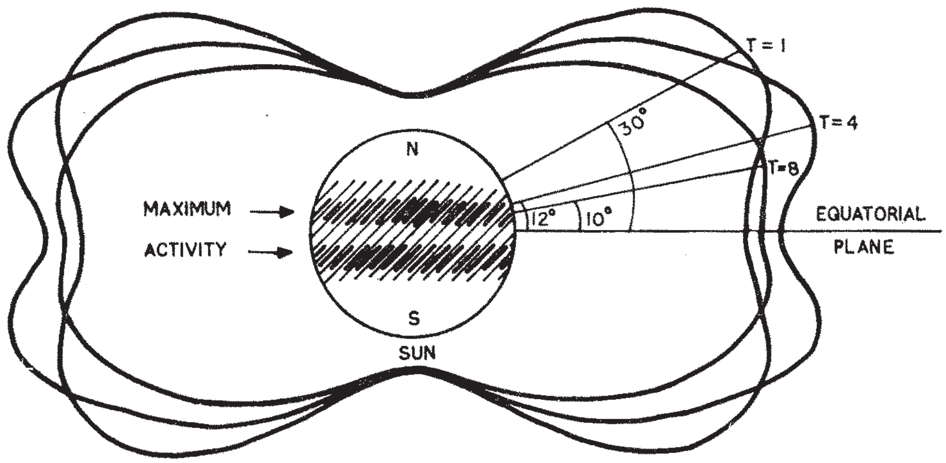

FIG. 5.—Hypothetical contours of equal galactic cosmic-ray intensity in interplanetary space in a meridional plane of the Sun. Notice that the contour intersects the equatorial plane at a closer distance from the sun at the beginning ($T = 1$) and during the declining phase ($T = 8$) of the solar cycle than at $T = 4$ corresponding to the maximum of solar activity.

with the ecliptic. Proton primaries of energy greater than about 50 GeV would not be significantly affected by the interplanetary magnetic field of magnitude 3–4 γ normally expected at distances from the Sun beyond 1 a.u.

In the absence of magnetic-field irregularities at points such as P and Q along a line of force, the Earth receives interstellar intensity sampled along the solar equatorial plane. However, due to a magnetic-field inhomogeneity of scale length l at a point such as P or Q, galactic cosmic rays having a gyroradius comparable to l would tend to get scattered out. By the same token, as indicated in Figure 6, *b*, the scattering centers would now scatter, into the solar equatorial plane, intensity from regions at higher heliolatitudes. We assume that transverse scattering in the vicinity of Earth does not produce a short circuit large enough to alter materially the differences in the radial gradients of intensity at different heliolatitudes.

Following the nomenclature used by Parker (1964*b*), $K_{||} = \nu L^2$ is the diffusion coefficient parallel to the magnetic field, where ν is the number of collisions in unit time of a cosmic-ray particle traveling along the field line and L is the step the particle makes along the magnetic field. Likewise $K_{\perp} = \nu S^2$ is the diffusion coefficient normal to the field line, where S is the gyroradius of the particle in the magnetic field B. If $\epsilon = K_{\perp}/K_{||}$, we have for isotropic diffusion $\epsilon = 1$, while for anisotropic diffusion along the magnetic field $\epsilon \ll 1$. It is clear that ϵ is dependent on the rigidity of a cosmic-ray particle, on its pitch angle, on the magnitude of the field, and on the scale length l of the irregularities.

While the rigidity is invariant, the pitch angle as well as the gyroradius alter along the path of cosmic rays. Hence scattering at magnetic-field irregularities can take place selectively for particles of appropriate pitch angles and gyroradius. The diffusion across zones with different gradients of cosmic-ray intensity can show up on Earth as an anisotropy corresponding to a sink or as an isotropic decrease depending on the distribution of the irregularities in the neighborhood of Earth and on whether some pitch angles or all pitch angles are affected.

In Figure 6, *c*, we show for the hypothetical case considered here the dependence of ϵ on radial distance from the Sun for cosmic-ray particles of a particular rigidity. The radial dependence of ϵ can normally be considered in three regions. In the first region, the magnetic-field configuration is largely without field irregularities and $\epsilon \ll 1$. In the third region, where the solar wind becomes subsonic with a shock transition at $R = 30 \sim 40$ a.u., we have $\epsilon = 1$. In the intermediate region, there is an increase of ϵ either continuously or in discrete steps. Magnetic-field irregularities at points such as P and Q however produce a sudden increase of ϵ over a short distance. With the passage of time t,

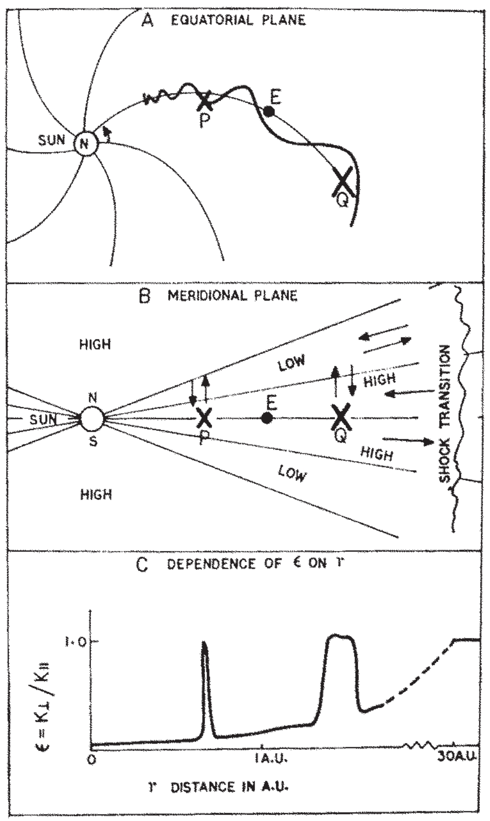

FIG. 6.—An idealized diagram illustrating some features of the diffusion of galactic cosmic rays ($E < 50$ GeV) into the solar system. (*a*) Along the spiraling lines in the equatorial plane of the Sun with magnetic irregularities at points P and Q; (*b*) in the meridional plane the transverse scattering at points P and Q from a zone of relatively high cosmic-ray intensity to low cosmic-ray intensity; (*c*) the radial dependence of ϵ. Note the abrupt increase of ϵ at magnetic-field irregularities P and Q.

if no fresh irregularities occur, the irregularities at P and Q move radially away from the Sun.

IV. MAGNETIC-FIELD IRREGULARITIES IN INTERPLANETARY SPACE

We can consider two circumstances in which magnetic-field irregularities can be produced and propagated outward in interplanetary space. In one case, they are created at or near the Sun, as, e.g., when there is a sudden expansion of the corona (Parker 1961) or due to a longitudinal gradient of solar-wind velocity (Sarabhai 1963*a*). In the other case, they appear for the first time at some distance r from the Sun, as, e.g., when turbulence sets in or there is a shock transition from supersonic to subsonic velocity at a distance $R = 30$–50 a.u. (Parker 1963; Axford, Dessler, and Gottlieb 1963) or when wind over two active zones interacts in the manner suggested by Sarabhai (1963*b*).

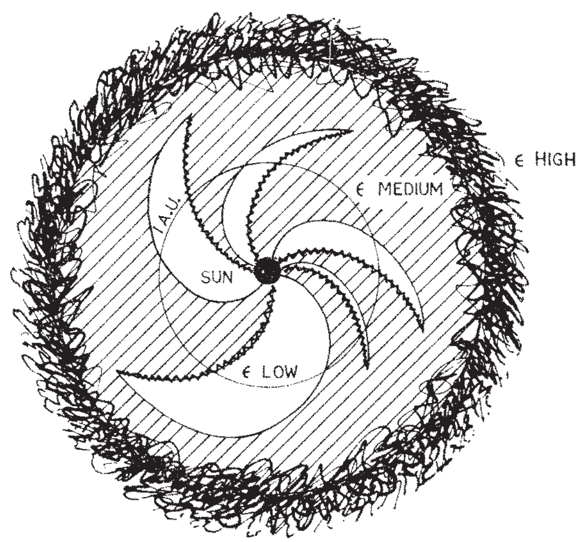

FIG. 7.—Diagram showing structuring of interplanetary space into sectors enveloped within a shell due to non-uniformity of solar-wind velocity. The sectors consist of shock transition, regions of magnetic-field irregularities, and cavities with relatively smooth field lines.

The irregularities may appear quickly, in times of the order of a day, compared to the period of weeks over which the general character of the wind beyond the orbit of Earth may change. When the irregularities appear, they increase $K_\perp$ enormously for those particles whose gyroradii are comparable to the scale of the irregularities. The increased $K_\perp$ provides a short circuit between the sectors of high and low cosmic-ray intensity illustrated in Figure 6, *b*. If, for instance, the short circuit occurs at P, an observer in a region of low intensity would see a sudden increase if looking toward Q. In this way, the rather sudden occurrence of a short circuit may appear to an observer as a source or sink in the direction along the general spiral field. The source or sink may continue for as long as the isolated short circuit is maintained, and the strength of the source or sink will vary with the degree of short circuit and the difference in the cosmic-ray intensity in the high and low regions. The energy spectrum of the source or sink depends upon the scale distribution of the irregularities and may have either a positive or a negative exponent.

We show in Figure 7 regions of low, intermediate, and high distribution of magnetic-field irregularities in the equatorial plane around the Sun with a number of zones of activity. Where $\epsilon \ll 1$, smooth field lines occur in sectors extending only up to a certain radial distance from the Sun. These have been earlier designated cavities (i.e., β-regions) and α-regions by Sarabhai (1963*a*). The sectors alternate with others where ϵ has a higher value and a co-rotating shock transition occurs as an envelope at one edge. At a much larger distance the system is closed by a shell outside of which $\epsilon \approx 1$, since the magnetic-field lines must have many irregularities due to the interaction of fast wind from adjacent active regions at the same heliolatitude. During periods of high solar activity, the distance of the closed shell can well be less than 1 a.u. The 27-day recurrence of geomagnetic disturbance would then be hard to discover even though there might be high degree of geomagnetic disturbance.

Irregularities of a given dimension coast outward with the solar wind and even though their scale length increases by a factor r, their effectiveness decreases approximately by a factor r^2. The protons which can be effectively scattered are progressively less energetic. Thus, during the recovery phase of Forbush decreases, the higher energies recover quicker than the lower energies (Sarabhai, Pai, and Rao 1961).

V. DISCUSSION

Through our model of the asymmetric diffusion of cosmic rays in the solar system and scattering at magnetic-field irregularities along spiraling lines of force in interplanetary space, we have a plausible basis for understanding the time variations of intensity and energy spectrum as well as the anisotropy of galactic cosmic rays. We suggest that the model provides a means of understanding the following observed features:

a) A daily variation of cosmic rays which has $T_{\max} - T_{\min} \approx$ 9–10 hours and, in consequence, has a significant semidiurnal component. This arises from a modulation corresponding to an azimuthal streaming and a sink along the garden-hose or anti-garden-hose direction.

b) The 27-day variations and the day-to-day changes of the level of isotropic cosmic-ray intensity which are attributed to the efficiency of scattering of cosmic-ray particles by magnetic irregularities distributed as sectors which co-rotate with the Sun in interplanetary space.

c) A spectrum of variation of the daily variation which varies from day to day and has often a positive exponent indicating that the anisotropy is not present at low energies (2–15 GeV) to the same extent as at high energies (15–60 GeV).

d) The feature of the 11-year cycle of cosmic-ray modulation wherein cosmic-ray intensity at a given level of solar activity is lower in the descending phase than in the ascending phase. This can be related to the zones of minimum cosmic-ray intensity drifting to lower heliolatitudes. The effect of this is felt even in the solar equatorial plane because of transverse diffusion corresponding to a small but finite value of ϵ in the vicinity of Earth at most times.

The interpretation offered here hinges on the existence of a gradient of galactic cosmic rays normal to the equatorial plane in the inner solar system ($\sim$1 a.u.). It would be very desirable to test experimentally the existence of such a gradient. An obvious method is to examine the change of cosmic-ray intensity measured on Earth as it reaches maximum heliolatitude north and south of the equatorial plane on September 5 and March 5. If solar activity is equal in the northern and southern hemispheres, we should observe a semiannual variation with minima at these epochs. The snags in this analysis arise from geomagnetic disturbances also having a semiannual variation and the complicating effects of Forbush decreases which occur irregularly. It is advantageous to analyze data during a period before the minimum of solar activity, when Forbush decreases are infrequent and the zones of solar activity have drifted close to the equatorial plane. Moreover, since we wish to study transverse diffusion, it is advantageous to analyze data from a polar or high-latitude station, which is much more susceptible to scattered intensity from higher heliolatitudes than intensity measured by detectors whose asymptotic cones look along the plane of the ecliptic.

The role of scattering centers in the interpretation of the sink is capable of clear demonstration through an experiment conducted in deep space outside the magnetosphere. The differential energy spectrum for cosmic-ray proton intensity arriving in the garden-hose and the anti-garden-hose directions would exhibit abrupt depressions at energy intervals which are most susceptible to scattering at the magnetic-field irregularities. There should be differences in the energies at which the depressions occur in the two directions. Moreover, as the irregularities are carried with the solar wind, the depression would shift toward lower energies.

The authors are deeply grateful to Professors E. N. Parker, S. Olbert, K. G. McCracken, W. I. Axford, and Dr. G. L. Pai for stimulating discussions. Support to this investigation from the Department of Atomic Energy of the Government of India is gratefully acknowledged.

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Procs of IQSY Symp, New Delhi (1966)

Characteristics of the anisotorpy of galactic cosmic rays during IQSY - a day to day analysis

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ABSTRACT

Data for the period 1964-65, mainly from superneutron monitors, have been used to determine on a day to day basis the energy spectrum of the anisotropy which causes daily variation. Characteristics of the anisotropy on days with zero, negative and positive exponent of the spectrum of variation are identified and compared with what one may expect from one or other of four processes for the generation of anisotropy in interplanetary space.

The comparison suggests that in addition to azimuthal streaming and possibly radial streaming, scattering at magnetic field irregularities and latitudinal gradients of galactic cosmic rays can cause the observed anisotropy. The various processes are effective to different extents on different days depending apparently on interplanetary conditions.

1. INTRODUCTION

It is well known that the characteristics of the anisotropy of galactic cosmic rays vary from day to day. a study of the anisotropy on a day to day basis has been made for the period 1958-63 by SARABHAI and SUBRAMANIAN (1963) and SUBRAMANIAN (1964), using data from a network of stations. In the present paper we extend the study to the years 1964-65 using data mainly from superneutron monitors. The detectors used are shown in Table 1. They have an hourly Poisson standard error of ~ .12%, and their geomagnetic cut-off rigidities range from .2 GV to 4.9 GV. Though they are situated at 30° to 60° geographic latitudes, their asymptotic cones of acceptance lie essentially along the eqatorial plane. The energy spectrum of variation of the cosmic ray anisotropy can be expressed

Table 1.

Characteristics of deterctors used in the analysis

Detector	cut-off rigidity in GV	Geographic Lat. In degrees	Geographic Long. In degrees	Hourly Poisson Standard error %
Churchill	.21	58.75	-94.09	.11
Deep River	1.04	46.10	-77.50	.13
Sulphur Mountain	1.15	51.20	-114.61	.11
Climax	3.06	39.37	-106.18	.15
Dallas	4.30	32.78	-96.80	.11
Hermanus	4.90	-34.42	19.22	.31

as a power law in energy (E) between the limits E_{min} and E_{max} as (DORMAN, 1957)

$$\frac{\delta D(E)}{D(E)} = a(\lambda,\psi)E^{\chi} \quad \text{for } E_{min} \leq E \leq E_{max} \qquad \dots (1)$$
$$= 0 \quad \text{when} \quad E \leq E_{min}$$
$$\text{or} \quad E \geq E_{max}$$

where 'a' is the source strength of anisotropy along a direction in space specified by latitude λ and longitude ψ measured from local meridian.

An anisotropy of galactic cosmic rays in interplanetary space can arise due to the following different physical processes:

Process -1: PARKER (1964) has shown that an azimuthal streaming of cosmic rays should occur in the inner solar system having relatively smooth field lines beyond 1A.U. and bounded by a shell containing magnetic field irregularities. The anisotropy would be diurnal in character having its direction of maximum along 1800 hours, and having an energy spectrum of variation with an exponent χ equal to zero. The process could be effective upto an $E_{max} \sim 200$ GeV (AXFORD, 1965; KRIMSKIY, 1964).

Process-2: When solar wind velocity or the diffusion coefficient of cosmic ray particles in interplanetary space is not symmetrical around the sun, as in the sector structure (PARKER, 1964) has shown that there will be a radial or azimuthal streaming depending upon the position within the sector. This process differs from the earlier process in causing an anisotropy with a variable direction of maximum. The effect may extend upto energy E_{max} =300 H.ℓ where ℓ is the characteristic dimension of the sector. When the dimension is small, the anisotropy will not be observed by detectors sensitive to higher energies. This would be interpreted as a negative exponent for the energy spectrum of the anisotropy.

Process-3: Irregularities along magnetic field lines could provide a short-circuit between regions of high and low intensity at different heliolatitudes (SARABHAI and SUBRAMANIAN, 1966), the occurrence of which may appear to an observer as a source or sink in the direction along the general spiral field. On harmonic analysis the source or sink will give rise to diurnal and semidiurnal components. The energy spectrum of variation will depend upon the distribution of the scale lengths of the irregularities and may have either a positive or a negative exponent.

Process-4: Anisotropy can arise from latitudinal gradients in a smooth magnetic field as envisaged by SUBRAMANIAN and SARABHAI (1966). It will have diurnal and semidiurnal components whose relative magnitudes will depend on the nature of the distribution of cosmic ray density with heliolatitudes. The exponent of the energy spectrum of variation of the semidiurnal component will generally be positive, though occasionally it may be negative. The exponent for the diurnal component also could be positive or negative. The direction of maximum could be perpendicular or parallel to the magnetic field, depending on whether the cosmic ray intensity increases or decreases with heliolatitude.

In the present study we try to identify the extent to which the various processes which can create an anisotropy are operative on any particular day. We first fit energy spectra with assumed values for X and E_{min} separately to the observed diurnal and semidiurnal components of the daily variation as discussed in (1) and (2). The process 1, corresponding to azimuthal drift, is identified by picking up all days on which the exponent X is zero for the diurnal component. A further restriction is imposed by requiring that the semidiurnal component should not have a positive exponent X. Days on which this occurs are classified as group A. Processes 2 and 3 are identified by picking up all days on which the exponent X is negative for diurnal component, while the exponent is not positive for the semidiurnal component. Days on which this occurs are classified as group B. Process 4 is identified by picking up days on which the exponent X of the semidiurnal component is positive but the exponent for the diurnal component is not zero. Days on which this occurs are classified as group C. The days belonging to these three groups account for 58.7% of the total days.

2. RESULTS AND DISCUSSION

In Fig.1 are shown the frequency distributions of the direction of maximum (T_{max}) and the direction of minimum (T_{min}) of the anisotropy during the year 1964-65 for the three groups. The most probable value of T_{max} is 1800 hours in group A which substantiates our assumption that the anisotropy on these days is caused by process 1. The diurnal nature of the anisotropy on these days is brought out by a separation of 12 hours between T_{max} and T_{min} as seen in the figure.

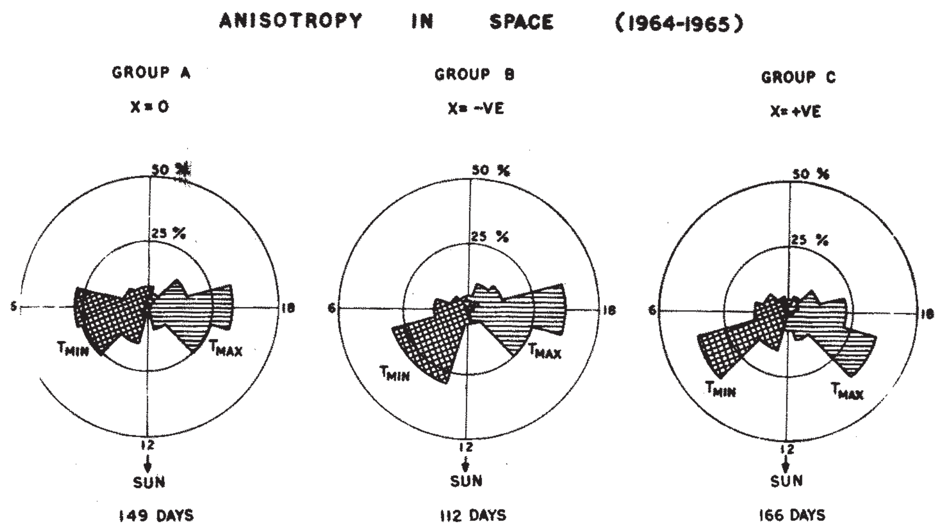

Fig.1. The frequency distribution of T_{max}, the direction of maximum, and T_{min}, the direction minimum, of anisotropy for the days in group A, group B and group C, during 1964-65.

In group B the most probable direction of minimum T_{min}, is 0800 hours i.e. along the garden-hose direction. The anisotropy having a negative exponent for variation spectrum on these days can arise either due to process 2 or process 3. The occurrence of T_{min} along the garden-hose direction indicates that process 3 is likely to be dominant in group B. Moreover the direction of T_{max} along 1800 hours indicates that the azimuthal streaming arising from process 1 is also present.

In group C the most probable value of T_{max} is about 1500 hours and the most probable value of T_{min} is 0800 hours. The difference between T_{max} and T_{min} is about 0700 hours which indicates that the semidiurnal component is predominant. The direction of maximum along the perpendicular to the interplanetary magnetic field, the observation of T_{min} along the field, together with a large semidiurnal component for days in group C support our assumption that the anisotropy is caused principally by process 4. One of course expects that there would be some contribution of azimuthal streaming. But this is not separately estimated.

The frequency distributions of the time of maximum (T_{max}) and the time of minimum (T_{min}) of daily variation at Deep River and Huancayo.neutron monitors during 1964 are shown in Fig.2 for the days in group C, after correcting for geomagnetic bending. T_{min} as measured by Huancayo neutron monitor, which has a higher mean energy

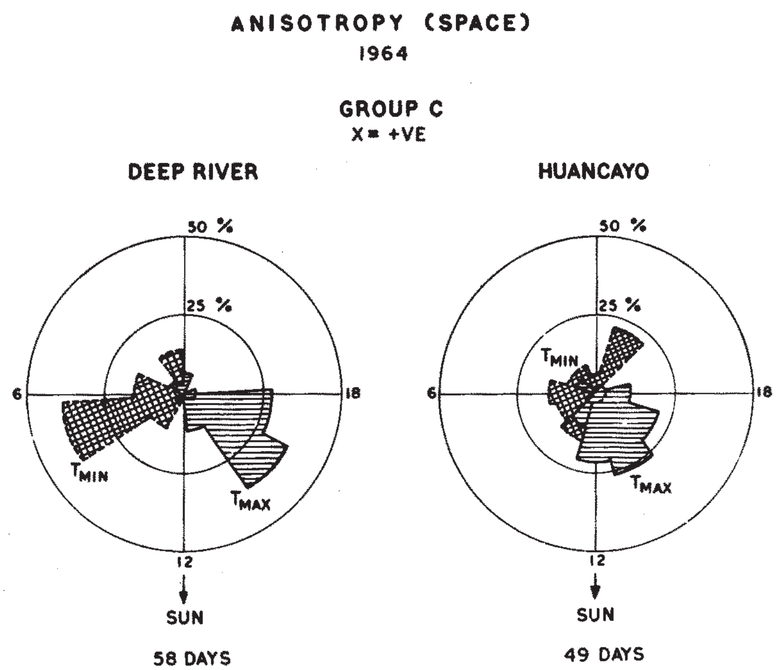

Fig.2. The frequency distributions of the time of maximum and the time of minimum obtained from Deep River and Huancayo neutron monitors, corrected for geomagnetic bending for the days in group C during 1964. Noteworthy is the flipping over of T_{min} for Huancayo.

of response ($\sim$30 GeV) than Deep River neutron monitor (12 GeV) flips over from garden-hose direction to anti-garden hose direction, while for Deep River, it is essentially along the garden-hose direction. This phenomenon is in agreement with an earlier study by SARABHAI, PAI and WADA (1965) and SARABHAI and SUBRAMANIAN (1966) using daily variation of cosmic ray intensity obtained from neutron and meson detectors at Deep River.

3. SUMMARY

At least three physical processes giving rise to cosmic ray anisotropy are distinguishable by means of super neutron monitor data during the period 1964-65. In this preliminary study we find agreement between some of the predicted and the measured characteristics of the anisotropy.

We thank the Department of Atomic Energy, Government of India for support.

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THE VALUE OF SPACE ACTIVITY FOR DEVELOPING COUNTRIES

Vikram Sarabhai*

I deem it a great privilege to be invited to address this meeting on the Impact of Space Exploration on Society. The navigation of the Mariner IV space-craft to successfully accomplish a fly by mission to Mars and the telemetry of television pictures from a distance of 13.5 million miles are mile-stones in technological and scientific progress. While applauding the magnificent accomplishment that these represent, we should also appreciate the understanding displayed by the organisers of the mission of their responsibility to the scientific community and to the society at large to preserve the possibility of detecting life on Mars uncontaminated by biological organisms transferred from the earth.

At first sight it may appear odd that a developing nation such as India, where the annual per capita income is about 80 dollars at current prices, where the average expectancy of life is 45 years and the population grows by about 13 millions each year, should think of things other than the immediate problems of population control and of providing food, clothing, housing, education and the social services. What is the value of space research to such a country? People seriously ask this question both at home and in foreign lands. And yet we have a modest space programme with which I have been connected from its inception some four years ago. I, therefore, feel it appropriate to share my thinking with you.

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*Chairman, Indian National Committee for Space Research

Some of the comments which I make are perhaps applicable to all developing countries. Others are of special significance to India. I will deal here first with the close relationship between understanding science and the ability of a nation to develop through the application of science and technology. Secondly, I will deal with the role of international cooperation in an advanced field, such as space research, in the transfer of know-how and technology and the creation of an overall climate, vitally necessary for a developing nation. Thirdly, I will discuss the significance of collaboration between advanced nations in jointly undertaking assistance to a developing nation and of the U. N. sponsorship of the International Rocket Launching Facility in India. And finally, what is perhaps most important in an immediate sense, I will relate the value of space research in India for improving understanding of equatorial aeronomy and some factors governing everyday life in the Indian Ocean region.

Clearly the development of a nation is intimately linked with the understanding and application of science and technology by its people. It has sometimes been argued that the application of technology by itself can contribute to growth. This is certainly true as an abstract proposition, but fails in practice. Witness the state of development and social structure of countries of the Middle East, where for decades resources of oil have been exploited with the most sophisticated technology. History has demonstrated that the real social and economic fruits of technology go to those who apply them through understanding. Therefore a significant number of citizens of every developing country must understand the ways of modern science and of the technology that flows from it.

An ability to question basic assumptions in any situation is fostered by probing the frontiers of science, whatever field one may be engaged in, whether it is Biology, Genetics, Atomic Science or Space Research. It is this ability rather than an empirical hit and miss approach which proves most effective in tackling the day to day problems of the world. It follows from this that countries have to provide facilities for its nationals to do front rank research within the resources which are available. It is equally necessary, having produced the men who can do research, to organise task oriented projects for the nation's practical problems. In India, space activities may be allocated during the next few years about 4 per cent of the total available funds for non-military research and development by Government.

Pursuit of cosmic rays and space research does not require an apology in a developing nation provided the activities are within a total scheme of priorities in the allocation of national resources. Many of us who are engaged in pure science are also involved in the organisation and conduct of education, of planning and of industrial development in fields such as electronics and chemicals. The role of space activities in stimulating the growth of technology and industry in advanced fields such as electronics, communications, cybernetics and in materials engineering is well recognised in the advanced nations. This applies equally to developing nations such as India.

When a developing nation gets actively interested in a field such as space research, it inevitably establishes collaborative relationships with organisations as well as scientists and technologists in foreign lands. Through these relationships it starts looking outwards from its encapsulated existence born out of an emergent nationalism. It learns to deal with peers, to establish a mutuality even when the flow of know-how and technology is largely in one direction to start with. International cooperation in science contributes to the creation of a climate for development which is essential in an age where colonialism has largely ended. When a nation succeeds in setting up a scientific programme with sounding rockets, it develops the nucleus of a new culture where a large group of persons in diverse activities learns to work together for the accomplishment of a single objective.

In appreciating the value of space activities to a developing nation one should recognise some inherent problems. They arise from the glamour that attaches to space activities. There is a real danger that developing nations may adopt a space programme largely for this glamour, devoting resources not through a recognition of the values of which we are talking about here, but from a desire to create a sham image nationally and internationally. International cooperation in space activities may stimulate this state of affairs. There is no easy way to prevent such perversion. However, the following factors may prevent this from happening. One should ensure that nationals of the country at the operative level of the programme are sufficiently committed and are willing to stretch themselves to the fullest before they expect help from outside. Moreover, one should also have a tangible demonstration of commitment at the institutional and national levels. Arnold Frutkin* has discussed at length these questions. The International Programme of NASA has always conveyed to me a strong feeling that these considerations are realised. The moral has relevance much beyond the field of space activities and can well be taken up by other national and international agencies connected with international cooperation and assistance for development.

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*Arnold W. Frutkin, International Cooperation in Space., Prentice-Hall Inc., 1965.

International cooperation in jointly assisting a developing nation, has a special significance to the advanced countries. In a world in which the East-West conflict has dominated the international scene for almost a decade and a half, there are understandable political overtones in the area of technical assistance. On the other hand, many people believe that 10 to 20 years from now, the important problem facing the world will no longer be the East-West issue in its classical form, but one arising from the disparity of the standards of living of vast areas of the earth's population. Indeed the security of the world will then depend on the effectiveness of common endeavour to ameliorate the situation. Programmes such as IGY, IGC and the International Indian Ocean Expedition constitute international cooperation in fields relatively remote from current practical problems. The International Rocket Launching Facility at Thumba in South India is a unique experiment in international cooperation in the field of space research. At Thumba, the space organisations of France, U.S.A. and the U.S.S.R. and of the host country, which is India, have actively participated. The resolution of the UN Committee on the Peaceful Uses of Outer Space brings out the nature of the project. I quote from the official document:-

"The Committee:

(i) Believes that the creation and use of sounding rocket launching facilities (especially in the equatorial region and the southern hemisphere) under United Nations sponsorship would contribute to the achievement of the objectives of General Assembly resolution 1721 (XVI) by greatly furthering international collaboration in space research and the advancement of human knowledge, and by providing opportunity for valuable practical training for interested users;

(ii) Notes that such facilities would open possibilities for nations which wish to enter the field of space research and would provide opportunities for practical instruction and training in this field, and would also make possible space research by Member States which are unable, because of economic or technological factors, or the unsuitability of their territories, to support sounding rocket programmes except through co-operative efforts, and would also allow States already possessing facilities to conduct research for peaceful scientific purposes in other regions".

In 1962, COSPAR drew attention to major gaps in the world coverage of sounding rocket launching sites. It pointed out: "The equatorial region has special scientific interest for meteorology and aeronomy. In particular, the magnetic equator is highly significant in the investigation of the earth's magnetic field and the ionosphere". It therefore urged that a sounding rocket launching facility on the magnetic equator be established as soon as possible, as a first step in creating and using international sounding rocket facilities under United Nations sponsorship.

India has a long tradition, going back to several decades, of research in geophysics, solar physics and earth-sun relationships. Scientists have been working in Universities, in Research Institutions and in Government Departments, in meteorology, geomagnetism, ionospheric physics and other areas of aeronomy, on cosmic radiation, solar optical and radio astronomy, the electromagnetic conditions of interplanetary space and theoretical astrophysics. The magnetic equator passes through the southern tip of the Indian peninsula and a range of geomagnetic latitudes from -1^{o} to 25^{o} N is thus available. The strength of the field in India is about the highest that is reached anywhere along the equator and in consequence the distance between the F-2 layer and the lower limit of the radiation belts is about 800 km. over India as compared to 200 km. in Peru. The presence of high mountains has permitted the establishment of high altitude laboratories near the equator as well as in the Himalayas.

The scientific programme in aeronomy, which is backed up by extensive ground-based observations routinely conducted in India, is of particular interest in understanding the problems dealing with the interaction of neutral and charged particles in the presence of the earth's magnetic field. The studies which are currently undertaken involve, along with sounding rocket experiments, measurements with ground-based equipment of related parameters, analysis of real time telemetry data from satellites and radio propagation studies using satellite beacons. Rocket experiments provide photographs of artificial vapour clouds which give information on wind velocities, shears and regions of turbulence in the vertical profile of the neutral atmosphere from an altitude of 80 km. through the E region up to 180 km. The chemical composition of the ionosphere and the vertical profile of electron density are also studied. Special emphasis is on understanding the nature of the D layer and of the sporadic E. Using magnetometers, the structure, the extent and the movements of the current systems involved in the equatorial electrojet are investigated.

Agriculture is the most important activity on the sub-continent of India. A large majority of the population of 480 millions earn their livelihood from this occupation which is largely dependent on rain that occurs during the monsoons. It is hardly necessary in this audience to stress therefore the importance to India's economy of a better understanding of the processes by which the monsoon rains occur, processes which commence over the vast Indian Ocean, where there are relatively few observing stations undertaking even the normal observations at surface or with balloons. What applies to the economy of India applies to the economy of most of the countries in the Indian Ocean region. Space meteorology which permits the acquisition of valuable data from satellites as well as with the use of sounding rockets has therefore a special significance for us.

Another area of practical importance is the field of satellite communications. Geographically situated as it is at 75^{o} to 90^{o} E meridian, with a volume of international telecommunications second only to Japan in Asia, a satellite communications earth station is of great importance not only for national needs, but for international hook-ups. Assisted by the U. N. Special Fund, an Experimental Satellite Communications Earth Station is now being set up. Independent of this, it is proposed to have a commercial station in the future. The experimental station would provide unique facilities for training scientists and technologists, particularly from the developing nations, in the new field of space communications.

These then are the reasons why India has embarked on a space programme with particular reference to a region which can be covered neither by satellites nor by balloons. With continued cooperation from the advanced nations, we hope through this activity not only to stimulate the progress of our nation, but also to contribute to science.

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CONSEQUENCES OF THE DISTRIBUTION OF GALACTIC COSMIC-RAY DENSITY IN THE SOLAR SYSTEM

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ABSTRACT

The authors have estimated the anisotropy of galactic cosmic rays in interplanetary space arising from three assumed distributions of cosmic-ray density, dependent on heliolatitude according to a model recently suggested by them (*A.J.*, **145**, 206, 1966). While all distributions have larger cosmic-ray densities at high heliolatitudes than in the equatorial plane, the first has symmetry with respect to the equatorial plane, the second has a north-south asymmetry, and the third is symmetrical with respect to the equatorial plane but has two minima of cosmic-ray density at heliolatitudes $\pm 10°$ corresponding to the zones of maximum solar activity. The cosmic-ray gradient in the vicinity of Earth has been assumed to be 6 per cent/a.u. for particles of rigidity $P > 2$ GV, perpendicular to the plane of the ecliptic.

The authors discuss a mechanism which can explain the direction and magnitude of the semidiurnal component of cosmic-ray intensity. Change of 24-hour mean cosmic-ray intensity and a diurnal anisotropy are also produced and, like the semi-diurnal component, are related to the cosmic-ray density gradients normal to the ecliptic and the magnitude of the interplanetary magnetic field. The diurnal anisotropy discussed in this model should reverse its direction of maximum with the reversal of the direction of the interplanetary magnetic field as well as with the reversal of the direction of the cosmic-ray gradient. Averaged over a solar rotation the diurnal component will therefore be negligible in comparison with the diurnal anisotropy arising from azimuthal streaming.

The authors have calculated daily variation and 24-hour mean intensity for neutron monitors at Huancayo and Deep River using the model and with assumed form and magnitude of the latitudinal gradient. The derived cosmic-ray effects are consistent with experimental observations. Of particular interest is the ability of the model to explain the direction, magnitude, and the energy dependence of the semidiurnal component. Along with the mechanism of outward convection of cosmic rays by the solar wind and the anisotropic diffusion inward, the model therefore appears to be a good candidate for developing an integrated interpretation of cosmic-ray variations. The model moreover provides the interesting possibility of sampling the conditions of interplanetary magnetic field and cosmic-ray density in regions of the solar system at 1 a.u. but extending to $\pm 30°$ outside the equatorial plane, using quantitative data of cosmic-ray anisotropy and day-to-day changes of omnidirectional intensity.

I. INTRODUCTION

The authors have recently suggested (Sarabhai and Subramanian 1965, 1966) that, on account of the latitudinal dependence of solar activity, the 11-year modulation of galactic cosmic-ray density at any point in interplanetary space at a given distance from the Sun should depend on the heliolatitude. In the present communication, we derive quantitative implications of this model to the diurnal and the semidiurnal components of the solar anisotropy and to the 27-day variation of galactic cosmic rays. Of particular interest is the process by which a semidiurnal component can arise, as already outlined qualitatively by the present authors (Subramanian and Sarabhai 1965). Most recent observations (Sarabhai, Pai, and Wada 1965; Ables, McCracken, and Rao 1965) have indee l indicated a semidiurnal anisotropy perpendicular to the interplanetary magnetic field and with an amplitude of about $0.1 \sim 0.4$ per cent on individual days, as is expected from the present interpretation. We therefore conclude that the anisotropy of galactic cosmic rays can arise not only (i) from azimuthal streaming (Parker 1964; Axford 1965; Krimskiy 1964). and (ii) from streaming due to non-uniform diffusion in a longitudinal sector structure in interplanetary magnetic field (Parker 1964), but (iii) also from scattering at irregularities along the interplanetary magnetic field short-circuiting latitudinal gradients (Sarabhai and Subramanian 1965, 1966), and (iv) latitudinal gradients in a smooth magnetic field as described here.

We should note that while, due to the first two processes, omnidirectional intensity in interplanetary space should remain unchanged, the third and fourth processes would be perceived through virtual sources or sinks, generating semidiurnal and diurnal components as well as a variation of omnidirectional intensity.

II. ANISOTROPY RELATED TO DEVIATION FROM SPHERICALLY SYMMETRICAL DISTRIBUTION OF COSMIC RAY DENSITY IN INTERPLANETARY SPACE

Let $N(P,r,\theta,\phi,T)\,dp$ be the density of cosmic-ray particles having rigidities between P and $P + dp$ at a point specified by heliocentric distance r, latitude θ, and longitude ϕ referred to Sun-Earth line, during a particular phase T of the 11-year cycle of solar

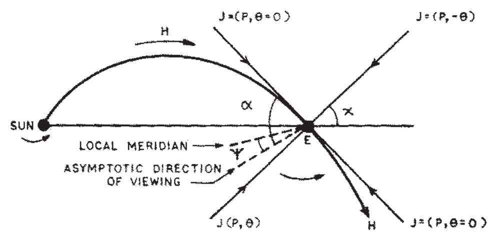

FIG. 1*a*.—Interplanetary magnetic field is shown in solar equatorial plane. Cosmic-ray intensity that will be measured by a detector is indicated when it views along the magnetic-field line or perpendicular to it.

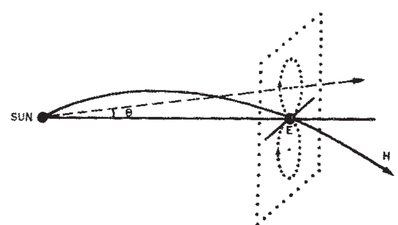

FIG. 1*b*.—Particle orbits are shown in a plane perpendicular to the solar equatorial plane and to the magnetic line of force. The heliolatitude of the gyrocenter θ_g is also indicated in the figure.

activity. For the present, we neglect the inclinations of the equatorial planes of the Sun and Earth to the ecliptic plane. In Figure 1*a* is shown the interplanetary magnetic field in the solar equatorial plane. Ideally, it forms an Archimedean spiral. Near Earth the field is assumed to be uniform over a domain which has the dimensions of the order of the gyroradius of the particle. In this domain the coefficient of diffusion of galactic cosmic rays transverse to the magnetic field ($K_\perp$) would be negligible compared to the coefficient for diffusion parallel to the field ($K_\parallel$). The mechanism which we discuss here would not therefore apply to galactic cosmic rays of energy greater than about 100 GeV for which the domain would have to be as large as 1.0 a.u. when the field is 5γ.

In Figure 1*b* the particle orbits are shown in a plane perpendicular both to the magnetic field and to the solar equatorial plane. Viewing along the magnetic field, a detector on Earth measures cosmic-ray flux characteristic of the equatorial plane. On the other hand, looking along a direction (in the equatorial plane) making an angle α with respect to the magnetic field, the detector having unit area and subtending a solid angle $d\Omega$, measures intensity $j(P,\theta_g)$ corresponding to cosmic-ray density characteristic of a region at heliolatitude θ_g. Thus

$$j(P,\theta_g)\,dp = N(P,\theta_g)\,v\,\frac{d\Omega}{2\pi}\,dp\,, \tag{1}$$

where v is the velocity of the particles; θ_g is the heliolatitude of the gyrocenter and is related to the rigidity by the expression

$$\theta_g = \tan^{-1} \frac{(P \sin \alpha)}{45H}, \tag{2}$$

where H is the interplanetary field in gammas. More generally, for a detector which scans a latitude λ of the celestial sphere, it can be shown that the heliolatitude of the gyrocenter is given by the expression

$$\theta_g = \tan^{-1} \frac{P \cos \lambda \sin \alpha}{45H} \tag{3}$$

For a given rigidity, θ_g is the highest when the direction of viewing is at right angles to the magnetic field. In Figure 2 is shown the relationship of the heliolatitude of the gyrocenter to the particle rigidity for three different values of the magnetic field. Examination

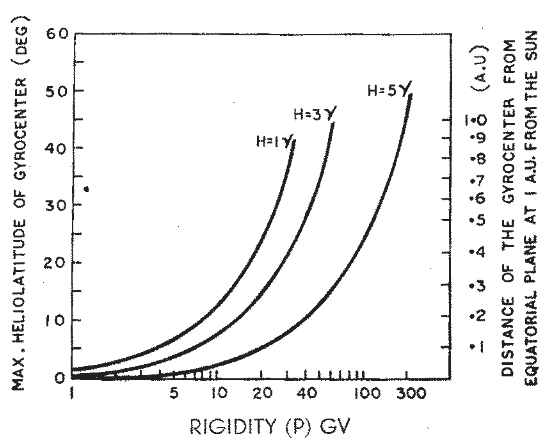

FIG. 2.—The heliolatitude of the gyrocenter has been calculated for particles of different rigidities assuming three different values for interplanetary magnetic field. Also is shown the distance of the gyrocenter (in a.u.) from the equatorial plane when $r = 1$. a.u.

of the figure indicates that the influence at Earth of cosmic-ray intensity corresponding to higher heliolatitudes would be larger when the interplanetary magnetic field is weaker. Moreover, the effect would be larger for cosmic rays of higher rigidity.

In the course of a day, a detector on the spinning Earth measures cosmic-ray intensity twice along the magnetic field and twice perpendicular to it. In consequence, diurnal and semidiurnal components are generated in the measured intensity. Their relative magnitudes will depend on the nature of distribution of cosmic-ray density with heliolatitude. As explained earlier, experimental observations should demonstrate a composite daily variation due to latitudinal gradients as well as streaming and scattering in interplanetary magnetic fields.

III. TYPES OF LATITUDINAL DISTRIBUTIONS OF GALACTIC COSMIC-RAY INTENSITY

Direct measurements of $N(P,\theta)$ except for measurements in the ecliptic plane ($\theta = 0$), have not been made so far. Based therefore on the model proposed by us earlier (Sarabhai and Subramanian 1965, 1966) wherein the zonal character of solar activity has been considered, we assume here three cases for the distribution of $j(P,\theta)$ with heliolatitude

(Fig. 3). In all these cases, it is assumed that cosmic-ray density at high heliolatitude is larger than that at the equatorial plane.

In Case I, which is the simplest, the distribution of cosmic-ray density is assumed to be symmetrical about the equatorial plane and to have larger intensity on either side of it. In Case II, the cosmic-ray density distribution is similar to Case I except that the distribution is symmetrical about θ_1 ($\neq 0$). This type represents conditions during a year such as 1963 when a marked north-south asymmetry has been observed in green coronal emission as well as in other indices of solar activity. In Case III, the distribution is symmetrical about the equatorial plane and has two regions of minimum cosmic-ray

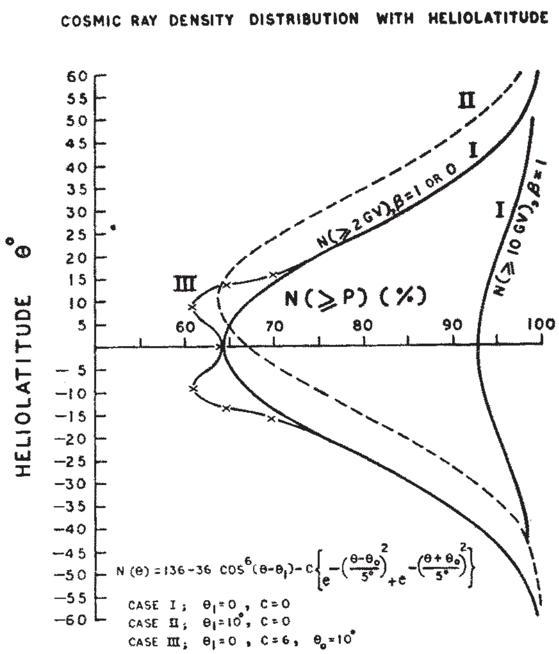

Fig. 3.—A single empirical formula is chosen to represent the three cases of latitudinal dependence of cosmic-ray intensity. According to the formula full galactic cosmic-ray density is obtained when $\theta = 90°$. The energy dependence of the distributions when $\beta = 1$ is illustrated for integral intensity of particles N with rigidity ≥ 2 GV and ≥ 10 GV.

density corresponding to the two zones of maximum solar activity at intermediate heliolatitudes (15°). We used the following empirical expression to describe the three distributions:

$$N(P,\theta)dP = A(P)[1 - P^{-\beta}\{B_0 + B\cos^n(\theta - \theta_1) + C\exp[-(\theta/\theta_3 - \theta_2/\theta_3)^2] + D\exp[-(\theta/\theta_5 - \theta_4/\theta_5)^2]\}]dP. \quad (4)$$

$A(P)$ is the unmodulated interstellar cosmic-ray intensity. B_0 determines the intensity at the poles where $\theta = 90°$, while B determines the over-all decrease between the poles and the equator; n determines the rapidity of decrease of cosmic-ray intensity with decreasing heliolatitude; θ_1 is the latitude about which the distribution of cosmic-ray intensity is symmetrical; C and D determine the magnitudes of the two depressions; θ_2 and θ_4 correspond to the centers of heliolatitudes where the dips are situated, while θ_3 and θ_5 are the half-widths of the dips in the northern and the southern hemisphere, respectively. The half-width of a dip can be defined as the difference between the heliolatitude of the center of the dip and the heliolatitude where the dip is $1/e$ times its peak value.

Expression (4) represents

Case I	when	$\theta_1 = 0$	and	$C = D = 0$,
Case II	when	$\theta_1 \neq 0$	and	$C = D = 0$,
Case III	when	$\theta_1 = 0$	and	$C = D \neq 0$.

In expression (4) β determines the rigidity dependence of the latitudinal variation of cosmic-ray density. An appropriate choice of β is of course important. In our model the latitudinal distribution of galactic cosmic rays in the solar system arises from different degree of 11-year modulation at different heliolatitudes. The rigidity spectrum of the 11-year modulation of cosmic-ray intensity observed in the plane of the ecliptic can be expressed as

$$\frac{\delta j(P,T)}{j(P,T_0)} = a[z(T)]P^{-\nu[z(T)]}. \tag{5}$$

Inspection of expression (5) shows that, in order to derive the latitudinal distribution of cosmic-ray density, we should know the dependence of solar activity z on heliolatitude θ at a given time T, from experimental observations of the Sun, and the dependence of a and ν on the solar activity z, relevant to the ecliptic plane; a and ν are usually obtained using cosmic-ray data from a network of detectors on Earth during the course of a solar cycle of activity. For a precise formulation, it would be necessary to know β and the rigidity range over which it remains constant as functions of heliolatitude at any particular phase of the solar cycle. In our present analysis we consider both β as well as the rigidity range over which it remains constant to be independent of θ. However β varies from about 2 during minimum sunspot activity to a value 0.5 or less during the maximum sunspot activity (Webber 1965).

IV. AN ANALYTICAL TREATMENT OF COSMIC-RAY EFFECTS IN INTERPLANETARY SPACE ARISING FROM A LATITUDINAL DISTRIBUTION OF GALACTIC COSMIC RAYS

Some consequences of the model discussed above can be illustrated by the following analytical treatment of Case II where the distribution of galactic cosmic-ray density can be described by

$$\frac{\delta N(P,\theta)}{N(P,\theta_1)}\,dP = \tfrac{1}{2}BP^{-\beta}n(\theta-\theta_1)^2 dP. \tag{6}$$

When θ_g is small, from expression (3) we have

$$\theta_g = \frac{P\cos\lambda\sin\alpha}{45H}; \tag{7}$$

θ_g varies with α, as the equatorial plane is scanned, giving rise to a time variation of cosmic-ray intensity expressed as a fraction as follows:

$$\frac{\delta N(P,\theta_g)}{N(P,\theta_1)}\,dP = \tfrac{1}{2}BnP^{-\beta}(\theta_1^2 - 2\theta_g\theta_1 + \theta_g^2)\,dP. \tag{8}$$

On substituting for θ_g, we get

$$\begin{aligned}\frac{\delta N(P,\theta_g)}{N(P,\theta_1)}\,dP &= \tfrac{1}{2}BnP^{-\beta}\left[\theta_1^2 - 2\,\frac{P\cos\lambda\sin\alpha}{45H}\,\theta_1 + \left(\frac{P\cos\lambda\sin\alpha}{45H}\right)^2\right]dP \\ &= \tfrac{1}{2}BnP^{-\beta}\left[\theta_1^2 + \tfrac{1}{2}\left(\frac{P\cos\lambda}{45H}\right)^2 - \tfrac{1}{2}\left(\frac{P\cos\lambda}{45H}\right)^2\cos 2\alpha - 2\theta_1\frac{P\cos\lambda}{45H}\sin\alpha\right]dP.\end{aligned} \tag{9}$$

Equation (9) indicates that all effects related to latitudinal gradients diminish in amplitude with increasing strength of the interplanetary magnetic field.

a) Semidiurnal Component

Referring to expression (9), it is evident that the third term in the brackets represents a semidiurnal component with amplitude

$$r_2(P)\,dP = \tfrac{1}{4}BnP^{-\beta}\frac{P^2\cos^2\lambda}{(45H)^2}\,dP\,. \qquad (10)$$

Its direction of maximum is perpendicular to the magnetic field.

The energy spectrum of variation of the semidiurnal component has an exponent $2-\beta$ which could be positive whenever β is less than 2, as is the case during most periods of the solar cycle. When the exponent is positive, a neutron monitor which responds to lower energies can show a smaller semidiurnal component than a meson detector. The same effect could be seen at a neutron monitor situated at a higher latitude with a lower mean energy of response than a neutron monitor situated at the equator. The latitude effect of semidiurnal component is further accentuated by its $\cos^2\lambda$ dependence on asymptotic latitude of viewing of the detector. The amplitude of the semidiurnal component which is often more prominent at equatorial stations than at high-latitude stations supports the present interpretation (Katzman and Venkatesan 1960; Ahluwalia 1960).

When the exponent of the energy spectrum of the 11-year variation β is low as during solar activity maximum, the semidiurnal component should be high, other factors remaining the same. In practice, this effect would not normally be observed because of two factors. First, during this period we have small latitudinal gradients in the region $\pm 30°$ compared to the gradients during the declining phase of solar activity. Second, we have a greater number of active regions meridionally distributed at low latitudes and hence more non-uniformity of solar wind than the number during the increasing phase of solar activity. Thus the size of the domains with smooth field lines and correspondingly the energy up to which the semidiurnal component can be observed would be small.

b) The Diurnal Component

The fourth term within the brackets of equation (9) represents a diurnal component whose amplitude is given by

$$r_1(P)\,dP = \tfrac{1}{2}BnP^{-\beta}\theta_1\frac{P\cos\lambda}{45H}\,dP \qquad (11)$$

with a direction of maximum which is perpendicular to the magnetic field. This diurnal component will reverse its direction of maximum with reversal of interplanetary field or with a change of sign of θ_1 in equation (11) when the north-south asymmetry of solar activity reverses. Another distinguishing feature of this diurnal component is that its energy dependence is as $P^{1-\beta}$ in contrast to P^0 for the azimuthal drift. Note that this diurnal component has an amplitude which depends on asymptotic latitude of viewing as $\cos\lambda$, the same way as the diurnal component due to azimuthal drift (Sandstrom, Dyring, and Lindgren 1962; McCracken and Rao 1965).

c) The Omnidirectional Intensity

The second term in the brackets of equation (9) represents a change of omnidirectional intensity which has the same magnitude as the semidiurnal component in space and has the same latitude and energy dependence. As observed by a detector on Earth, the 24-hourly mean intensity change will be more than the amplitude of the semidiurnal component which is attenuated by the finite opening angle of the detector and by the dispersion of particle trajectories in the geomagnetic field.

The first term in the brackets of expression (9) represents the contribution of intensity from high-heliolatitude regions to the cosmic-ray mean intensity that would be observed in the equatorial plane. Therefore, the variation of 24-hour mean intensity observed at Earth is not only a function of solar activity along the equatorial belt but also of the activity at other heliolatitudes.

V. ESTIMATES OF DAILY VARIATIONS AND 24-HOUR MEAN INTENSITY VARIATIONS FOR NEUTRON MONITORS FOR THREE ASSUMED DISTRIBUTIONS OF GALACTIC COSMIC-RAY DENSITY

In the preceding section we have considered analytically the consequences of a distribution of galactic cosmic-ray density as given by Case II. We now calculate numerically the cosmic-ray effects that could be observed by neutron monitors at Deep River and Huancayo for the three cases of latitudinal dependence of cosmic-ray intensity indicated in Figure 3.

For the three assumed distributions of cosmic-ray density, we obtain the cosmic-ray intensity at any time t, measured at an instrument situated at a height h, on the spinning Earth, from the relation

$$I(t)dt = \sum_{P} \sum_{\substack{\text{zenith}\\ \text{angle}}} \sum_{\substack{\text{azimuth}\\ \text{angle}}} j[P,\theta_g(t)]m(P,h)Rd\Omega dPdt, \tag{12}$$

where $m(p,h)$ is the specific yield function of the secondary cosmic-ray component given by Webber (1962), Ω is the solid angle, and R is the effective area. The intensity varies with time as θ_g varies with the pitch angle α. From Figure 1a

$$\alpha = \frac{2\pi}{24}(t - t_0) + \psi(P) \tag{13}$$

where t_0 corresponds to the garden-hose direction of the interplanetary magnetic field and $\psi(P)$ is the asymptotic longitude measured from the local meridian. For a given zenith and azimuth angle, the asymptotic direction of approach of a cosmic-ray particle of rigidity P is determined by calculating its trajectory in a sixth-degree simulation of Earth's magnetic field (IQSY Committee 1965). From equations (3), (12), and (13) the contributions to the cosmic-ray intensity, from all zenith and azimuth angles and from particles of all rigidities, can then be obtained. The resulting intensity variation is harmonically analyzed in order to obtain variation of 24-hour mean intensity as well as the diurnal and the semidiurnal components of the daily variation.

Calculations made for neutron monitors situated at Huancayo and Deep River are presented in Table 1. The variation with primary rigidity of the particles is assumed to extend from 2 GV up to an upper limiting rigidity $P_{\max} = 100$ GV. Within this range we have considered $\beta = 0$ and $\beta = 1$. In the latitude range $\pm 6°$ the gradient of galactic cosmic rays perpendicular to the plane of the ecliptic is assumed in all cases to be 6 per cent a.u. for integral intensity of particles having rigidity greater than 2 GV. The relevance of this assumption is discussed later.

a) Daily Variation

In Table 1 it is seen that a semidiurnal component of 0.35 per cent can arise for an interplanetary field of 3γ for $\beta = 1$ in Case III. For Cases I and II, on the other hand, the amplitude can be much smaller, being 0.065 per cent. Corresponding to these values the diurnal component is of comparable magnitude in Case II, while in Cases I and III, it is less by at least an order of magnitude. In all cases, where $\beta = +1$, there is little difference in the amplitude between Huancayo and Deep River. When corrected for the deflection in the geomagnetic field, the diurnal as well as the semidiurnal components are oriented with their directions of maxima normal (but sometimes parallel) to the direction of the interplanetary magnetic field.

Case III illustrates the complicated changes of the semidiurnal component that can occur with changes in the conditions of the interplanetary magnetic field. When the field decreases from 5γ to 1γ, the direction of maximum of the calculated semidiurnal component remains essentially constant at Deep River, while at Huancayo the direction flips over by 7.8 hours. The reason for this is that the heliolatitude of the gyrocenter of particles in the energy interval which contributes significantly to the counting rate of the instrument crosses the dip in the distribution of cosmic-ray density. A similar flipping

TABLE 1

CALCULATED DAILY VARIATION OF NEUTRON INTENSITY ARISING FROM LATITUDINAL GRADIENTS

Type of Distribution	Exponent β (11-Year Variation)	Magnetic Field (γ)	Deep River Monitor				Huancayo Monitor			
			r_1 (Per Cent)	T_1 (Hrs L.T.)	r_2 (Per Cent)	T_2 (Hrs L.T.)	r_1 (Per Cent)	T_1 (Hrs L.T.)	r_2 (Per Cent)	T_2 (Hrs L.T.)
Case I (symmetrical about $\theta=0$)	−1	5	0.003	0.7	0.025	1.1	0.002	21.6	0.024	11.9
	−1	3	0.005	0.7	0.064	1.0	0.045	21.6	0.063	11.9
	−1	1	0.015	0.7	0.50	0.9	0.013	21.5	0.350	10.9
	0	5	0.047	1.3	0.54	1.6	0.085	23.6	0.085	0.8
Case II (symmetrical about $\theta=\theta_1$)	−1	5	0.34	0.6	0.025	1.1	0.29	21.9	0.025	11.9
	−1	3	0.56	0.6	0.67	1.1	0.47	21.5	0.061	11.8
	−1	1	1.67	0.6	0.48	0.9	1.25	21.1	0.33	11.0
	0	5	0.37	1.2	0.51	1.6	0.48	23.2	0.087	2.6
Case III (symmetrical about $\theta=0$ with two dips at $\theta_2=\theta_4\neq0$)	−1	5	0.002	0.4	0.150	6.9	0.001	20.6	0.15	4.4
	−1	3	0.003	0.5	0.38	6.6	0.003	22.6	0.35	2.7
	−1	1	0.009	0.9	1.68	6.0	0.015	21.6	0.47	10.5
	0	5	0.002	0.4	0.6	7.1	0.002	23.4	0.26	4.8

over of the direction of semidiurnal component is possible due to the lowering of heliolatitude (θ_3) of the sunspot zones and could be observed by cosmic-ray monitors whose mean energy of response E (GeV) corresponds to

$$E = 45H\,\theta_3\,. \tag{14}$$

b) *24-Hourly Mean Intensity Changes and 27-Day Variation*

The percentage contributions to the counting rates of neutron monitors arising from intensity of particles with gyrocenters outside the equatorial plane are shown in the fourth and fifth columns of Table 2. These contributions are obtained from equations (11) and (12) by summing $I(t)$ over a period of 24 hours. Note that the contribution is dependent on the exponent of the energy spectrum of 11-year variation as well as on three other factors, namely, the magnitude of the latitudinal gradient, the form of the distribution of galactic cosmic-ray density with heliolatitude, and the magnitude of the interplanetary magnetic field. Since all three are dependent on the distribution and character of quasi-permanent active regions on the Sun, a 27-day variation of omnidirectional intensity in space (measured as a 24-hourly mean intensity by detectors on the spinning Earth) arises as a direct consequence of the rotation of the Sun.

In Table 3 are shown the expected changes of mean intensity at Deep River and Huancayo for the three forms of latitudinal distributions, when the interplanetary magnetic field changes from 5γ to 1γ. Changes of intensity up to 1 per cent can arise due to this factor alone as the interplanetary magnetic field in the environment of Earth alters with the rotation of the Sun. Note that the change of intensity at Huancayo could be more or less than that at Deep River depending on the form of latitudinal distribution. The occurrence of a positive exponent for the energy spectrum of variation of mean intensity can be properly understood only if we take into account the latitudinal distribution of cosmic-ray density, as in Cases I and II.

VI. DISCUSSION

Whether or not cosmic-ray detectors on Earth would measure the effects discussed earlier depends on two principal factors: first, on the existence of latitudinal gradients of galactic cosmic rays and, second, on the interplanetary magnetic field in the vicinity of Earth being not so irregular as to permit isotropic diffusion of cosmic rays within the rigidity interval that significantly contributes to the counting rate of the detector.

TABLE 2

CONTRIBUTION IN THE ECLIPTIC PLANE OF INTENSITY WITH $\theta_g \neq 0$

Type of Distribution	Exponent β (11-Year Variation)	Magnetic Field (γ)	24-Hour Mean Intensity (Per Cent)	
			Deep River	Huancayo
Case I (symmetrical about $\theta=0$)	−1	5	3.0	4.25
	−1	3	3.0	5.4
	−1	1	3.8	6.5
	0	5	0	3.0
Case II (symmetrical about $\theta=\theta_1$)	−1	5	3.8	5.2
	−1	3	3.8	5.35
	−1	1	4.5	6.9
	0	5	1.0	3.5
Case III (symmetrical about $\theta=0$ with two dips at $\theta_2=\theta_4\neq 0$)	−1	5	2.3	4.7
	−1	3	2.3	4.2
	−1	1	1.5	4.3
	0	5	2.5	2.0

TABLE 3

CHANGES OF MEAN INTENSITY RELATED TO VARIATION OF INTERPLANETARY MAGNETIC FIELD

Type of Latitudinal Distribution*	Per Cent Change per γ†		$[dI/I$ (Deep River)$]/[dI/I$ (Huancayo)$]$
	Deep River	Huancayo	
Case I........	−0.1	−0.55	0.36
Case II.......	−0.2	−0.45	0.44
Case III......	0.2	0.1	2.0

* See Table 1 for descriptions of Cases I–III.

† Average of $1/I\ (dI/dH)$ corresponding to interplanetary magnetic fields in the range 5γ to 1γ are indicated in the table. Exponent of the energy spectrum of the 11-year variation β is assumed to be −1.

Isotropic diffusion can indeed occur selectively for particles in a limited rigidity interval since it is caused by scattering which is most effective when the scale length of irregularities is comparable to the gyroradius of the cosmic rays in the interplanetary magnetic field.

The latitudinal gradient assumed in our model follows from the basic process responsible for the 11-year variation of galactic cosmic rays where modulation occurs during diffusion over an extended path length along the spiraling interplanetary magnetic field tied to specific regions of the Sun but terminating at some distance beyond Earth (Parker 1963). The irregularities along the interplanetary magnetic field and the velocity of the solar wind are both involved in the modulation. Moreover, since irregularities are created, amongst other causes, by the non-uniformity of solar wind from adjacent regions on the Sun at the same heliolatitude (Sarabhai 1963), the 11-year modulation in interplanetary space should be related to the degree of activity at different heliolatitudes.

Our supposition that the cosmic-ray density at high heliolatitudes would be larger than at the equatorial plane is consistent with the decrease of solar activity near the poles as indicated by the latitudinal distribution of the brightness of the corona observed in 5303 Å (Sarabhai and Subramanian 1965; Subramanian and Sarabhai 1965). The model is also consistent with the flattening of the coronal electron-density contour over the poles as observed at distances of 100 solar radii during occultation of radio stars (Slee 1961). Moreover, Type I tail activity of comets, indicative of interaction with solar wind, has been shown, in a statistical investigation of fifty-one comet apparitions at distances of about 1 a.u., to decrease with increasing heliolatitude of their perihelia (Stumpff 1959).

An estimate of the latitudinal gradient of cosmic rays near the equatorial plane has been made by Dorman and Fischer (1965). They have analyzed the monthly mean cosmic-ray intensity as a function of the heliolatitude of Earth, which changes within the limits $\pm 7\frac{1}{2}^{\circ}$, when Earth goes around the Sun. Their conclusion that the latitudinal gradient does not exceed 5 per cent/a.u. is derived from measurements with surface neutron monitors with mean energy of response greater than 10 GeV. In the present calculations we assume a latitudinal gradient of 6 per cent/a.u. near the equatorial plane for primary particles of energy greater than 2 GeV. This corresponds to a mean energy of response of 3–4 GeV, and the assumed gradient is therefore conservative.

Observations of the radial gradient along the plane of the ecliptic have been made for protons with $E > 150$ MeV. The major contribution in these measurements is of particles with rigidity below the threshold of sensitivity of surface neutron monitors. In any case, since the coefficient for diffusion of galactic cosmic rays transverse to the magnetic field ($K_{\perp}$) would be negligible compared to the coefficient for diffusion parallel to the field ($K_{\parallel}$), transverse gradients could be much higher than radial gradients. Therefore experimental evidence from spacecraft with orbits in the plane of the ecliptic is not directly relevant to judge the appropriateness of the latitudinal gradient which has been assumed in our calculations.

Interplanetary magnetic conditions in the neighborhood of Earth which inhibit diffusion transverse to the field lines are essential for the occurrence of cosmic-ray variations related to the latitudinal gradients. We require a relative absence of irregularities where scattering could contribute to transverse diffusion. The same condition is of course necessary to sustain the anisotropy caused by the azimuthal streaming of cosmic rays. The detection of a diurnal variation leading to a maximum intensity generally oriented along the direction in space corresponding to $18^{h}00$ L.T. has been interpreted as evidence that the anisotropy due to the streaming is present on a large number of days. The presence of impact zones associated with solar-flare events and characteristic anisotropy preceding a Forbush decrease and during its recovery phase give further support to the contention that conditions of anisotropic diffusion near Earth are usually satisfied.

For the sake of simplicity in the present calculations we have assumed a uniform magnetic field over an extended region. As long as the field does not reverse in direction, a variation of its magnitude within the region makes no qualitative difference to our interpretation and can be accounted for by introducing a second-order refinement under any given condition, observed or assumed. Measurements of the interplanetary field in the ecliptic plane show that averaged over 3 hours (Wilcox and Ness 1965) the magnetic field during December, 1963–February, 1964, retained the same sense, toward or away from the Sun, over sectors ranging from 80° to 105° in heliolongitude. Assuming the field to retain the same direction in a meridional plane over $\pm 26°$ in heliolatitude would mean that the process outlined here would be qualitatively applicable to rigidities up to 100 GeV when the average field is 5γ.

Scattering at irregularities along magnetic-field lines and a latitudinal distribution of galactic cosmic-ray density were proposed by us to explain the deficiency of cosmic-ray intensity along the interplanetary magnetic field observed by Sarabhai, Pai, and Wada (1965). The deficiency can generate a semidiurnal component, as a detector on the spinning Earth scans it. The semidiurnal component would have a maximum in a direction perpendicular to the interplanetary magnetic field. This process and the one described in the present communication constitute at present the only two which explain the observed orientation of the semidiurnal component. Moreover, the present interpretation provides a plausible explanation for understanding the following observed cosmic-ray effects: (*a*) a semidiurnal component which can be larger at equatorial stations than at high latitude stations (Katzman and Venkatesan 1960) and (*b*) a positive exponent for the energy spectrum of daily variation which means that the daily variation of cosmic-ray intensity is sometimes greater in the energy range, say from 20–50 GeV than from 2 to 20 GeV when analyzed on a day-to-day basis (Sarabhai and Subramanian 1963, 1965).

It is worthwhile to note that a cosmic-ray detector at a polar station is almost solely sensitive to the cosmic-ray intensity diffusing along the plane of the ecliptic. On the other hand, an equatorial station samples galactic cosmic rays corresponding to gyrocenters at different heliolatitudes depending on the rigidity of the particles, the direction of viewing with respect to the interplanetary magnetic field, and the strength of the magnetic field.

The following predictions arising out of our model can be verified: (1) The dependence of the semidiurnal anisotropy on the latitude of viewing should, in general, be different from that of the diurnal component. (2) The diurnal component arising out of the latitudinal gradients should reverse its direction with reversal of either the magnetic field or the north-south asymmetry of solar activity. (3) The anisotropy is dependent on the magnitude of the interplanetary magnetic field other factors remaining unchanged.

A direct experimental test for the validity of our suggestion can be secured using a deep-space probe or a satellite outside the magnetosphere with spin axis perpendicular to the plane of the ecliptic. The experiment would involve directional detectors sensitive to different energy ranges of galactic cosmic rays. The detectors would scan the pitch-angle distribution of the cosmic rays with respect to the interplanetary magnetic field. If, indeed, our model of latitudinal distribution of galactic cosmic rays and the mechanism proposed by us for the occurrence of virtual sinks or sources correspond to real conditions in interplanetary space, we have a powerful method of probing conditions, outside the plane of the ecliptic, using cosmic-ray intensity variations in detectors on Earth. The model of latitudinal distribution of cosmic rays proposed by us appears to be a good candidate for relating in an integrated way the 11-year cycle of variation, some aspects of the 27-day variation, and the anisotropy of galactic cosmic rays with conditions in interplanetary space, namely, the orientation of the interplanetary magnetic field and scattering centers along the magnetic-field line not only close to Earth but in the Sun-Earth region and beyond Earth.

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SHORT-PERIOD VARIATIONS OF COSMIC-RAY INTENSITY*

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(Received 26 June 1967)

Hitherto it has not been possible to establish the occurrence of time variations of galactic cosmic rays with very short periods, of the order of a few minutes, because large detectors that give a really high counting rate were not available. An attempt by Torizuka and Wada,[1] with a counting rate of around 10^5 counts/min, has not yielded conclusive results. However, a large-area scintillation muon detector has been operated for several years by the Bolivian Air Shower Joint Experiment (BASJE) at Chacaltaya at an altitude of 17 200 ft, longitude 68° 10′ W and geomagnetic latitude −5.0°. The authors have been fortunate to have had the opportunity of using the output of the BASJE detector with a counting rate of a million counts/min for conducting an investigation from April 1964 to June 1966. 15 scintillation detectors each of 4 m^2 were used (Suga *et al.*[2]). The total array of 60 m^2, housed in a cave, was shielded by 3 m water equivalent of galena so that the electron component was absorbed. The outputs of sets of five detectors were combined to provide three independent channels for intercomparison. Accurate time was maintained by using a crystal controlled electronic clock. Cosmic-ray data were recorded every 12 sec while one-minute recordings of barometric pressure were also made using a digital servobarometer. The 12-sec data from the three channels were intercompared and unless one or more channels exhibited erratic behavior, data from the three independent channels were combined for successive one-minute intervals. The constants used for power spectrum analysis were $n = 180$, $m = 30$, and $t = 1$ min, where n is the number of data points in each set, m is the total lag, and t is the averaging interval for each point. This gave us spectral estimates at 31 points equally spaced in frequency from 0 to 30 cycle/h. The significance of spectral-density estimates was evaluated using the method suggested by Blackman and Tucky.[3] For the chi-squared distribution, we have $2(n/m-\frac{1}{3})\sim 11$ degrees of freedom.

Spectral estimates show variability in individual samples of three-hourly intervals. As more samples are superposed, peaks in the spectral frequency range of 1 to 6 cycle/h get smeared out by superposition. However, persistent peaks at 18 and 25 cycle/h are observed. These appear at 99% confidence limits for the superposition of 487 three-hourly sets during November 1965 to March 1966, as shown in Fig. 1. Records[4] of the magnetic field taken by Mariner IV in the magnetosheath region a year earlier indicate that at 200-sec period (18 cycle/h), there was large spectral activity. Ness, Scearce, and Cantarano[5] have found spectral peaks of 600-, 300-, 180-, and 120-sec periods in the interplanetary magnetic field recorded by Pioneer VI on 16 December 1965 from 1715 to 2015 h. Cosmic-ray data for the same interval show similar periodic fluctuations which are shown in Fig. 2.

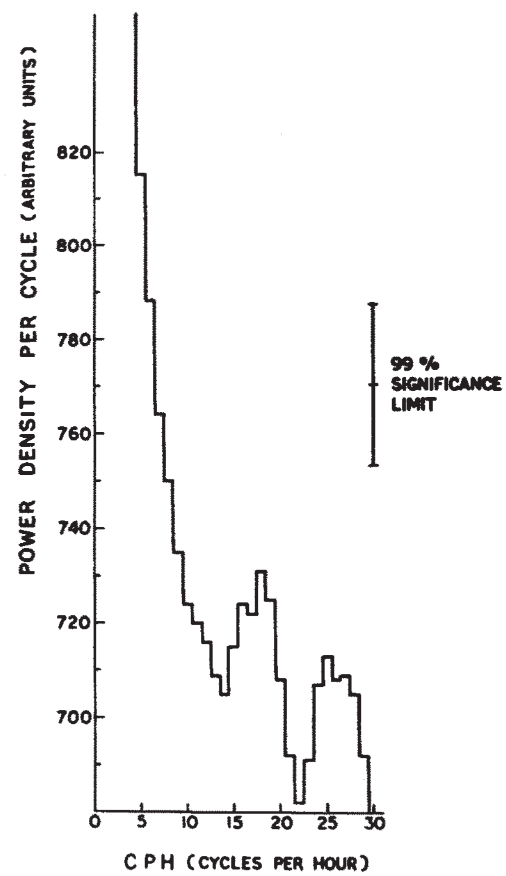

FIG. 1. The superposed spectral density for 487 three-hourly sets (November 1965 to March 1966) indicating peaks at 18 and 25 cycle/h.

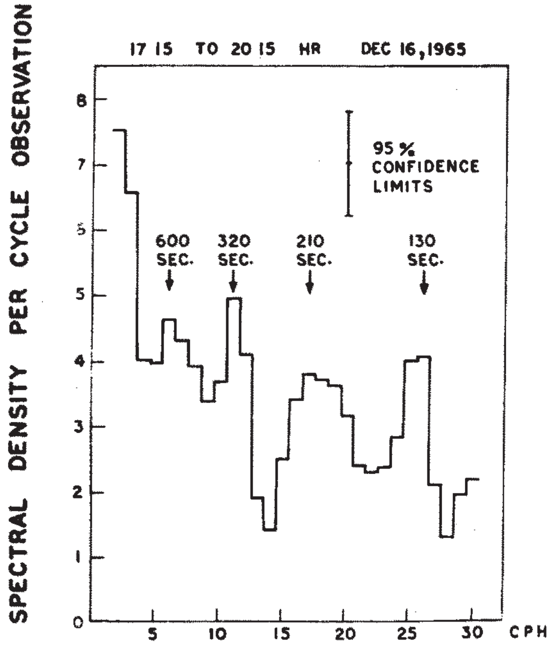

FIG. 2. The spectral density estimates for cosmic rays corresponding to the three-hourly interval when Pioneer VI was simultaneously recording interplanetary magnetic field.

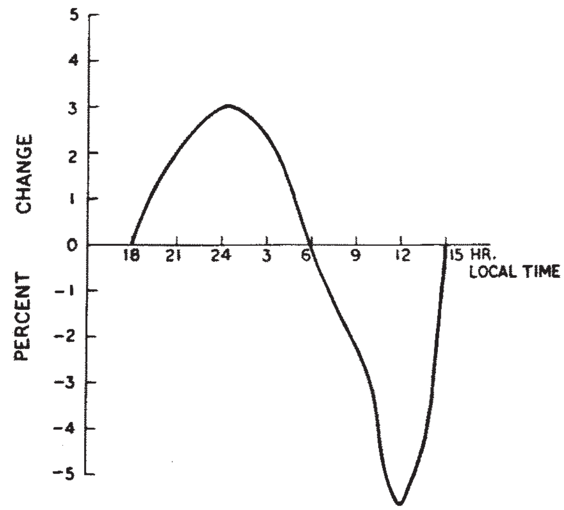

FIG. 3. The percentage change from the average of spectral density in the solar and antisolar directions for 18 cycle/h.

Local time dependence of the spectral density has been studied for 18 cycle/h. Figure 3 corresponding to 487 intervals indicates that the variation has large amplitude when the detector is in the antisolar direction.

The barometric pressure at one-minute intervals has been subjected to power-spectrum analysis. The absence of any peaks of pressure in the region of interest corresponding to cosmic-ray peaks indicates that the cosmic-ray peaks are not due to barometric pressure changes. An attractive possibility of explaining the short-period fluctuation of cosmic rays appears through the periodic change of geomagnetic cutoff rigidities. For 487 three-hourly intervals the average amplitude of the 18-cycle/h periodicity is about $(0.04 \pm 0.01)\%$. To account for these periodic changes, which have been observed for the first time in the present investigation at the geomagnetic equator, we estimate by using the coupling coefficient given by Dorman[6] for the meson component that there need to be periodic changes of about 20γ in the dipole field. Fluctuations of this order of magnitude in the magnetosheath have been observed[4] for 18-cycle/h periodicity.

Related to this interpretation, three interesting points require to be understood: First, the manner in which periodic fluctuations of the interplanetary-magnetic field are translated to periodic changes of geomagnetic field relevant to changes in the cutoff rigidity of primary cosmic rays. Interplanetary periodicities measured by magnetometers on space probes are most likely the result of the spatial structure in the plasma wind. For a wind with a radial velocity of 400 km/sec the observed 18-cycle/h fluctuations correspond to a scale length of 0.5×10^{-3} A.U. of the irregularities in the plasma wind. The fluctuations of the energy density impinging on the magnetosphere resulting from these irregularities could be the means through which the periodicities are generated in the geomagnetic field. Second, there is perhaps a difference in the sharpness of the spectral peaks observed in cosmic rays at 18 cycle/h compared to the other peaks. One would like to know whether this is genuine and caused by the inherent resonant and dissipative characteristics of the magnetosheath for energy transmitted through it. Third, the larger amplitude of 18-cycle/h spectral density in the antisolar direction (3%) compared to the solar direction (−5.5%) could probably indicate the variation in the amplitude of the oscillations of the distant geomagnetic field in the tail of the cavity and in the direction of the bow shock. More quantitative analysis with additional data from space craft is necessary to pursue these points.

The authors are grateful to the investigators of the BASJE project, particularly I. Escobar, B. Rossi, G. Clark, K. Suga, and K. Kamata. We are also deeply grateful to H. S. Ahluwalia and R. Vidaurre of the Chacaltaya Laboratory, and S. R. Thakore, Chief of the Computing Center at the Physical Research Laboratory.

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Experimental determination of Temperature Effect on μ Mesons recorded at Trivandrum

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The temperature affect on the μ meson intensity is well established. However the evaluation of its contribution to the daily variation, poses many problems (Sarabhai, et al Proc. Ind. Acad. Sc. 37, 287 (1953), Quenby and Thambyah Pillai, Phil. Mag. 8, 585, (1960), Barcovitch, Can. J. Phy. May 68). Crossed telescopes have been used in the past, to provide comparative data from two different azimuths, with a view to derive the features of primary anisotropy, free from the error from an unknown contribution due to temperature effect.

Recent studies (V.Sarabhai and G. Subramanian Prof. Int. Conf. Cos. Rays, London 1965, 1, 204. D.Patel et al Can. J. Phys May 1968) which derive the anisotropy in space on each day from a world wide net work of neutron monitor stations, now provide a means of deriving the temperature effect, by comparing the observed daily variation in vertical and inclined telescopes with the expected variation due to the primary anisotropy and barometric pressure changes.

D. Patel and V. Sarabhai (Private Communication) have established the energy spectrum of variation, the direction in space and the amplitude of the anisotropy on individual days.

In the present analysis, we have selected the days on which the energy spectrum of the anisotropy has a zero exponent during the period 1964 to 1965. Knowing the daily variation in free space on these days as seen by vertical and inclined G.M. counter telescopes at Trivandrum has been calculated, after allowing for geomagnetic bending and the width of the asymptotic cones of acceptance of these telescopes.

Using a pressure coefficient of -.14%/m.b, the pressure corrected daily variation as observed at Trivandrum is derived.

The vector difference between the expected and the observed pressure corrected daily variation may be attributed to changes in temperature in the upper atmosphere. We have attempted to test this hypothesis by comparing the profile of the residual variation with the daily variation of temperature in the lower atmosphere.

Figure 1 shows the temperature effect at Trivandrum obtained using the above method. It may be seen, that the diurnal maximum of temperature effect occurs at late after-noon hours (local time) consistant with the result obtained by Quenby and Thambyah Pillai (1960) and Mori et al (Proc. Int. Conf. Cos. Rays, London 1, 498, 1965). However the amplitude of the temperature effect may depend on the location of observation.

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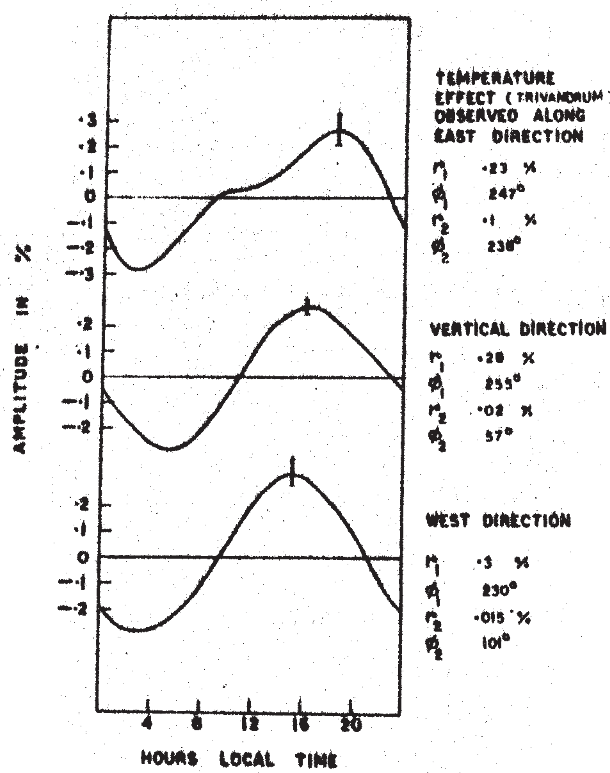
TEMPERATURE EFFECT (TRIVANDRUM) OBSERVED ALONG EAST DIRECTION
r_1 ·23 %
ϕ_1 247°
r_2 ·1 %
ϕ_2 238°
VERTICAL DIRECTION
r_1 ·28 %
ϕ_1 255°
r_2 ·02 %
ϕ_2 57°
WEST DIRECTION
r_1 ·3 %
ϕ_1 230°
r_2 ·015 %
ϕ_2 101°
AMPLITUDE IN %
HOURS LOCAL TIME
4
8
12
16
20

Fig 1

Back

Gradient of galactic cosmic rays normal to the solar equatorial plane[1]

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Received June 21, 1967

Predictions concerning the anisotropy of galactic cosmic rays due to a gradient of cosmic-ray density perpendicular to the solar equatorial plane have been verified experimentally as follows. (1) The energy spectrum of the variation of the semidiurnal component has a positive exponent. (2) The diurnal and the semidiurnal components are oriented with respect to the interplanetary magnetic field. (3) A deficiency of cosmic-ray intensity, T_{min}, is observed along the direction of the interplanetary magnetic field on days when the energy spectrum of the diurnal variation has an exponent different from zero.

We have recently estimated the anisotropy of galactic cosmic rays in interplanetary space arising from three distributions of cosmic-ray density assumed such that the density at a high heliolatitude is larger than the density in the equatorial plane in accordance with a model suggested by us earlier (Sarabhai and Subramanian 1966*b*; Subramanian and Sarabhai 1967). A semidiurnal component, as well as a diurnal component (both oriented with respect to the interplanetary magnetic field), arises as a consequence of the dependence of the cosmic-ray density on the heliolatitude. The process also produces a change in the 24-hour mean cosmic-ray intensity measured on the earth. A most striking characteristic of the semidiurnal component generated by this process is that it is more for medium energies (10–30 GeV) than for lower energies (10 GeV). We have looked for this fingerprint in the daily variation recorded by a network of super neutron monitors during 1964–65. Predictions concerning the anisotropy can be verified experimentally—noting, however, that there are other processes which also produce anisotropy and the different processes are active to different degrees on any particular day. These other processes—i.e. azimuthal streaming (Parker 1964; Axford 1965; Krimsky 1964), streaming due to nonuniform diffusion in a longitudinal sector structure of the interplanetary magnetic fields (Parker 1964), and scattering at irregularities along the interplanetary magnetic field short-circuiting latitudinal gradients (Sarabhai and Subramanian 1966*b*)—have their own characteristic spectra of variation, different from that with positive exponent mentioned here. Therefore, the crucial tests involve the following:

1. A demonstration that the spectrum of variation of the semidiurnal component can have a positive exponent. This is in contrast to the diurnal component, which should have primarily a zero exponent related to the azimuthal streaming process. The spectrum is determined on each day, using the procedure described by Sarabhai and Subramanian (1966*a*).

Figure 1 shows the frequency of occurrence of spectra determined from the diurnal and semidiurnal components occurring on individual days. The following observations can be made:

(*a*) The diurnal variation has principally a spectrum with a zero exponent, and $E_{min} = 2$ or 4 GeV.

(*b*) The semidiurnal variation has principally a spectrum with a positive exponent (+0.6 to +1.0) while $E_{min} = 2$, 4, or 8 GeV.

(*c*) For $E_{min} = 8$ GeV, negative exponents occur in both diurnal and semidiurnal components. However, since in the grid of stations there is no detector with a cutoff rigidity greater than 4.2 GeV, good resolution is not achieved.

We therefore conclude from a study of day-to-day anisotropies that the diurnal and semidiurnal components have characteristically different spectra of variation. This is confirmed

[1]Presented at the Tenth International Conference on Cosmic Rays, held in Calgary, June 19–30, 1967, MOD-71,72.

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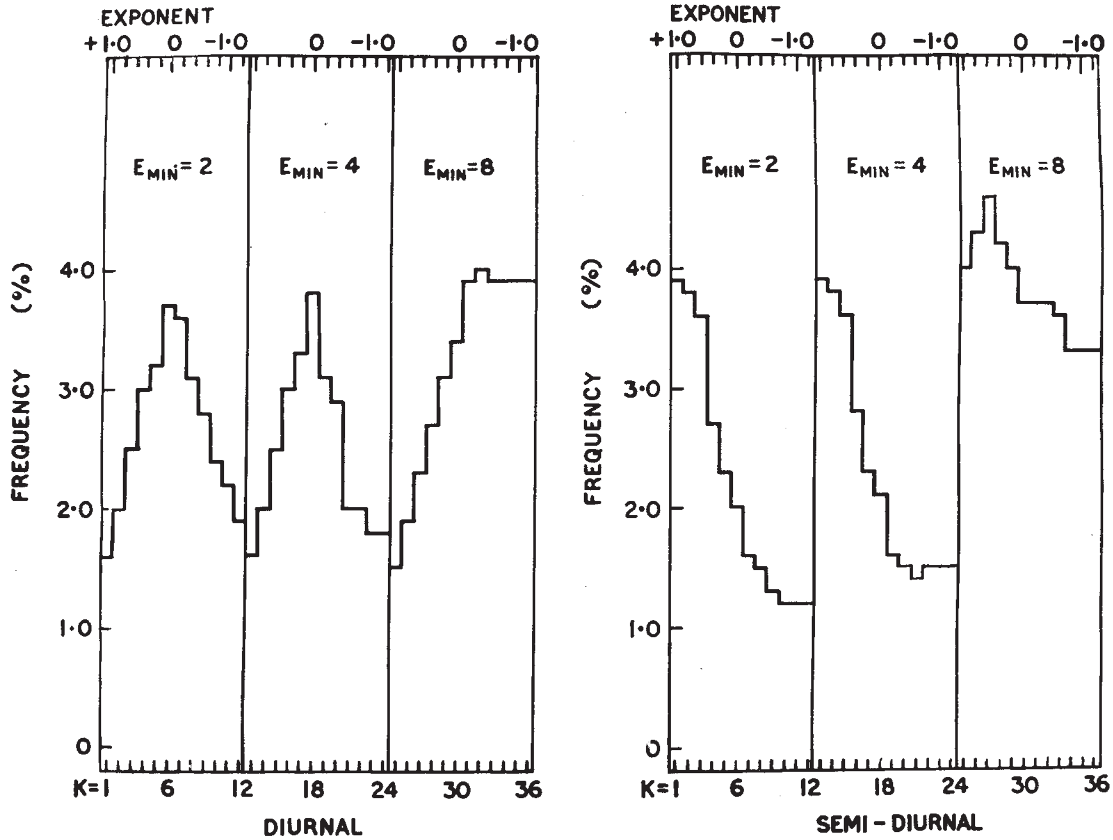

FIG. 1. The frequency distribution of the occurrence of the different energy spectra of variation is shown for the years 1964–65. The determination of the spectrum of variation was done separately for diurnal and semidiurnal components on each day.

through the comparison in Fig. 2 of the diurnal and semidiurnal amplitudes of the average daily variation during 1964–65, measured at a set of stations with geomagnetic cutoff rigidities ranging from 2 to 13 GeV. Allowance has been made for the attenuation of the diurnal and semidiurnal components due to the width of the asymptotic cones of acceptance of the detectors (Ables, McCracken, and Rao 1966). Note that while the diurnal component has a spectrum of variation which essentially is independent of rigidity and has an exponent $X = 0$, the semidiurnal component has a spectrum which has a positive exponent.

2. The diurnal and the semidiurnal components associated with positive exponents of the spectrum should be oriented with respect to the interplanetary magnetic field. In Fig. 3, the directions of maximum and minimum are studied for the three groups of variation spectra. For days with positive exponent of the spectrum, T_{min}, the direction of minimum intensity, is along the interplanetary magnetic field and T_{max}, the direction of maximum intensity, is almost perpendicular to the field, significantly inclined to the 1800 direction for azimuthal streaming. This may be contrasted with T_{max} along 1800 hours and T_{min} along 0600 hours when the exponent is zero.

3. The diurnal anisotropy should reverse as the magnetic field or the gradient reverses. The effect would be superimposed on the diurnal variation produced by azimuthal streaming. The resultant should exhibit a change of amplitude with a reversal of interplanetary magnetic field. This has been verified by using data for the magnetic field measured by IMP-1.

4. Because of scattering at magnetic field

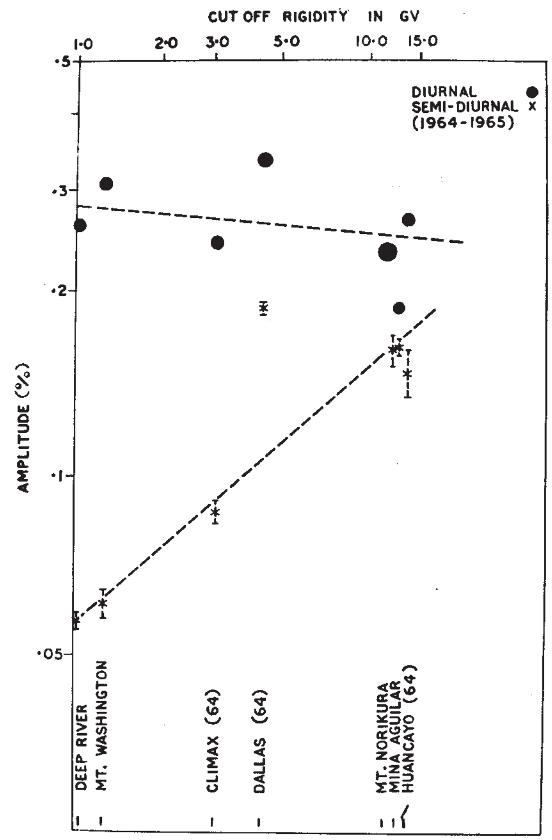

Fig. 2. The energy spectrum of variation of the annual mean diurnal and semidiurnal amplitudes which are corrected for the width of asymptotic cones of acceptance of the respective station.

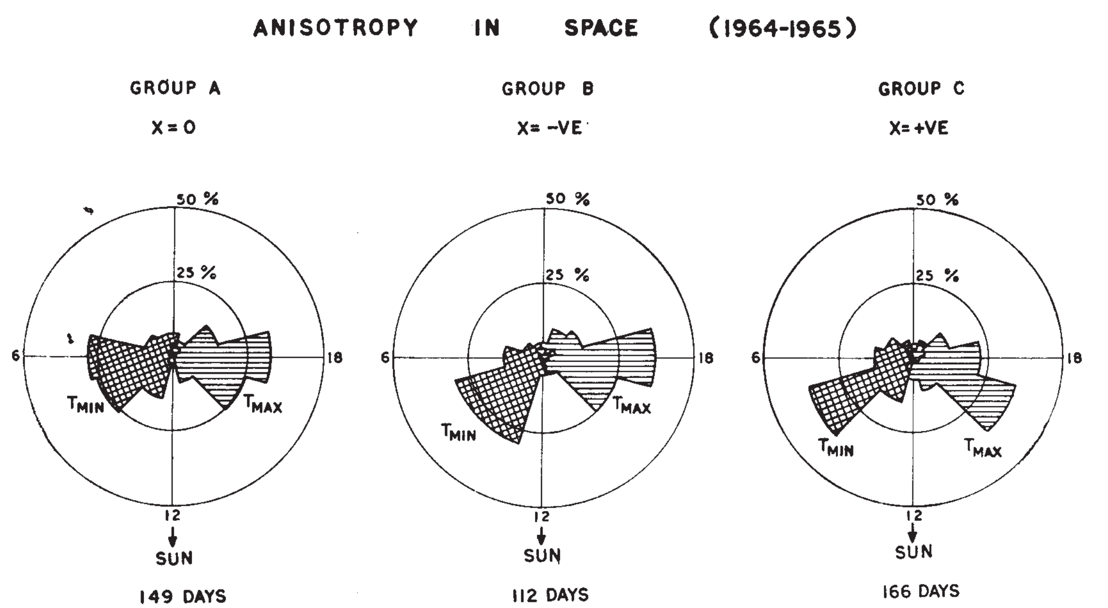

Fig. 3. The frequency distributions of $T_{\max}$ and $T_{\min}$ are shown for three different energy spectra of variation.

irregularities along the interplanetary magnetic field, $T_{\min}$ will be observed when the intensity along the plane of the ecliptic is higher than the intensity on either side of it. This is observed on days when the spectrum has an exponent different from zero.

We conclude that the heliolatitudinal distribution of galactic cosmic rays gives rise to anisotropies oriented with respect to the interplanetary magnetic field. The semidiurnal component observed in galactic cosmic rays and a deficiency from the directions of the interplanetary magnetic field appear to be related to the latitudinal gradient, which could have a magnitude of up to 10%/AU. We suggest that it is possible to sample the conditions of the interplanetary magnetic field and cosmic-ray density in regions of the solar system at 1 AU but extending to about 15° outside the equatorial plane, using quantitative data of the cosmic-ray anisotropy.

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ANISOTROPIES OF GALACTIC COSMIC RAYS

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The anisotropies of galactic cosmic rays due to a gradient of cosmic ray density perpendicular to the plane of the ecliptic are studied through the diurnal component, the semidiurnal component and the deficiency in intensity measured by monitors on the spinning earth. The energy spectrum of variation that fits best (Sarabhai and Subramanian, Proc.Int.Conf. London 1, 204, 1965), the daily variation observed by a set of neutron monitors during 1964-1965 is derived for the diurnal and semidiurnal components separately for each day. The following consequences arising from the model proposed by Subramanian and Sarabhai (Astro.Phys.J.149, 417, 1967) can be confirmed.

1. The diurnal and the semidiurnal components should be oriented with respect to the interplanetary magnetic field.

In Fig.1 are shown the frequency distributions of Tmax and Tmin during 1964-65. For the days with positive exponent (Group C), Tmin the direction of minimum intensity is along the interplanetary magnetic field and Tmax, the direction of maximum intensity is almost perpendicular to the field. Tmax - Tmin $\approx$ 7 hours, which indicates that the semidiurnal component is predominant. This may be contrasted with Tmax along 1800 hours and Tmin along 0600 hours when exponent X = 0 (Group A). Due to scattering at field irregularities along the interplanetary magnetic field, Tmin will be observed when the intensity along the plane of ecliptic is higher than the intensity on either side of it. This is observed on days when the spectrum has an exponent different from zero.

2. Energy spectrum of variation of semidiurnal component should have a positive exponent.

(a) The comparison in Fig.2 of the energy spectrum of the diurnal and semidiurnal amplitudes of the average daily variation during 1964-65, measured at a set of stations with geomagnetic cut-off rigidities ranging from 2-13 GV, confirms that the diurnal component has a spectrum of variation which is essentially independent of rigidity and has an exponent $\chi \approx 0$ where as the semidiurnal component has a spectrum which has a positive exponent $\chi \gtrsim +.6$)

(b) On a day to day basis the semidiurnal component is significantly larger when the spectrum has a positive exponent (Group C) than when it has a negative (Group B) or zero (Group A) exponent.

3. The diurnal anisotropy should reverse as the magnetic field or the gradient reverses. The effects would be superimposed on the diurnal variation produced by azimuthal streaming. The resultant should exhibit change of amplitude with a reversal of the interplanetary magnetic field. This is verified using a set of neutron monitors during IMP-1 period for 6 solar rotations when interplanetary magnetic field direction in different sectors has been identified (Wilcox and Ness, J.Geophys.Res.70, 5793, 1964). The mean diurnal component for a set of stations is higher when the field is away from the sun, than when the field is directed towards the sun. The evidence presented here supports the view that there is a gradient of galactic cosmic rays perpendicular to the plane of the ecliptic. It moreover makes important contribution to the anisotropy of the cosmic rays in interplanetary space.

The authors are thankful to the Department of Atomic Energy, Government of India, for financial support.

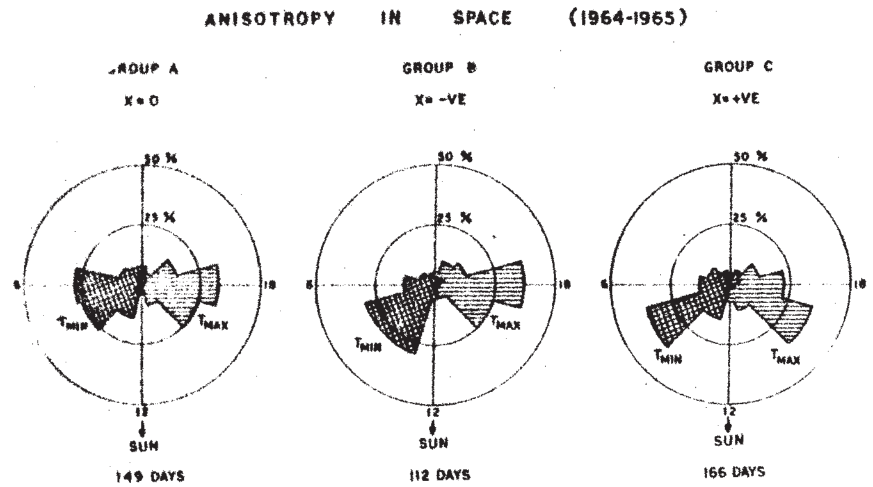

Fig.1 : The frequency distribution of Tmax and Tmin for the different energy spectrum of variation during 1964-1965.

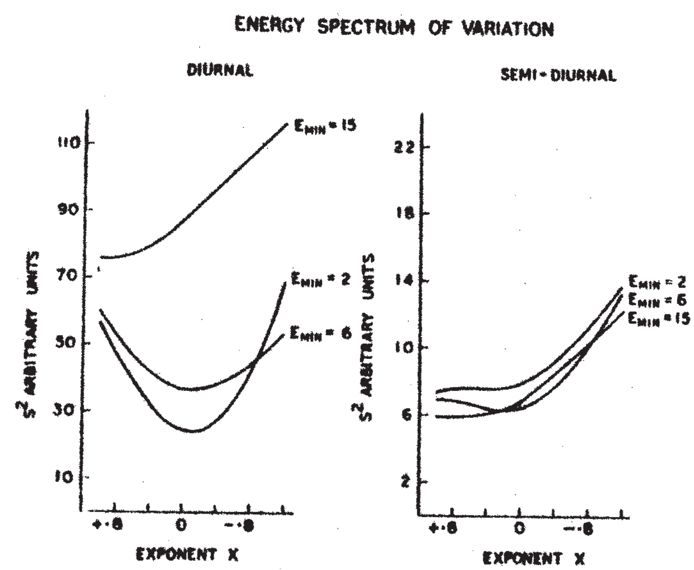

Fig.2 : S^2, the variance of the difference between the observed and free space amplitudes are plotted for various values of X and Emin. The S^2min for the diurnal anisotropy corresponds to $X = 0$, while for the semidiurnal anisotropy it corresponds to $X = +.6$.

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ANISOTROPIES OF GALACTIC COSMIC RAYS IN THE SOLAR SYSTEM

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(*Received* 9 *April* 1968)

Abstract—At least four processes appear capable of contributing to the creation of an anisotropy of galactic cosmic rays in interplanetary space. All need not necessarily be active on a particular day to the same extent. The processes are (1) azimuthal streaming, (2) streaming due to non-uniform diffusion in a longitudinal sector structure, (3) the scattering at irregularities along the interplanetary magnetic field, and (4) latitudinal gradients in a relatively smooth magnetic field. The characteristics of the daily variation which must be expected from each process are quantitatively evaluated.

Observational evidence derived from measurements of the daily variation from a network of super neutron monitors is used to derive, with precision, the spectrum of variation, the amplitude and the principal direction of maximum and minimum intensity in interplanetary space, on each day during 1964–65. The experimental results are compared with predictions to derive conclusions as to the process which operates on individual days.

It is demonstrated that the diurnal and the semi-diurnal components of the anisotropy have characteristically different energy spectra of variation. The predominant process responsible for the diurnal component is the azimuthal streaming while the semidiurnal component appears to be due to scattering at magnetic field irregularities and latitudinal gradients. The manner in which the results can be used to derive the threshold energy below which isotropic diffusion seems to occur on individual days in the inner solar system is demonstrated. The results of the study strongly support the postulate of a gradient of galactic cosmic rays in the solar system perpendicular to the ecliptic.

1. INTRODUCTION

Anisotropies of galactic cosmic rays are studied through the diurnal component, the semi-diurnal component and the deficiency, which often appears along the direction of the interplanetary magnetic field, in intensity measured by monitors on the spinning Earth. The characteristics of the anisotropies and the level of the isotropic intensity collectively provide a finger-print for identifying modulating processes and the electro-magnetic state of interplanetary space in the neighbourhood of the Earth (Sarabhai and Subramanian,[1] Subramanian and Sarabhai[2]).

We can derive the following characteristics of the anisotropy from cosmic ray intensity measured on the Earth. First, we have an energy spectrum of variation of the anisotropy specified by the exponent x, and limiting energies $E_{\min}$ and $E_{\max}$ in the relation,

$$\frac{\delta D(E)}{D(E)} = aE^x \quad \text{for} \quad E_{\min} \leq E \leq E_{\max}$$
$$= 0 \quad \text{for} \quad E < E_{\min} \quad \text{or} \quad E > E_{\max}$$

where $D(E)$ is the differential energy spectrum of primary cosmic ray particles of energy, E and $\delta D(E)$ is the energy spectrum of the variational part. Second, we have the directions in space of maximum intensity $T_{\max}$, and of minimum intensity $T_{\min}$. Third, we have the magnitude of the anisotropy in space defined in terms of a per cent change in the 24 hourly mean intensity of galactic cosmic rays. We present in Section 2 the method of analysis of the anisotropies and their characteristics during 1964–65.

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At least four processes appear to contribute to produce an anisotropy. All need not necessarily be active on the same day to the same extent. They are (1) azimuthal streaming (Parker,[3] Axford,[4] Krymskiy[5]) (2) streaming due to nonuniform diffusion in a longitudinal sector structure of interplanetary magnetic fields; (Parker[3]), (3) scattering at irregularities along the interplanetary magnetic field short-circuiting latitudinal gradients (Sarabhai and Subramanian[1]) and (4) latitudinal gradients in a relatively smooth magnetic field (Subramanian and Sarabhai,[2] Lietti and Quenby[16]). In Section 3, we describe the characteristics of the daily variation which must be expected from each process. Moreover, we try to understand the type of ambiguity that can occur in identifying from a given set of observational data the existence of interplanetary conditions corresponding to a particular process.

In Section 4 we compare observational evidence with the predictions of theory to derive conclusions as to the processes which operate on individual days. From this we deduce that in addition to azimuthal streaming giving rise to a diurnal component with a maximum in the 1800 direction, there is indeed evidence which indicates that processes 3 and 4 do, in fact, occur and produce anisotropies oriented with respect to the interplanetary magnetic field. Since both these processes are dependent on the existence of a latitudinal gradient of cosmic rays in interplanetary space, we interpret the evidence to support the existence of such gradients. The seasonal variation of cosmic ray intensity provides confirmatory evidence.

2. THE ENERGY SPECTRUM OF VARIATION OF THE ANISOTROPY OF GALACTIC COSMIC RAYS DURING 1964–65

Data from neutron monitors which are indicated in Table 1 are used for our analysis. Note that the asymptotic direction of viewing of each neutron monitor is itself dependent on the energy spectrum of variation of anisotropy. Moreover all stations scan interplanetary space in the range of latitudes $\pm 30°$.

Bi-hourly cosmic ray data corrected for variations of barometric pressure by the experimenters, and for day to day changes of level of 24 hr mean intensity, have been analysed to derive the amplitudes r_1 and r_2 and the phase angles ϕ_1 and ϕ_2 of the diurnal and the semi-diurnal components as well as the peak to peak amplitude (A), T_{max} and T_{min} for the composite variation produced by the superposition of the two components (Rao and Sarabhai[6]).

The energy spectrum of variation of anisotropy is derived for each day by the method of best fit taking into consideration r_1, ϕ_1, r_2, ϕ_2 for each of the 5 stations shown in Table 1 (Sarabhai and Subramanian[7]). To start with, we consider spectra designated by the serial numbers $K = 1$ to 36 indicated in Table 2. The exponents cover a range from $-1{\cdot}2$ to $+1{\cdot}0$ while E_{min} ranges from atmospheric cut off to 8 GeV. It would be desirable to extend E_{min} to higher energies up to 18 GeV by including an equatorial neutron monitor in the Indian Ocean region. However, a high counting rate instrument was not operational in this area during 1964–65. E_{max} in all cases is taken as 250 GeV.

For each assumed spectrum of variation K, we compute a parameter $S_K{}^2$ to provide a measure of the scatter of derived r_1, ϕ_1, r_2, ϕ_2 in space, corresponding to the observed variation at each station. The minimum value of $S_K{}^2$ indicates the best fit of the experimentally measured daily variation at each station with the variation that can be expected on the basis of the assumed spectrum. This provides the criterion for selecting the spectrum. The determination of the spectrum is done separately for the diurnal and the semi-diurnal components of the variation.

Even though 36 different spectra have been considered by us, the inherent resolution that is possible in discriminating between spectra has to be taken into account before interpreting the results. The criterion that is applied is $\chi^2(N)$ which is the standard error of $S^2_{\min}$. It depends on the number of stations N. If one has a group of spectra for which the S^2 values differ from $S^2_{\min}$ by more than $\chi^2(N)$, then the value of K for which the minimum occurs is deemed to be the spectrum of choice. Moreover other values of K which differ by less than $\chi^2(N)$ from $S^2_{\min}$, are also considered possible alternative choices, within the resolution of the method. If on the other hand the range of S^2 for the different spectra on a particular day, does not exceed $\chi^2(N)$, the determination of the energy spectrum is impossible. The procedure is best understood by an examination of Fig. 1, which indicates the value of S^2 corresponding to three different days. Figure 1a corresponds to a day when conditions are particularly favourable and only 6 equally acceptable spectra i.e. $K = 4$ to 8 and 17, emerge as possible candidates. On a different day conditions are as shown in Fig. 1b. The spectrum $K = 6$, can be chosen, since it corresponds to $S^2_{\min}$. However 18 other spectra are equally acceptable. Figure 1c, illustrates conditions on a day for which determination of the spectrum is not possible.

TABLE I

CHARACTERISTICS OF COSMIC RAY STATIONS (1964-65)

STATION:	HOURLY COUNTING RATE X 10^5	STANDARD ERROR+ (%)	CUT OFF RIGIDITY++ (G V)	ASYMPTOTIC LATITUDE (DEGREES++). FOR 10 GV	25 GV	MEAN DEFLECTION IN LONGITUDE FOR DIURNAL COMPONENT (IN HOURS) CASE I*	CASE II*	CASE III*	SOURCE OF DATA
CHURCHILL	7·74	·032	·21	33·0	45·7	1·03	1·28	1·41	D. C. ROSE
DEEP RIVER	6·26	·038	1·04	5·4	28·7	1·64	2·33	3·06	J. F. STELJES & H. CARMICHAEL
SULPHUR MOUNTAIN	8·80	·031	1·15	5·5	26·1	1·26	1·73	2·51	B. G. WILSON
CLIMAX	4·21	·043	3·06	−24·0	9·1	1·93	3·24	5·34	J. A. SIMPSON
DALLAS	7·88	·032	4·30	−31·4	2·6	2·08	3·47	5·39	K. G. McCRACKEN
HERMANUS	·10	·089	4·90	32·5	−6·8	1·88	3·55	6·12	A. M. VAN WIJK

+ STANDARD ERROR IN HARMONIC COEFFICIENT (EACH DAY)
++ IQSY INSTRUCTION MANUAL NO. 10 (1965)
* CASE I — EXPONENT $X = +\cdot 6$, $E_{MIN} = 2$ GEV
CASE II — EXPONENT $X = 0$, $E_{MIN} = 2$ GEV
CASE III — EXPONENT $X = -1\cdot 0$, $E_{MIN} = 2$ GEV

Of the 728 days during 1964–65, for which an attempt was made to determine the spectrum of variation, the analysis cannot be done for 4·0 per cent of days, which were rejected since $S^2_{\min}$ was very high ($\geqslant 400$). Almost all days on which major Forbush decreases have occurred or when data from one or more of the stations is erratic are rejected on this criterion. On account of lack of resolution between various spectra no determination was possible on another 4·3 per cent of days for the diurnal component and 31·9 per cent of days for the semi-diurnal component. For each remaining day, a spectrum corresponding to $S^2_{\min}$ and one or more equivalent spectra are identified.

Figure 2 shows the frequency of occurrence of spectra determined from the diurnal and semi-diurnal components. Primary as well as equivalent spectra have been included.

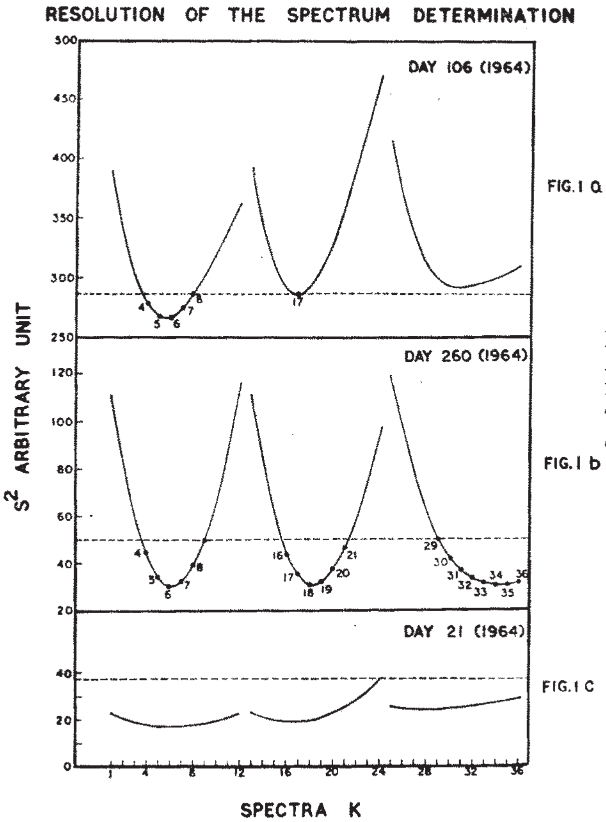

FIG. 1. S^2 VALUES FOR THREE TYPICAL DAYS ARE PLOTTED FOR DIFFERENT SPECTRA DESIGNATED BY 1 TO 36 AS INDICATED IN TABLE 2. The broken line indicates the χ^2 limit which determines the resolution between spectra (see text).

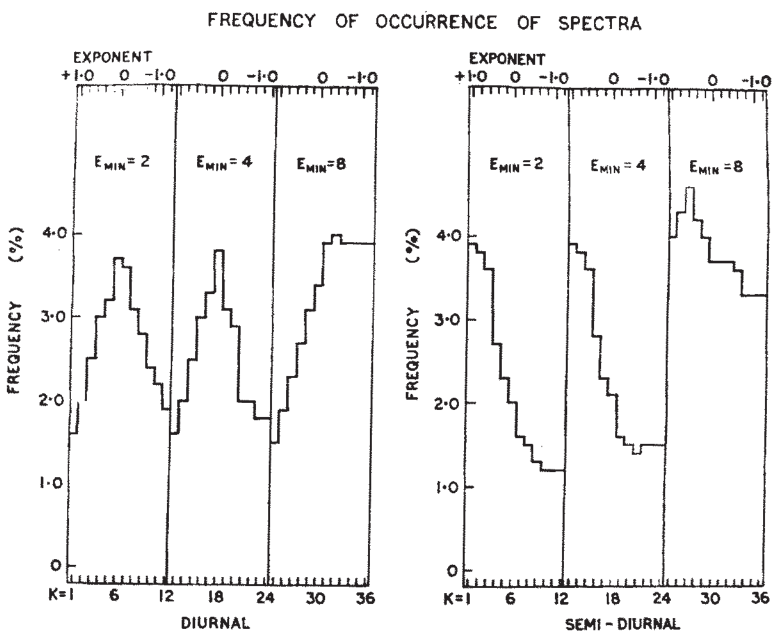

FIG. 2. THE FREQUENCY DISTRIBUTIONS OF OCCURRENCE OF THE ENERGY SPECTRA OF VARIATION FOR DIURNAL AND SEMIDIURNAL COMPONENTS DURING THE YEARS 1964–1965.

The following observations can be made:

(a) The diurnal variation has principally a spectrum with a zero exponent and E_{min} = 2 or 4 GeV. The spectra of choice are therefore $K = 6$ and 18.

(b) The semi-diurnal variation has principally a spectrum with a positive exponent (+0·6 to +1·0) and E_{min} = 2, 4, or 8 GeV. (K = 1 to 3, 13 to 15 and 25 to 27.)

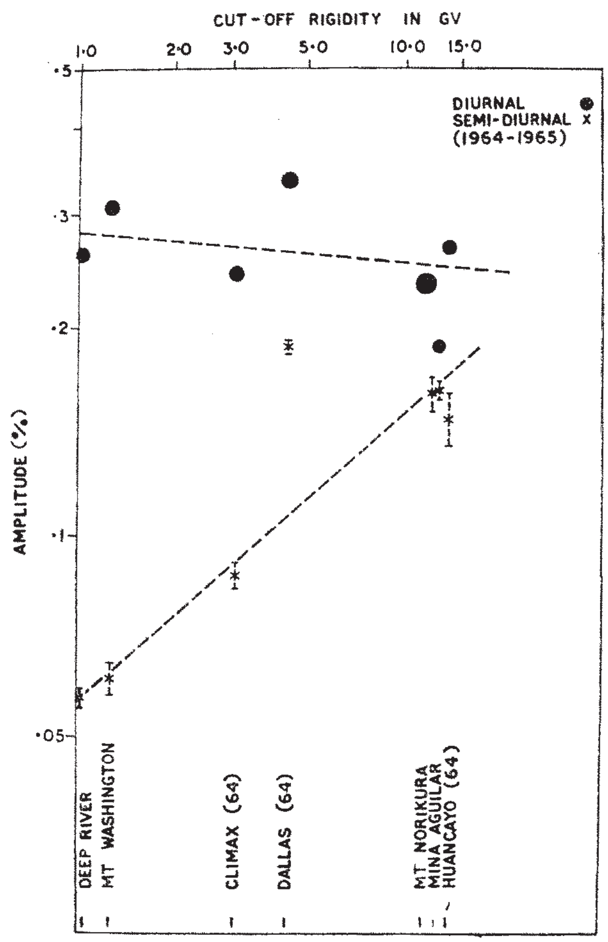

FIG. 3. THE DEPENDENCE OF AMPLITUDE OF THE ANNUAL AVERAGE DIURNAL AND THE SEMI-DIURNAL COMPONENTS ON CUT-OFF RIGIDITY FROM 1 TO 15 GV.

(c) For E_{min} = 8 GeV, negative exponents occur in both diurnal and semi-diurnal components. However, since in the grid of stations, there is no detector with a cut-off rigidity greater than 4·2 GV, good resolution is not achieved. (K = 31 to 36.)

We therefore conclude from a day to day study of anisotropies that the predominant spectra of variation of the diurnal and semi-diurnal components are characteristically different. This is confirmed through the comparison in Fig. 3, of the diurnal and semi-diurnal amplitudes of the average daily variation during 1964–65, measured at a set of stations with geomagnetic cut-off rigidities, ranging from 2–13 GV. Allowance has been made for the attenuation of the diurnal and semi-diurnal components due to the width of the asymptotic cones of acceptance of the detectors (McCracken and Rao[8]). Note that while the diurnal component has a spectrum of variation which is essentially independent of rigidity and has an exponent $X \approx 0$, the semi-diurnal component has a spectrum which has a positive exponent.

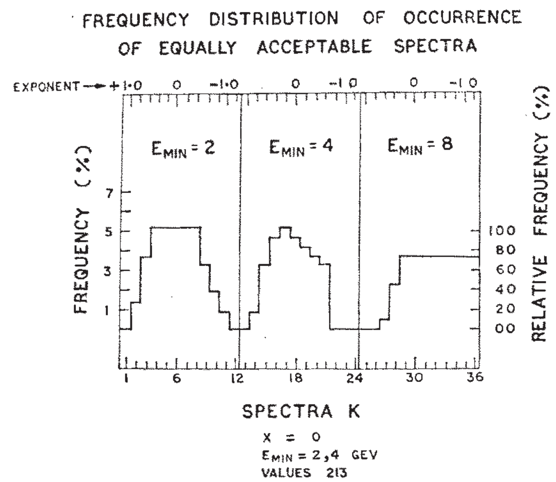

FIG. 4. THE FREQUENCY DISTRIBUTIONS OF EQUIVALENT SPECTRA ASSOCIATED WITH THE SPECTRA $K = 6$ AND 18, CORRESPONDING TO A ZERO EXPONENT AND $E_{\min} = 2$ AND 4 GeV.

The three prominent types of spectra which are identified from Fig. 2, have been further investigated to ascertain separately for each of them the extent to which other spectra are equally acceptable. For this purpose a frequency distribution is drawn of occurrence of spectra which are equally acceptable as the spectrum of choice. Figure 4, shows the distribution when spectra 6 and 18 with an exponent $X = 0$, and $E_{\min} = 2$ or 4 GeV respectively are selected on the criterion of being associated with $S^2_{\min}$. Spectra $K = 4$ to 8 and 17 occur with the same frequency as the spectra of choice $K = 6$, and 18, and are grouped as equivalent spectra. Thus the resolution with available data is such as to make it necessary to group together days on which the exponent is $+0{\cdot}4$ to $-0{\cdot}4$ with $E_{\min} = 2$ GeV and those on which the exponent is $+0{\cdot}2$ with $E_{\min} = 4$ GeV. The procedure is repeated for the spectra with an exponent $X = +1$ and $E_{\min} = 2$, 4 and 8 GeV for the second group and with an exponent $X = -1$ and $E_{\min} = 8$ GeV for the third group. Additionally we also identify a fourth group of spectra which are equivalent to the spectrum with an exponent $x = -1{\cdot}0$ and $E_{\min} = 2$ or 4 GeV.

Clusters of equally acceptable spectra associated with each of the four types are indicated in Table 2. The per cent frequency of occurrence of each of the four clusters of spectra in the diurnal anisotropy and in the semi-diurnal anisotropy are shown in Table 3. Only days on which it was possible to determine spectra of variation for diurnal as well as semi-diurnal anisotropies are considered for this analysis. Note that the semi-diurnal variation predominently appears with a positive exponent of spectrum. Negative exponent can also occur, but rarely zero exponent. On the other hand the diurnal variation can occur with anisotropies having spectra with negative, zero, and positive exponents. It is because of

TABLE 2

DIFFERENT ENERGY SPECTRA OF VARIATION K

E_{MIN} IN GEV \ X	+1·0	+·8	+·6	+·4	+·2	0	−·2	−·4	−·6	−·8	−1·0	−1·2
2	1	2	3	4	5	6	7	8	9	10	11	12
4	13	14	15	16	17	18	19	20	21	22	23	24
8	25	26	27	28	29	30	31	32	33	34	35	36

GROUP I → GROUP III →

GROUP II → GROUP IV →

TABLE 3

PERCENTAGE FREQUENCY OF VARIATION SPECTRA FOR DIURNAL AND SEMI-DIURNAL COMPONENTS DURING 1964-65

ANISOTROPY	GROUP I X = 0 E_{MIN} = 2,4 GEV %	GROUP II X = +1 E_{MIN} = 2,4,8 GEV %	GROUP III X = −1 E_{MIN} = 8 GEV %	GROUP IV X = −1 E_{MIN} = 2,4 GEV %
DIURNAL	16·2	23·7	26·0	23·5
SEMI-DIURNAL	2·0	51·1	24·6	12·8

this mix of spectra, that the average diurnal and semi-diurnal variations show different characteristics which we observed in Fig. 3.

3. CHARACTERISTICS OF PROCESSES PRODUCING ANISOTROPIES IN INTERPLANETARY SPACE

3.1 *Azimuthal streaming*

This process has been extensively studied by several workers (Parker,[3] Axford,[4] and Krymskiy[5]). For the process to occur it is necessary that in interplanetary space $\varepsilon = K_{\perp}/K_{\parallel}$ should be less than 1; $K_{\parallel}$ and $K_{\perp}$ are the coefficients for cosmic rays diffusing parallel and perpendicular to the direction of the interplanetary magnetic field respectively. ε depends on the density and scale length of the field irregularities and on the gyroradius of the cosmic ray particles. The finger-print of the process giving rise to azimuthal streaming is that in the range of energies for which the process is effective, the spectrum of variation should correspond to co-rotation of cosmic rays with the Sun. In consequence an excess of cosmic rays should appear to arrive from the 1800 direction giving rise to a time of maximum in the daily variation corresponding to this direction.

The spectrum of variation could have a low energy cut-off $E_{\min}$, if the scale lengths of irregularities are such that $\varepsilon = 1$ for low energy particles (Sarabhai and Subramanian[7]). At the high energy end there would be a cut-off for the modulating process, which depends in Axford's derivation on the gyro radius of co-rotating cosmic ray particles within a domain of field lines determined by the extent of the sector structure. Figure 5 illustrates the relationship of E_{max} with the width of the sector structure for three assumed values of the interplanetary magnetic field. During the last period of minimum solar activity, sectors corresponding to 6–8 days have been observed. These would imply an E_{max} between

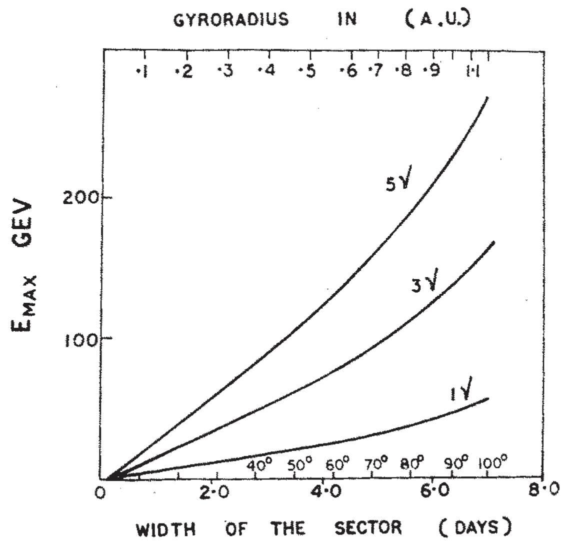

FIG. 5. THE RELATIONSHIP OF E_{max} WITH THE WIDTH OF THE SECTOR STRUCTURE FOR THREE VALUES OF THE INTERPLANETARY MAGNETIC FIELD.

100–200 GeV, depending upon the strength of the interplanetary magnetic field. With increase of solar activity if the width of each sector diminishes one would expect E_{max} also to diminish provided the strength of the interplanetary magnetic field does not also alter with solar cycle. Note however that an increase in the value of the interplanetary magnetic field with increased solar activity may compensate partially or totally the effect of reduced width of the sector.

We have estimated the nature of the daily variation that would be observed by the neutron monitors at Deep River, and at the equatorial station, of Huancayo due to azimuthal streaming, assuming a range of values of E_{min} and E_{max}. Instead of the maximum amplitude due to azimuthal streaming which would be 0·6 per cent for the diurnal variation, the expected amplitude is smaller and can be expressed as

$$\gamma_1 = 0{\cdot}6\alpha_1$$

where α_1 is calculated using variational coefficients by the method outlined by McCracken, Rao and Shea.[9] In the present case, in considering the effects of azimuthal streaming we choose coefficients for a spectrum with exponent $X = 0$. α_1 is shown in Fig. 6 for Huancayo and for Deep River as a function of E_{min} for several values of E_{max}. At an equatorial station α_1 does not change with E_{min} in the range 2–15 GeV but decreases for $E_{min} >$ 15 GeV. The decrease is rapid when E_{max} is low. On the other hand, for a neutron monitor situated at a high latitude α_1 starts decreasing rapidly for $E_{min} > 4$ GeV. α_1 is altogether less sensitive to changes of E_{max} than it is to changes of E_{min} for a neutron monitor at middle or high latitudes.

Figure 7 shows the ratio of α_1 at Huancayo to that at Deep River as a function of E_{min} for various values of E_{max}. The ratio increases with E_{min}, only for $E_{min} > 4$ GeV. As long as one uses neutron monitors situated on the surface of the Earth at latitudes where geomagnetic cut off energy is not greater than 4 GeV, we cannot derive significant information concerning E_{min} involved in the azimuthal streaming process. Similarly, unless the daily variation with meson detectors is studied it is difficult to draw conclusions concerning

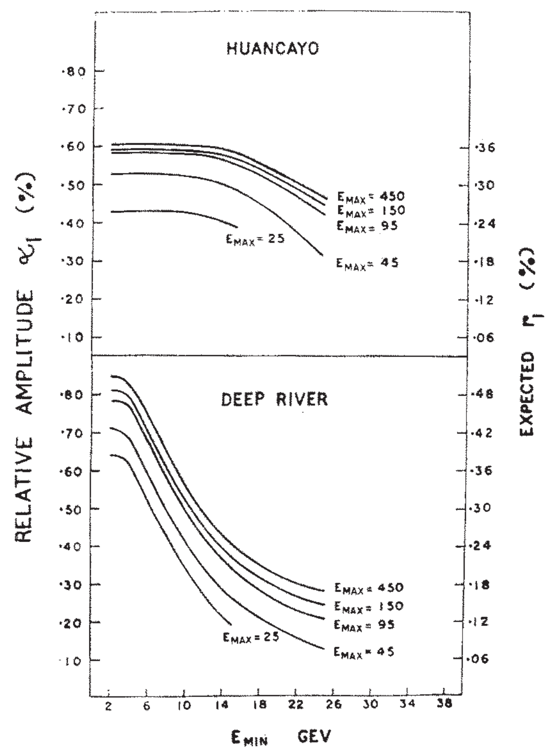

FIG. 6. THE RELATIVE DIURNAL AMPLITUDE α_1 FOR A SPECTRUM WITH AN EXPONENT $X = 0$, IS SHOWN FOR HUANCAYO AND DEEP RIVER, AS A FUNCTION OF E_{min} FOR DIFFERENT VALUES OF E_{max}.

changes of E_{max}. Only if the ratio of amplitude of diurnal variation at Huancayo to Deep River lies in the range 0·65 to 2·0, the spectrum can be represented by a zero exponent using combinations of E_{min} from 4 to 15 GeV and E_{max} from 25 to 450 GeV. Thus a ratio in this range is a necessary condition for attributing the variation to azimuthal streaming.

In the study of cosmic ray anisotropy several authors have suggested that positive and negative exponents occur in the expression for the spectrum of variation (Rao and Sarabhai,[6] Rao *et al.*,[10] Sarabhai and Subramanian,[7] Nagashima *et al.*[11]). The conclusion is based on an analysis of the characteristics of the daily variation simultaneously measured by detectors situated at locations with different cut off rigidities or by meson and neutron detectors. An important characteristic is the ratio of the amplitude of the diurnal variation measured by the neutron monitor at Huancayo (HN) and Deep River (DR). For $E_{min} = 2$ GeV, corresponding to atmospheric cut-off and $E_{max} = 250$ GeV one can calculate the ratio (α_1HN/α_1DR) for various values of the exponents in the range $-1{\cdot}2$ to $1{\cdot}0$. The ratio is less than 0·62 for negative exponents. This implies that when a negative exponent occurs, we must look to a process other than azimuthal streaming. However for positive exponents the situation is more complex. We have indicated in Fig. 7 by horizontal lines the ratios corresponding to exponents, $X = 0$, $+0{\cdot}2$, $+0{\cdot}4$, $+0{\cdot}6$, $+0{\cdot}8$ and $+1{\cdot}0$ when $E_{min} = 2$ GeV and $E_{max} = 250$ GeV. Each horizontal line intersects the family of curves drawn in the same figure indicating the E_{min} and E_{max} with a zero exponent which would produce the same ratio as a spectrum with the particular positive exponent. The alternative spectrum with zero exponent would then be consistent with azimuthal streaming provided two further conditions are satisfied. First, that the amplitude of the variation as shown in

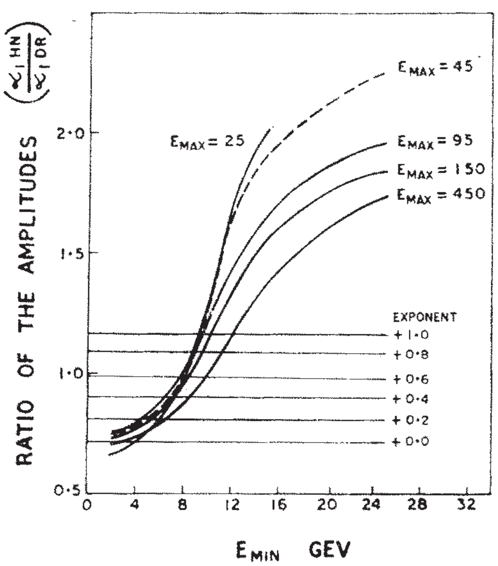

FIG. 7. THE RATIO OF THE AMPLITUDE α_1 AT HUANCAYO TO THAT AT DEEP RIVER AS A FUNCTION OF E_{min} FOR SEVERAL VALUES OF E_{max}.

The horizontal lines indicate the ratio corresponding to different exponents of the spectrum of variation.

Fig. 6, is consistent with the process of azimuthal streaming and values of E_{max} and E_{min} as may be chosen, and second, the direction of maximum is close to 1800 hours. Thus not all days on which the spectrum has a positive exponent can be regarded as arising out of a process other than aximuthal streaming. On the other hand several days for which exponent is positive can be associated with azimuthal streaming. Large negative exponents derived from data of neutron monitors alone would not be consistent with azimuthal streaming occurring by itself.

3.2 *Streaming in longitudinal sector structure*

When the solar wind velocity, or the density of irregularities change with helio-longitude, additional streaming of cosmic rays would occur as discussed by Parker.[3] The resulting anisotropy should generally be diurnal with an exponent $X = 0$. T_{max} and T_{min} will not be along 1800 and 0600 hours respectively and the amplitude could be larger than 0·6 per cent. The other considerations discussed in the earlier section related to azimuthal streaming would generally apply to this process.

3.3 *Scattering at magnetic field irregularities*

Scattering at magnetic field irregularities along smooth field lines short circuits the latitudinal gradients. If the cosmic ray intensity decreases with increasing heliolatitudes as could be the case in a region $\pm 15°$, lower cosmic ray density will be observed along the direction of interplanetary magnetic field (Sarabhai, Pai and Wada,[12] Sarabhai and Subramanian[7]). If the efficiency of scattering due to irregularities along the field line, excluding the domain of interplanetary space in the neighbourhood of the Earth, is the same for all cosmic ray particles upto an energy E_{max} 80–100 GeV, the exponent of the spectrum of the anisotropy will be the same as that of the 11 yr variation of cosmic ray intensity. The ratio of the relative amplitudes of the diurnal and semi-diurnal components generated by this process, provides an indication of the pitch angle distribution of the scattered particles as they approach the Earth. When the distribution is broad the semi-diurnal component will be relatively less important. A consequence of this is that when the scattering centre is at some distance from the Earth, the pitch angle distribution would be narrower and hence a sharper deficiency would be observed along the garden hose direction. This process is particularly relevant in observing the travel outward of magnetic field irregularities generated close to the Sun as during the occurrence of blast waves associated with flares and type IV bursts which ultimately produce Forbush decreases in the cosmic ray intensity measured at the Earth. The characteristic of this process involves a spectrum with an exponent which is generally negative, a deficiency along the direction of magnetic field, usually in the direction of the Sun. The diurnal component involved in this anisotropy would be superposed on the diurnal component due to azimuthal streaming. In consequence T_{max} would normally be shifted from the 1800 direction.

3.4 *Latitudinal gradients of cosmic ray intensity*

The existence of latitudinal gradients of cosmic ray intensity in a domain of relatively smooth interplanetary magnetic field gives rise to semi-diurnal and diurnal components (Subramanian and Sarabhai[2]). A semi-diurnal variation is also explained by Lietti and Quenby[16] who have considered the gradient due to the decreasing tightness of the interplanetary magnetic field with increasing heliolatitude. The direction of maximum of the semi-diurnal anisotropy will generally be perpendicular to the interplanetary magnetic field and also in the sense of the N.–S. asymmetry of cosmic ray density, N. and S. of the equatorial plane. The exponent of the energy spectrum of variation of the resulting anisotropies will depend on the form of distribution of the cosmic ray intensity with heliolatitude and on the phase of the solar cycle of activity. Note that the diurnal component is related to a N.–S. asymmetry of the latitudinal gradient. The energy spectrum of variation of the diurnal component has an exponent $1 - \beta$, while the semi-diurnal component has an exponent $2 - \beta$ (Subramanian and Sarabhai[2]). β, determines the rigidity dependence of the latitudinal variation of cosmic ray density. As a first approximation it has been assumed that β is the same as for the spectrum of galactic intensity in the plane of the ecliptic and is independent of heliolatitude. However β ranges from 2 during minimum sunspot activity to 0·5 during maximum solar activity (Webber[13]). During most periods of the solar cycle β is less than 2. Hence it is expected that the semi-diurnal variation will have a positive exponent and the diurnal will have either positive or negative in contrast to zero exponent for the azimuthal drift. The diurnal and semi-diurnal components should be about 0·3 per cent and 0·2 per cent respectively for a transverse gradient of 6 per cent per A.U. for particles of energy $E > 2$ GeV and a N.–S. asymmetry of 14 per cent arising from an asymmetrical distribution of cosmic ray density about the equatorial plane (Subramanian and Sarabhai[2]). The North–South asymmetry is defined as

$$A = \frac{2(\rho_N - \rho_S) \times 100\%}{(\rho_N + \rho_S)},$$

where ρ_N is the average cosmic ray density for heliolatitudes 0 to $+30°$ and ρ_S is the average cosmic ray density for heliolatitudes 0 to $-30°$ at 1 A.U. Note that asymmetry for the coronal 5303 A intensity was about 60 per cent and 86 per cent during the year 1964 and 1965 respectively for heliolatitudes $\pm$ 30°. Modles considered by Lietti and Quenby[16] give a positive exponent for the energy spectrum of variation of the semi-diurnal component in the 1 to 15 GeV range with an amplitude of about 0·05% at 10 GV. The existence of a semi-diurnal component is a necessary condition for the occurrence of this process.

TABLE 4

CHARACTERISTICS OF ANISOTROPY ASSOCIATED WITH DIFFERENT PROCESSES

		PROCESS 1	PROCESS 2	PROCESS 3	PROCESS 4
	CHARACTERISTICS	AZIMUTHAL STREAMING	STREAMING IN LONGITUDINAL SECTOR STRUCTURE	SCATTERING AT IRREGULARITIES	LATITUDINAL GRADIENT
1	NATURE OF THE ANISOTROPY ARISING FROM THE PROCESS	DIURNAL	DIURNAL	DEFICIENCY ALONG THE FIELD LINE DIURNAL AND SEMI-DIURNAL	DIURNAL AND SEMI-DIURNAL
2	EXPONENT OF THE SPECTRUM OF VARIATION				
	(a) DIURNAL	0	0	GENERALLY NEGATIVE	POSITIVE OR NEGATIVE
	(b) SEMI-DIURNAL	—	—	—	POSITIVE
3	T_{MAX} HOURS	1800	VARIABLE	2100	1500 OR 0300
4	T_{MIN} HOURS	0600	VARIABLE	0900	0900 OR 2100
5	$T_{MAX} - T_{MIN}$ HOURS	1200	—	1100	0600
6	DIURNAL AMPLITUDE r_1	·4 %	·4 %	·4 %	·3 %
7	SEMI-DIURNAL AMPLITUDE r_2	—	—	·2 %	·2 %

All four processes producing anisotropies have one thing in common, which is that when the interplanetary magnetic field in the immediate neighbourhood of the Earth is disturbed as during the passage of a radially travelling blast wave or a corotating shock front causing Forbush decreases, the amplitude of anisotropies would be temporarily reduced.

4. *Identification of anisotropies occurring during* 1964–65

Table 4 summarises the main characteristics of the basic processes which can contribute to anisotropies. Our first task should be to demonstrate that all these processes occur. For this purpose we can, after following the procedure for unambiguous determination of spectrum of variation described in Section 2, show that $T_{\max}$ and $T_{\min}$ and the amplitudes of the daily variation are consistent with what each process demands.

The process corresponding to azimuthal drift, is identified by picking up all days on which the exponent X is zero for the diurnal component. A further restriction imposed is the requirement that the semidiurnal component should not have a positive exponent X and this allows the exclusion of the process corresponding to latitudinal gradient. Days on which this occurs are classified as group A. Process 3 described in Section 3.3, is identified by selecting all days on which the exponent X is negative for diurnal component while the exponent is not positive for the semi-diurnal component. Days on which this occurs are classified as group B. Process 4 is identified by selecting days on which the exponent of the semi-diurnal component is positive but the exponent for the diurnal component is not zero. Days on which this occurs are classified as group C. The days belonging to these three groups account for 58·1 per cent of the total days.

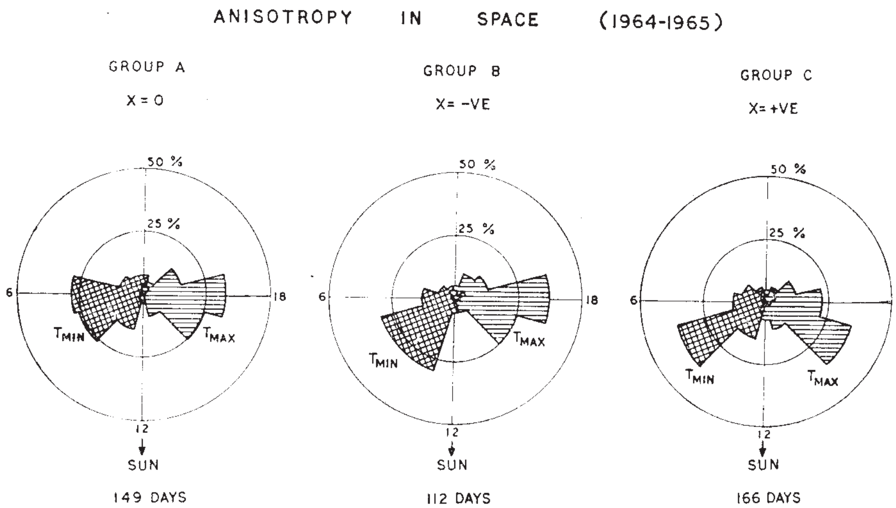

FIG. 8. THE FREQUENCY DISTRIBUTIONS OF T_{max} AND T_{min} FOR DIFFERENT ENERGY SPECTRA OF VARIATION CHARACTERISED BY EXPONENT $X = 0$ IN GROUP A, $X = -0{\cdot}6$ TO $-1{\cdot}2$ IN GROUP B AND $X = 0{\cdot}8$ TO $1{\cdot}0$ IN GROUP C.

In Fig. 8 are shown the frequency distributions of T_{max} and T_{min} for the three groups during 1964–65. In group A the most probable value of T_{max} is 1800 hours. The diurnal character of the anisotropy on these days is brought out by a separation of about 12 hr between the most probable values of T_{max} and T_{min}. The characteristics of anisotropy for days in this group are, therefore, consistent with azimuthal streaming being the principal process. Figure 9 shows the observed diurnal amplitude r_1 at Deep River as a function of the ratio of the observed amplitude of diurnal variation at Huancayo (HN r_1) and at Deep River (DR r_1) in the range 0·65 to 2·0 during 1964 for days when the process of azimuthal streaming is operative, i.e. $X = 0$. 26 per cent of total days in group A having a ratio less than 0·65 which is the minimum required for azimuthal streaming, have been eliminated in the diagram. While the scatter of observed r_1 for different ratios is quite large, an unmistakable trend can be seen in the value of the vector average of r_1 for days during which the ratio lies in discrete intervals. The diurnal amplitude decreases as the ratio increases, which is what one should expect for this process (see Fig. 6 and Fig. 7). An interesting consequence of this analysis is the possibility of estimating the limiting energy E_{min} below which the modulating process is inoperative on any particular day. As discussed in Section 3.1 E_{min} is interpreted as arising from the scale length of irregularities in the interplanetary magnetic field for which essentially isotropic diffusion of cosmic rays occurs.

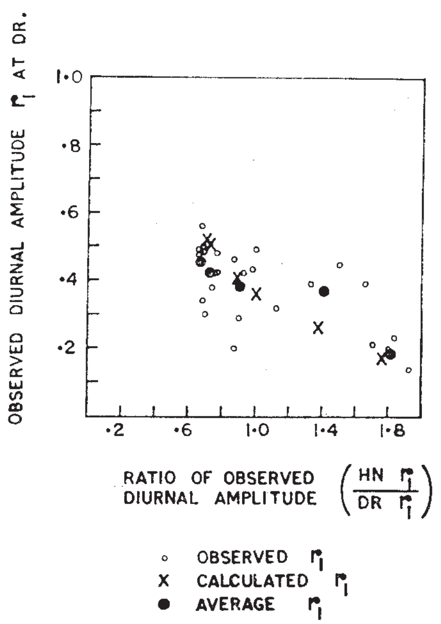

FIG. 9. THE OBSERVED DIURNAL AMPLITUDE AT DEEP RIVER IS SHOWN AS A FUNCTION OF THE RATIO OF THE OBSERVED DIURNAL AMPLITUDE AT HUANCAYO TO THAT AT DEEP RIVER, DURING 1964 FOR DAYS CORRESPONDING TO A SPECTRUM WITH AN EXPONENT $X = 0$.

In group B the most probable value of T_{min} is 0800 hours i.e. along the garden hose direction and of T_{max} along 1800 hours. T_{min} is consistent with the operation of scattering, a process which does not interfere with azimuthal streaming except through E_{min}. Hence T_{max} will still be along 1800 direction, but one can expect that on the average r_1 would be less than in group A. This is indeed observed in Fig. 10.

In group C the most probable value of T_{max} is about 1500 hours and the most probable value of T_{min} is 0800 hours, along the interplanetary magnetic field. The difference between T_{max} and T_{min} is about 0700 hours which indicates that the semi-diurnal component is predominant. The direction of maximum is along the perpendicular to the interplanetary magnetic field for this group. This is consistent with the anisotropy on these days being caused by the existence of latitudinal gradient in a smooth magnetic field.

Figure 10 shows the frequency distributions of the normalised amplitudes of diurnal and semi-diurnal components in space for the three groups. The diurnal amplitude is significantly higher in group A as compared to group C, while it is otherwise for the semi-diurnal component.

5. *Discussion*

The predictions from theory regarding the directions of maximum and of minimum, the nature of the anisotropy and its energy spectrum of variation are shown in Table 4. The essentially different energy spectra of variation of the diurnal and semi-diurnal components as predicted are experimentally observed for the anisotropy on day to day basis (Fig. 2) and for the average daily variation observed with a world wide net work of eight neutron monitors (Fig. 3). The diurnal component has a spectrum with an exponent $X = 0$ while the semi-diurnal component has an exponent $X \approx +0{\cdot}6$. On a day to day basis, the semi-diurnal component is significantly larger when the spectrum has a positive exponent than when it has a negative or zero exponent (Table 3). The predictions, concerning the three processes are substantiated in Fig. 8, where the directions of maximum and minimum for the anisotropy in three groups distinguished from their spectra of variation are indicated.

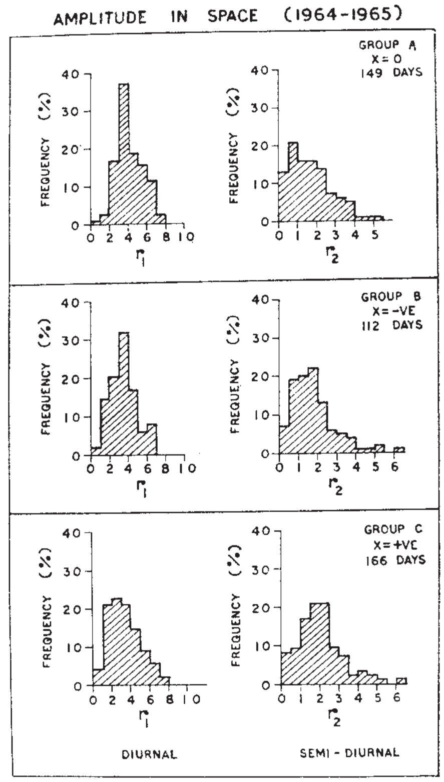

FIG. 10. THE FREQUENCY DISTRIBUTIONS OF THE NORMALISED AMPLITUDES OF DIURNAL AND SEMI-DIURNAL COMPONENTS IN SPACE FOR DIFFERENT ENERGY SPECTRA OF VARIATION DURING 1964–1965.

For days with positive exponent of the spectrum, T_{min} the direction of minimum intensity is along the interplanetary magnetic field and T_{max}, the direction of maximum intensity is almost perpendicular to the field, significantly inclined to the 1800 direction, characteristic for azimuthal streaming. $T_{max}-T_{min} \approx 7$ hr. This may be contrasted with T_{max} along 1800 hours and T_{min} along 0600 hours when the exponent is zero. T_{min} is clearly observed along 0900 hours when the exponent is -1.

Indeed the evidence that we have presented here is to be taken as supporting the postulated latitudinal gradients of cosmic ray intensity in the solar system, there should be confirmative evidence from two other directions. First the level of the isotropic intensity of cosmic rays should change as heliolatitude of the Earth alters with seasons. Dorman *et al.*,[14] have found the gradient of the cosmic ray intensity in the direction perpendicular to the ecliptic plane to be 13 per cent/A.U. for 1960.

Second, the diurnal anisotropy caused by the latitudinal gradients should reverse as the magnetic field or the gradient reverses. When the gradient is such that solar activity North of the equatorial plane is greater than South, the latitudinal gradient should give rise to a diurnal anisotropy with its direction of maximum on the average along 1500 hours when the field is directed away from the Sun (+) and along 0300 hours when the field is directed towards the Sun (−). Such an asymmetry will increase the amplitude of the diurnal component due to azimuthal streaming when the field is away from the Sun. This is verified using a set of neutron monitors during IMP-1 period (Wilcox and Ness[15]) for 6 solar rotations when interplanetary magnetic field direction in different sectors has been identified. In Table 5 are shown the mean diurnal components when the field is directed away from the

TABLE 5
MEAN DIURNAL COMPONENT DURING IMP 1
(NOV. 29-1963 TO FEB. 19-1964)

	STATION	POSITIVE SECTOR	NEGATIVE SECTOR
1	DEEP RIVER	·33 ± ·01	·27 ± ·01
2	SULPHUR MT.	·28 ± ·01	·24 ± ·01
3	CLIMAX	·31 ± ·01	·22 ± ·01
4	MT. WASHINGTON	·38 ± ·01	·18 ± ·02
5	MAWSON	·19 ± ·02	·09 ± ·03
6	WILKES	·28 ± ·02	·12 ± ·01
7	MINA AGUILAR	·21 ± ·01	·12 ± ·01
8	HUANCAYO	·20 ± ·01	·16 ± ·01
9	MT. NORIKURA	·15 ± ·01	·09 ± ·02

Sun, and when the field is directed towards the Sun. With a clear quantitative understanding of the implications of the various processes by which cosmic ray anisotropy and modulation occur in the solar system, coupled with increasingly accurate data from a worldwide network of cosmic ray super neutron monitors and meson detectors, we can look forward to step by step progress towards the use of terrestrially measured cosmic ray intensity for evaluating the state of interplanetary magnetic field and plasma. The present communication attempts to establish the link between the time variations of galactic cosmic rays observed in terrestrial detectors with the spectrum of variation of the modulating process and through the limiting energy of the spectrum and its exponent to the ratio of diffusion, parallel and perpendicular to the interplanetary magnetic field in the inner solar system.

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TELEVISION FOR DEVELOPMENT

by
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Chairman, Atomic Energy Commission

Presented at the Society for International Development Conference,
Delhi, November 14–17, 1969

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The introduction of television in India has until recently enjoyed low priority. Indeed, in adopting television, India stands almost the lowest amongst the nations of the world, including developing nations. In my view, this is largely attributable to four principal factors. First is the non-recognition of television as one of the most powerful media of mass communication, and therefore of direct relevance to development. Second is the inherently higher unit cost of a T.V. receiver compared to a receiver for sound broadcasting. In consequence, unless community T.V. is organised, it cannot reach the vast majority of our population. Third is the absence of broad-band telecommunication links throughout the country, or even between the major cities. These are necessary to provide .national programmes. And fourth is the large dependence, in the past, on importation of equipment and components for broadcasting or reception of television programmes.

The Chanda Committee, which submitted its report on Radio and Television to the Government of India in 1966, recognised the need for an early introduction of television because of the role it can play in social and economic development, and suggested that the plan of the Ministry of Information and Broadcasting which was inadequate in various respects should be replaced by a more ambitious plan.

As a Member of the Bhabha Committee which surveyed in 1964–65 the current status, future potential and scope of governmental initiatives for the development of electronics in India, I was struck by the meagre requirements projected for television by All India Radio. They had a plan which would start from the very large metropolitan areas of Delhi, Calcutta, Bombay, Madras and Kanpur/ Lucknow and extend to 17 large cities during the Fifth Plan and thereafter progressively to smaller urban areas.

Three years ago, the Department of Atomic Energy, which is responsible for promoting the peaceful uses of outer space, organised a study of the cost and significance of a synchronous satellite to link together isolated rural communities and distant centres of population in India, through a powerful national system for mass communication using television. We felt that there was necessity to gain insights on the manner in which television can be used as a direct instrument for promoting the developmental tasks of Government, so that it can be regarded as an investment rather than an overhead. The Krishi Darshan Programme was organised in 1967 in collaboration with All India Radio, Indian Agricultural Research Institute and the Delhi Administration through the establishment of community television receiving sets in 80 villages around Delhi. Parallel with this, a comparsion of the cost of deploying four alternative systems for providing television on a national scale was made. The following four systems were studied and we had the benefit of experience shared by the National Aeronautics and Space Administration of U.S.A. and participation of specialists from may Indian establishments and Departments of Government.

1. Conventional rebroadcast stations with terrestrial microwave interconnections.
2. Direct broadcast from a synchronous satellite.
3. Conventional rebroadcast stations with satellite interconnections.
4. A hybrid system involving direct broadcast to some areas and five rebroadcast stations for the densely populated regions.

The study carried out quantitatively was based on best current estimates. It indicates that alternative (4) would be one-third as expensive as alternative (1). Ineed all the half million villages of India can be provided television through community viewing centres and a national hookup for a total cost of about Rs. 160 crores under alternative (4). There may be some arguments concerning the precise saving through the use of a synchronous satellite, but every one is agreed that the saving would be very sizable and indeed the Indian estimates merely confirm the experience in other parts of the world whenever broad-band telecommunications have to be provided over an extended region. If we can allocate each year during the Fifth Plan a sum of Rs. 30 crores for this project, we could cover the entire country by the end of 1979 using a synchronous satellite. With the same annual expenditure of funds relying on existing technologies, it would take up to 1990 to achieve the same coverage.

A national programme which would provide television to about 80 per cent of India's population during the next 10 years would be of great significance to national integration, for implementing schemes of economic and social development and for the stimulation and promotion of the electronics industry. It is of particular relevance to the large population living in isolated communities.

For undertaking a programme to provide television nationally on the scale indicated, it would be necessary to rely largely on Indian expertise and indigenous supply of hardware. To use it effectively as a means of promoting national integration and development, experience requires to be gained on the side of content and programming, in applications to education, agricultural extension, promotion of family planning and national integration. Moveorver, insights in managerial and technical questions related to the operation and maintenance of television sets in rural areas, often with no established electric supply, would need to be gained.

Phase 1 from 1969 to 1973 would prepare the foundation for implementing the programme largely on an Indian base involving design, development and fabrication of equipment, establishment of management systems as well as software skills in each subject area. During this phase, practical experience would be gained through the DAE-NASA ITV Experiment, which is described in an attached background paper.

Phase 2 from 1974 to 1979 would involve progressive coverage through 100,000 or 150,000 new community reception centres each year.

Taking into consideration the cost of installing a television receiver and the purchasing power of the people, it is felt that the stated objectives will largely involve provision of television through community sets rather than through privately owned sets. It is estimated that not more than 1 to 2% of the total population would be viewing through privately owned sets. The balance of 98% can only be reached through community receivers. Therefore, unlike the field of radio, where individual listening has now become increasingly popular and accounts for the vast majority of coverage, the situation in teleivison would be qualitatively different and would involve the State or public bodies, organisations and institutions providing community viewing facilities. Indeed, the bulk of the cost of the project arises from this item.

II. Recent Technological Developments

The advent of synchronous communication satellites has a special relevance to developing nations which have not still acquired an extensive infra-structure of tele-communications with older technologies. Even though an optimum system in the future is expected to have ground tele-communications as well as satellite tele-communications, there are unique opportunities for optimising a system in respect of its cost and effectiveness where the existing investment is relatively small. India can profit from this situation provided it can use satellite communications for its national needs meaningfully and with imagination. The UNESCO Study Group on Satellite Instructional Television has endorsed the unique contribution which this new technology can make to developing nations and identified India as a particularly appropriate area for early implementation.

With increase of launching capabilities permitting satellites of heavier weight to be put into synchronous orbit, the power available in the satellite for the active reflection to the earth of radio transmissions has increased enormously. With increase in power, the size and sophistication of the ground station can be greatly reduced.

With the development of satellite technology, it is now possible to put a reffector on the satellite which will direct the radiated beam to a narrow region, thus economising on power as well as providing effective service in a desired area of limited extent. This is particularly important for reception of television signals. It is now possible to consider, as in the DAE-NASA experiment a system in which an augmented television set with a small chicken mesh antenna will itself be able to receive directly from a satellite, television programmes on a national or regional hook up.

A third major break–through has been in the reliability and effective life of operation of satellites. Current experience indicates that a satellite can provide dependable service for at least five years and could have an effective life time exceeding seven years.

III. Mass media for developmental tasks

In any developing country, one of the prime ingredients of development is the dissemination of information: information about new fertilizers, seeds, insecticides, cropping patterns, new technology, new findings and discoveries in all fields, new goods and services, new living patterns, etc. The process of education is basically related to an information dissemination/transfer process. For the rapid and sustained growth of developing countries, the urgent need to disseminate information to the masses is obvious.

Mass media are clearly the main component in this system of information transfer. Newspapers, movies, radio and television are the primary mass media. In India, we have a very large film industry — one of the biggest in the world. However, movie theatres are concentrated mostly in the larger towns and cities. Though there are some "travelling cinemas" which go around smaller towns and villages, these are few and a very small percentage of the total population is actually reached by them. Just over 4000 cinema theatres with a seating capacity of under 3 million are obviously inadequate for a population of over 500 million.

With the availability of inexpensive transistorised ralio sets costing less than Rs. 100/–, the radio is becoming the medium with the largest coverage amongst the masses. The battery operated transistorised set has also permitted it to reach the population living in large number of unelectrified villages.

Television is ideal as a medium to convey information and news to the broad masses of people — particularly to the illiterate segment of the population, on whom such an audio visual medium would have a profound impact.

The following questions immediately arise in developing a television system for India.

(a) Should one concentrate on providing the benefits first to urban communities and progressively go to rural areas? Direct broadcast of TV from a satellite represents the use of an advanced technology which for the first time does not impose a penalty on account of the dispersal of the receiving units away urban centres. The Indian economy in the next two or three decades must lean heavily on the development of rural areas. It therefore seems to me urgently necessary to take effective steps to enrich life in the isolated rural communities. Moreover, for continued stability and national integration, following the division of the country into linguistic administrative units, there is need to bring together different units through a common mass medium of communication reaching all sections of the population, the young and the old, men and women, the literate and the illiterate, the privileged and the underprivileged. I would submit therefore that the answer to this question can be clearly stated. It is that we should consciously reach the most difficult and least developed areas of the country and, because they are in this state, we should reach them in a hurry.

(b) In a state of economic and social backwardness, do we need to deploy imaginatvely the most powewrful techniques at our disposal or can we get by with less effective means? In concrete terms, can radio be an alternative to television? I suggest that television has a unique contribution to make because it has a rare credibility and is most persuasive.

(c) Can we regard T.V. largely as an instrument for development, an investment rather than an overhead of society? The answer to this question depends clearly on how we use the medium and who uses it. I cannot help nothing that much depends on the objectives and the assumptions of those who create the operating system. This is because the living culture of the system is determined by the people who are associated with it. I have no quarrel with those who wish to provide entertainment through media of mass communication, for society certainly needs entertainment. But I cannot see the same people determining policies and programming content related to education or instruction through the same medium.

(d) Recognising that Government has a number of different agencies responsible for individual fields such as information and broadcasting, education, agriculture, health, family planning, etc., how can one provide effective management of the system as a whole, alongwith use by the respective agencies of this powerful medium as an integral part of their promotional efforts? I would suggest that it should be possible for the other agencies to buy television time for programmes related to the discharge of their own responsibilities.

(e) Since Government has a very powerful role in promoting development, how can one prevent bureaucratisation of the system of mass communications with television? What would be the organisational framework in which programming initative can be developed competitively amongst independent groups of innovative and imaginative producers and artistes instead of through a monopolistic system where just a few official units produce all the programmes that are required? I would suggest the creation of a national authority, such as INTELSAT in the international scene, which merely owns, regulates and manages the mass communication system without itself taking total responsibility for software. Moreover, we should promote the development of agencies on a basis of redundancy to competitively provide software for individual clients who would buy time on the television system for promoting national objectives which fall within subjects allocated to them. One would have to provide a feed back system and an evaluation system to assist software development for developmental purposes.

It is quite clear that the problems of management and of software for television system to perform the role of an initiator of change and development are more formidable than the problem of hardware development. But when we have worked through our problems and learnt through experience, we would have gained something far more precious from the standpoint of development than the television system.

DAE-NASA SATELLITE ITV EXPERIMENT

Background paper to

"TELEVISION FOR DEVELOPMENT"

by

Vikram Sarabhai

Chairman, Atomic Energy Commission

The Department of Atomic Energy and the National Aeronautics and Space Administration of U.S.A. signed a Memorandum of Understanding on September 18, 1969 to conduct jointly an instructional television experiment using the ATS-F satellite. This satellite is planned to be launched during the second quarter of 1972. After an anticipated six months of space craft check out and other experimental efforts over the U.S., the space craft will be moved to a suitable position (20° E longitude or so), at which location it will be made available for the conduct of the experiment.

According to the Memorandum of Understanding, the scientific responsibilities of the Indian Government are :

First, to develop, provide and maintain in service the ground segment of the T.V. satellite experiment that will carry out the technical objectives of the experiment; and

Second, to develop and utilise ITV programme materials that will carry out the instructional objectives of the experiment.

The DAE-NASA experimental satellite T.V. project envisages the provision of 2,000 augmented type of T.V. receivers for direct reception from a synchronous satellite. The 2,000 receivers are proposed to be located in rural areas in clusters of about 500 each. The exact location of the clusters is to be chosen so as to get the widest possible range of meaningful experience from this experiment. The experiment will lay emphasis on community viewing and on instructional T.V. as an aid to development in the fields of education, family planning, agriculture, social education, etc.

This programme has now been integrated with the programme of All India Radio for the introduction of TV during the Fourth Plan which involves augmenting the capability of the transmitter at Delhi and the establishment of new transmitters at Srinagar, Bombay and Poona and later on in Madras and Calcutta.

The DAE–NASA experiment is related to the following specific Indian instructional and technical objectives :

1. **Indian Instructional Objectives Primary**

— Contribute to family planning objectives.

— Contribute to teacher training.

— Improve other occupational skills.

— Improve health and hygiene.

2. **Indian Technical Objectives**

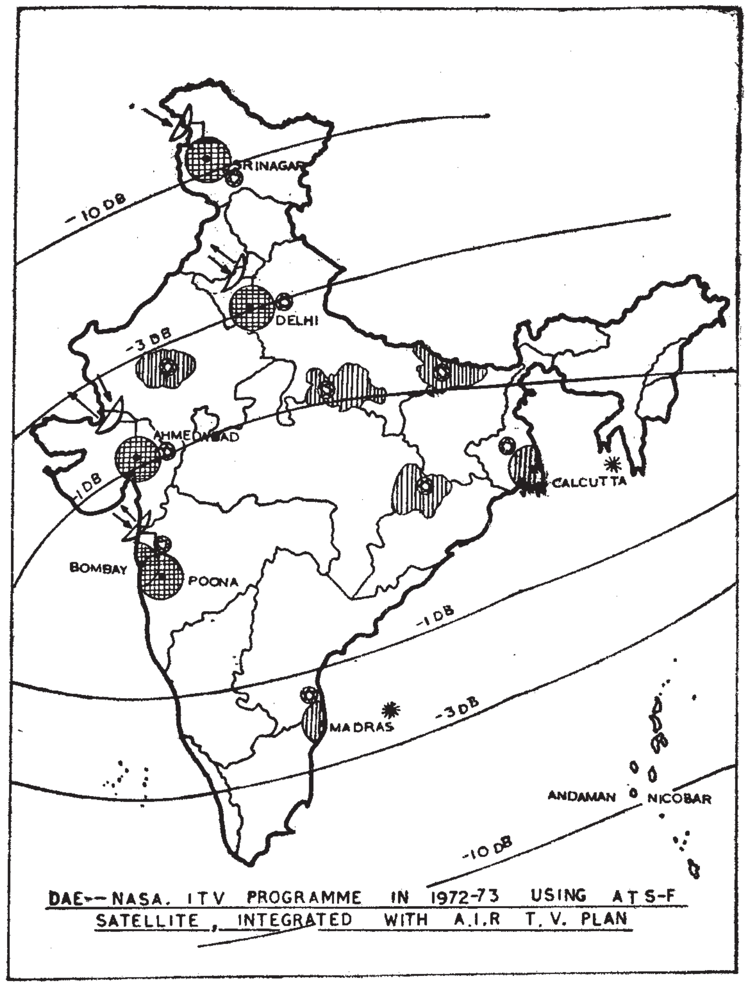
— Provide a system test of broadcast satellite TV for national development.

— Enhance capability in the design, manufacture, development, installation, operation, movement and maintenance of village TV receivers.

— Gain experience in the design, manufacture, installation, operation and maintenance of broadcast and/or distribution facilities to the extent that these are used in the experiment.

— Gain an opportunity to determine optimum receiver density, distribution, and scheduling techniques of audience attraction, and organisation and to solve problems involved in developing, preparing, presenting and transmitting TV programme materials.

Figure I gives the profile of the coverage that will be attempted in 1972–73. It will be noted that the experiment will permit a national hook-up through a hybrid system involving both direct broadcast and rebroadcast of television signals from ground stations. Since direct broadcast would be more advantageous in isolated communities where the receiver density is low and the scope for development greatest, we have identified our clusters based on the lowest level of development as described in Annexure 1.



Clusters using Rediffusion TV at V.H.F.

Receive only Satellite Earth Terminal

Clusters using Direct Broadcast TV at 850 MHz with about 500 Community Receivers each

Programming Centers

Transmit — Receive Satellite Earth Terminal

To be converted to Rediffusion TV

Figure 1

Annexure 1 to background paper on "Television for Development"

by

Vikram Sarabhai

In January 1965, the Planning Commission requested the State Governments to identify backward areas on the basis of a few indicators of development.

We can rank the following States in the order of lowest level of development.

1. Orissa.
2. Bihar
3. Madhya Pradesh
4. Uttar Pradesh
5. Rajasthan
6. Andhra Pradesh
7. West Bengal
8. Mysore.

Selection of Clusters

Orissa & Madhya Pradesh — Cluster No. 1

The Raipur district of Madhya Pradesh and Sambalpur district of Orissa are contiguous. These may, therefore, form a single cluster. The T.V. receivers could be spread out in the bottom level districts of Bustar, Korapur, Raigarh, Bilaspur, Kalahandi, Bolangir and Baudh Khandmals. The headquarters of this cluster could be at Raigarh which besides being contiguous to the package programme districts of Raipur and Sambalpur is itself a bottom level dstrict. AIR has broad-casting stations at Raipur and Sambalpur.

Bihar — Cluster No. 2

While Shahbad is a package programme area, Muzzafarpur is the intensive family planning district. Since Muzzafarpur is surrounded by Dharbhanga, Champaran and Saran which are all bottom level districts of Bihar, these may constitute the cluster No. 2. The headquarters of this cluster could, if necessary, be at Patna which has an air strip. AIR has a broadcasting station in Patna where an agricultural university is also planned.

Uttar Pradesh — Cluster No. 3

Aligarh in Uttar Pradesh is a package programme area while Kanpur and Allahabad are the intensive family planning districts. Aligarh and surrounding areas are at higher level of development while Kanpur is partly surrounded by bottom lvel districts. Allahabad on the other hand is surrounded by bottom level districts of Banda, Fatehpur, Rai Bareli, Pratapgarh, and Jaunpur. Cluster No. 3 may, therefore, be spread over these districts with its headquarters at Allahabad, where AIR has a broadcasting station. Allahabad has an agricultural college at Naini and is also accessiable by air.

Rajasthan — Cluster No. 4

While the district of Pali is the pacake programme centre, Udaipur which is the seat of an agricultural university is also intensive family planning district. Pali is surrounded by bottom level districts of Bhilwara, Nagaur and Barmer. Pali itself is a second level district. Cluster No. 4 may, therefore, be spread over these three districts with headquarter either at Ajmer where AIR has a transmitting station or at Pali itself.

GEOMAGNETIC FIELD - A MEASURE OF KINETIC ENERGY DENSITY OF SOLAR WIND

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At low latitudes, the horizontal component of the geomagnetic field attains a maximum value H_{max} around 1100 hours and minimum value H_{min} between 1800 hours and 0600 hours local time. The range of the daily variation ΔH which is the difference between H_{max} and H_{min}, may be an increase on the day side over a base level at H_{min}, or alternatively it could be a decrease on the night side from a base level H_{max}. In the former case, we should have a positive correlation between ΔH and H_{max}, with a poor correlation between ΔH and H_{min}. On the other hand in the latter case, we should get a negative correlation between ΔH and H_{min} and a poor correlation between ΔH and H_{max}.

Our study has been made using the magnetograms from the Observatory at Alibag (Geomagnetic latitude 9^{o}-30'N and geomagnetic latitude 143^{o}-36'E) for the years 1954 to 1964. To eliminate the influence of secular changes, 11 year variation and the seasonal variation in H_{min}, we have derived H^{*}_{min} on each day by taking deviations from 27 day moving average values. For uniformity in treatment of basic data, ΔH^{*} is derived similarly. Figure 1 shows the overall relationship between ΔH^{*} and H^{*}_{min}, where data for all the eleven years have been included. The correlation coefficient between 3992 values of H^{*}_{min} and ΔH^{*} is 0.791 ± 0.005. The area of each circle is proportional to the number of days having the appropriate pairs of values of ΔH^{*} and H^{*}_{min}. Since the correlation is negative, we can conclude that the daily variation of H at a low latitude station is due to a decrease of the ambient field on the night side rather than an increase during day side. Even at the geomagnetic equator, at a distance of 6.6 earth radii where the effect of the electrojet in the E region is negligible, satellite data from ATS 1 have demonstrated (1, 2) that the daily variation on an average day corresponds to a decrease of about 30 to 40 gammas along the anti-solar direction compared to the sub-solar direction.

The solar wind parameters have been experimentally measured by IMP-1 satellite plasma probe. Pai et al (3) have reported the three hourly averages of the plasma velocity (V_s), density (N_s), flux (ϕ_s) and Kinetic energy density (K.E.). From these, daily values have been obtained for each parameter for the period 27-11-1963 to 22-2-1964. The superposition of successive 27 day values provides the average values of the solar wind parameters for each heliographic longitude at central meridian passage (CMP). Similarly the values of H_{min} and ΔH have been computed.

Δ H has the dimensions $M^{1/2} L^{-1/2} T^{-1}$ and therefore a meaningful physical relationship can be expressed by considering $(\Delta H)^2$ and Kinetic energy density of the solar wind, both having the same dimensions. The correlation between the two is 0.78 ± 0.08 for the 27 day superposed values for the IMP-1 period. The scatter diagram is shown in figure 2. The expression connecting the two quantities is

$$\text{K.E. density} = (20 \pm 11) \times 10^{-10} + (3.65 \pm 0.45) \times 10^{-12} \times (\Delta H)^2 \ \text{ergs/cm}^3. \quad (1)$$

The solar particles in the pseudo-trapping region and mirroring at low latitudes on the night side, constitute a westward current, which however, does not extend far into the day side (Fig. 3). We suggest that this westward current which exists only for the night side, decreases the horizontal field during night time for low latitude stations. At high latitudes, no trapping is possible and the daily variation due to magnetospheric drift currents is not important. At intermediate latitudes between 40^o and 60^o a pseudo trapping region exists on the sunlit side but not on the night side, and in consequence there could be some reduction of the field on the day side.

Since E region currents would be largely absent on the night side, we suggest that the effect we observe is connected with the convective drift currents in the magnetosphere within the pseudo-trapping region, and the asymmetric part of the ring currents in the stable trapping region. Drift currents in the stable trapping region would influence H_{max} as well as the daily mean value of H.

Based on expression 1 which provides a caliberation of $(\Delta H)^2$ with the measured kinetic energy density of the solar plasma during the Imp-1 period, we have derived the solar cycle changes of kinetic energy density from the changes of ΔH each year from 1954 to 1964. These are shown in figure 4.

We believe that experimental evidence presented here indicates that the effects of ring currents can be measured on the surface of the earth at low latitudes stations on almost all days and that these dominate over the ionospheric dynamo currents. Moreover through variations of the geomagnetic field, the earth can be used as a plasma probe for the solar wind.

We are grateful to the Director of the Colaba and Alibag Observatories of Indian Meteorological Department and to H. S. Bridge and the plasma Group at M.I.T., Cambridge for the basic data on which the present study is based. We are also grateful to the Department of Atomic Energy for support.

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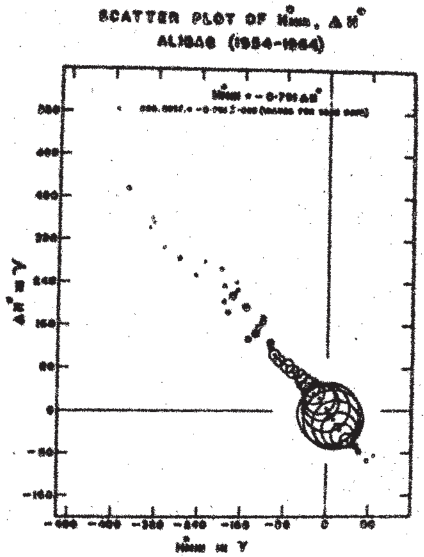

Fig. 1. H^*_{min}, ΔH^* relationship combining values for the years 1954 to 1964. The area of each circle is proportional to the number of days having appropriate pair of H^*_{min} and ΔH^*.

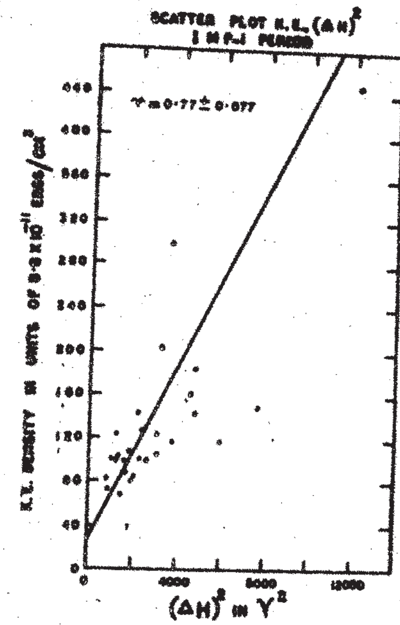

Fig. 2. Scatter plot of K. E density of the solar wind and $(\Delta H)^2$ of Alibag

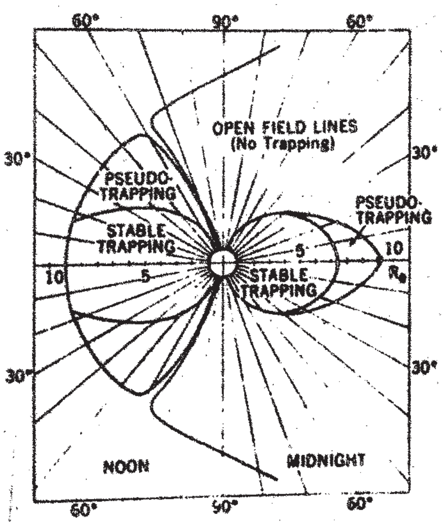

Fig. 3. Location of pseudo-trapping regions J. G. Roederer Int. Sym. on Physics of the Magnetosphere, Washington DC September 3-13, 1968

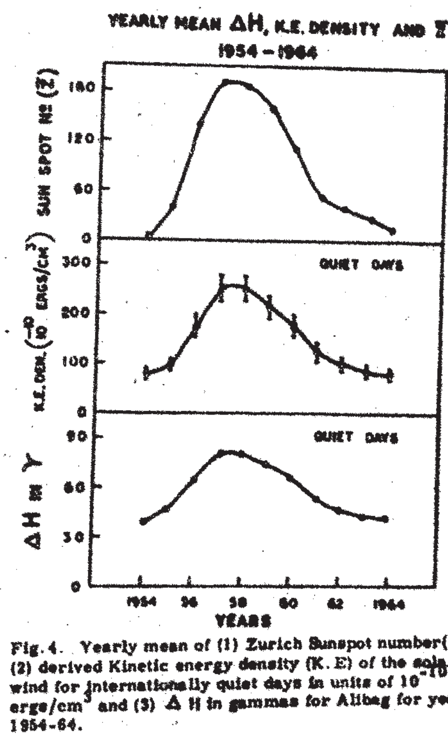

Fig. 4. Yearly mean of (1) Zurich Sunspot number(Z) (2) derived Kinetic energy density (K. E) of the solar wind for internationally quiet days in units of 10^{-10} ergs/cm^3 and (3) Δ H in gammas for Alibag for years 1954-64.

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Daily Variation of the Geomagnetic Field and the Deformation of the Magnetosphere

IT is well known that at low latitudes the horizontal component of the geomagnetic field has a maximum H_{max} around local noon and a minimum value H_{min} between 1800 and 0600 h local time. The range of the daily variation ΔH is strikingly enhanced in the region $\pm 3°$ geomagnetic latitude due to the electrojet current in the E-region. We have been interested in verifying whether at a low latitude station outside the influence of the electrojet, ΔH represents an increase on the day side over a base level at H_{min}, or alternatively it is a decrease on the night side from a base level at H_{max}. In the former case, we should have a positive correlation between ΔH and H_{max}, with poor correlation between ΔH and H_{min}. On the other hand, in the latter case, we should get a negative correlation between ΔH and H_{min} and a poor correlation between ΔH and H_{max}.

We have studied data on individual days from the geomagnetic observatory at Alibag (geomagnetic latitude 9° 30′ N and geomagnetic longitude 143° 36′ E) and find a good negative correlation of ΔH (correlation coefficient $-0{\cdot}803 \pm 0{\cdot}018$) with H_{min} as can be seen from the scatter diagram for the year 1961 shown in Fig. 1*a*. All days in the year have been considered and the values corresponding to those on which there were large sudden commencement or gradual commencement geomagnetic storms are indicated separately. The corresponding scatter diagram for ΔH and H_{max} is shown in Fig. 1*b* where the correlation between the two is only $+0{\cdot}315 \pm 0{\cdot}047$. The characteristics described here are seen not only in 1961 but in all years of the solar cycle 1954 to 1964.

We conclude from Figs. 1*a* and *b* that the daily variation of H at a low latitude station outside the effect of the electrojet is due to a decrease of the ambient field on the night side rather than an increase during the daytime. Even at the geomagnetic equator at a distance of 6·6 Earth radii where the effect of the electrojet in the E-region is negligible, satellite data from ATS 1 have demonstrated[1,2] that the daily variation on an average day corresponds to a decrease of about 30 to 40 gammas along the antisolar direction compared with the sub-solar direction. We also note that the degree of geomagnetic disturbance on individual days does not alter appreciably the relationship between ΔH and H_{min}.

Because E-region currents would be largely absent on the night side, we suggest that the effect we observe is connected with the convective drift currents in the magnetosphere within the pseudo-trapping region, and the asymmetric part of the ring currents in the stable trapping region. The decrease of the field at the surface of the Earth along the antisolar direction with respect to the sub-solar direction due to the compression of the magnetosphere according to the Mead–Williams model[3] would amount to only a few gammas and this effect is about an order of magnitude smaller than what is observed. Drift currents in the stable trapping region would influence H_{max} as well as the daily mean value of H.

The relationships of ΔH and H_{min} with solar wind parameters measured by the MIT plasma probe[4] superposed for three solar rotations are shown in Fig. 2. The kinetic energy density of the solar plasma is best related to ΔH. Indeed, for the individual 27-day values, the correlation

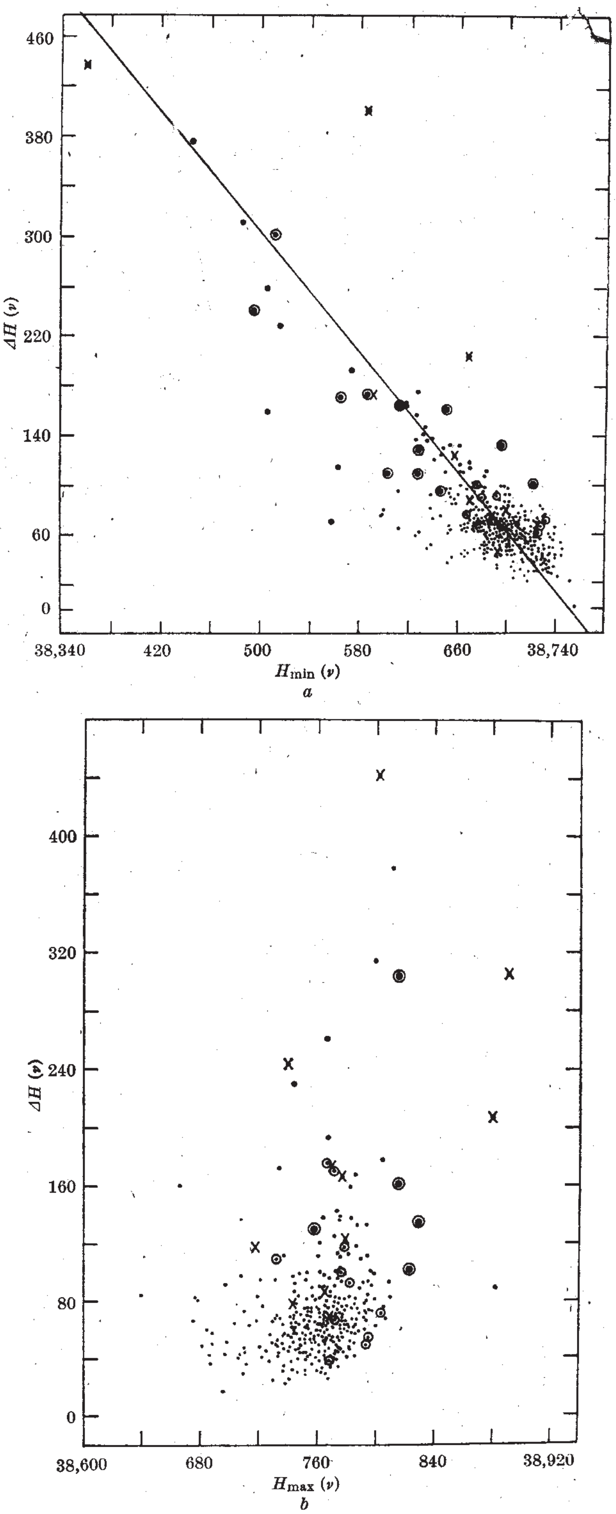

Fig. 1. *a*, Scatter plot of H_{min} against ΔH for year 1961. $r = -0{\cdot}803 \pm 0{\cdot}018$; *b*, scatter plot of H_{max} against ΔH for year 1961. $r = 0{\cdot}315 \pm 0{\cdot}047$. × and ○ respectively indicate days on which sudden commencement and gradual commencement storms occurred.

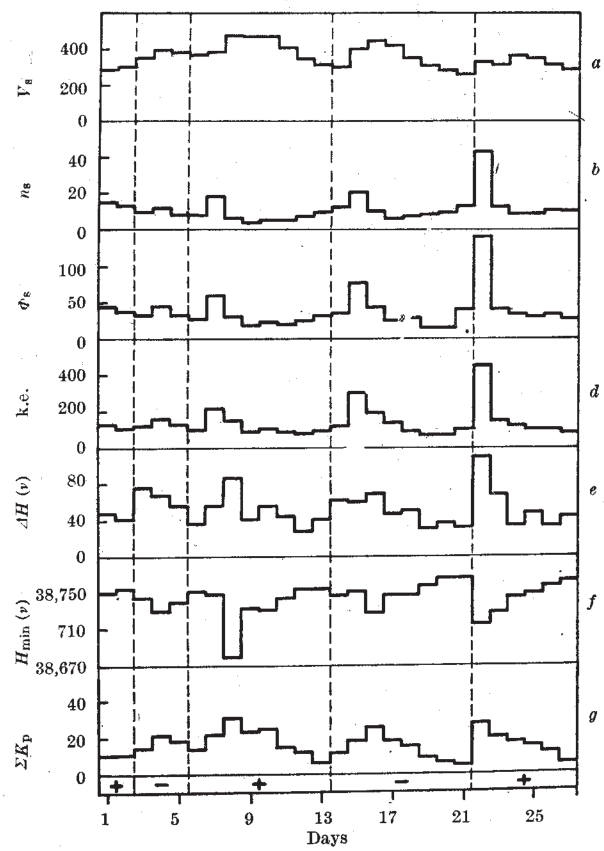

Fig. 2. 27-day recurrences during IMP-1 period of (*a*) solar wind velocity (V_s km s^{-1}); (*b*) solar wind number density (n_s protons cm^{-3}); (*c*) solar wind flux (Φ_s in units of $1{\cdot}16 \times 10^7$ cm^{-2} s^{-1}), (*d*) kinetic energy density (k.e. in units of $8{\cdot}3 \times 10^{-11}$ ergs cm^{-3}); (*e*) ΔH at Alibag in gammas; (*f*) H_{min} at Alibag in gammas and (*g*) daily total of K_p (ΣK_p).

coefficient between $(\Delta H)^2$ and kinetic energy density is $0{\cdot}770 \pm 0{\cdot}077$ and the regression equation is

$$\text{k.e. density} = (20 \pm 11) \times 10^{-10} + (3{\cdot}65 \pm 0{\cdot}45) \times 10^{-12} \times (\Delta H)^2 \text{ ergs cm}^{-3}$$

Alfven[5] examined the problem of a plasma drifting in crossed E and B fields near a magnetic dipole. The models of Axford and Hines[6] and Dungey[7] provide mechanisms to promote the drift currents. Freeman[8] has summarized experimental evidence supporting drift currents. We propose that our observations relating the kinetic energy density of the solar wind with $(\Delta H)^2$ through a simple relationship connect the convective drifts to the currents in the pseudo and stable trapping regions. Based on the 11 yr variation of ΔH during internationally quiet days we have computed the annual mean kinetic energy density of solar plasma from 1954 to 1964, as shown in Table 1. The relationship established by us needs further

Table 1. MEAN KINETIC ENERGY DENSITY OF THE SOLAR PLASMA, BASED ON THE 11-yr VARIATION OF ΔH DURING INTERNATIONALLY QUIET DAYS

Year	k.e. density in units of 10^{-10} ergs cm^{-3}
1954	81 ± 13
1955	97 ± 14
1956	174 ± 20
1957	253 ± 28
1958	253 ± 28
1959	215 ± 24
1960	179 ± 21
1961	123 ± 16
1962	101 ± 14
1963	84 ± 13
1964	78 ± 13

confirmation using interplanetary solar wind data over an extended period.

We believe that experimental evidence presented here indicates that the effects of ring currents can be measured on the surface of the Earth at low latitude stations on almost all days and that these dominate over the ionospheric dynamo currents which have been proposed before. Moreover, through variations of the geomagnetic field, the Earth can be used as a plasma probe for the solar wind.

We thank the director of the Colaba and Alibag Observatories of India Meteorological Department and H. S. Bridge and the plasma group at MIT, Cambridge, for the basic data. We also thank the Department of Atomic Energy for support.

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GEOMAGNETIC PLASMA PROBE FOR SOLAR WIND

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GEOMAGNETIC PLASMA PROBE FOR SOLAR WIND

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Received February 14, 1969

ABSTRACT

Magnetograms from Alibag reveal that the range $\triangle H$ of the daily variation of the horizontal component is negatively correlated with the minimum value $\triangle H_{min.}$ during a day. This relationship is largely unaffected by the degree of geomagnetic disturbance and holds good during all phases of the 11-year cycle of solar activity. From the nature of the relationship between $\triangle H$ and $\triangle H_{min.}$ it is concluded that the daily variation of the geomagnetic field at a low latitude station outside the influence of the equatorial electroject must be regarded as largely due to a weakening of the ambient field on the night side rather than an enhancement of the field on the day side due to ionospheric currents. There exists a good correlation between $(\triangle H)^2$ and the kinetic energy density of the solar wind in interplanetary space measured by IMP-1 satellite. It is suggested that $\triangle H$ is largely the result of the partial ring currents related to the convective drift of the plasma from the tail of the magnetosphere. Moreover, using the relationships established during the IMP-1 period, the annual mean kinetic energy density of solar wind for geomagnetically quiet days for the past 11-year cycle is estimated, treating the earth as a plasma probe.

INTRODUCTION

MUCH attention has been devoted to the daily variations S_q and D_{st} of the geomagnetic field as well as to a number of types of magnetic disturbances and planetary indices, like K_p and A_p which have been attributed to the influence of the particle radiation from the sun. The planetary indices however are not related to physical models of the magnetosphere. The present investigation illuminates a new and what appears to be a fundamental relationship that exists between kinetic energy density of the solar plasma, the daily range $\triangle H$ of the horizontal component at a low latitude station and the minimum value of the horizontal component of the magnetic field $H_{min.}$ during a period of 24 hours from midnight to midnight. It also indicates that outside the influence of the equatorial electrojet and excluding high latitudes, the daily variation is largely due to a weakening of the ambient field on the night side rather than an enhancement of the field on the day side due to dynamo currents in the ionosphere, as the classical theory has supposed. More likely, the daily variation is associated with the deformation of the magnetosphere under the influence of the solar wind and the convective drift currents that result from it. It therefore provides a method of estimating from entirely ground-based observations the kinetic energy density of the solar wind, using the earth as a plasma probe.

THE NATURE OF THE DAILY VARIATION OF H

Our study has been made using the magnetograms from the Observatory at Alibag (Geomagnetic latitude 9° 30′ N and geomagnetic longitude 143° 36′ E) for the years 1961, 1962, 1963 and 1964. Alibag is a typical station at low geomagnetic latitude, but outside the influence of the equatorial electrojet, and a magnetogram on a typical day is shown in Fig. 1.

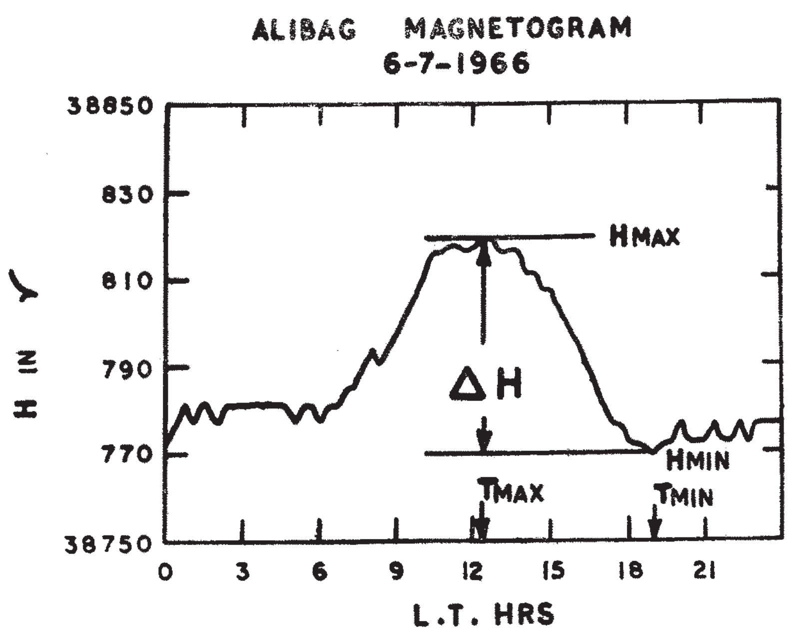

FIG. 1. A typical Magnetogram at Alibag.

Figure 2 shows for the individual years the histograms of the times of occurrence of the maximum ($T_{max.}$) and minimum ($T_{min.}$) of the daily variation of H. There is no qualitative change in the histograms from year to year. Taking all the four years together, Fig. 3 indicates the normalised histograms of $T_{max.}$ and $T_{min.}$ separately for (*a*) all days combined, (*b*) quiet days, (*c*) days with sudden commencement storms, (*d*) days with gradual commencement storms, (*e*) disturbed days and (*f*) internationally disturbed days but during which sudden commencement and gradual commencement storms did not occur. $T_{max.}$ histograms are relatively unaffected by the degree of geomagnetic disturbance. However, $T_{min.}$ occurs at 0500 hours significantly more often on geomagnetically quiet days than on all other groups of days. The almost complete absence of $T_{min.}$ between 0200 and 0600 hours on disturbed days is also noteworthy.

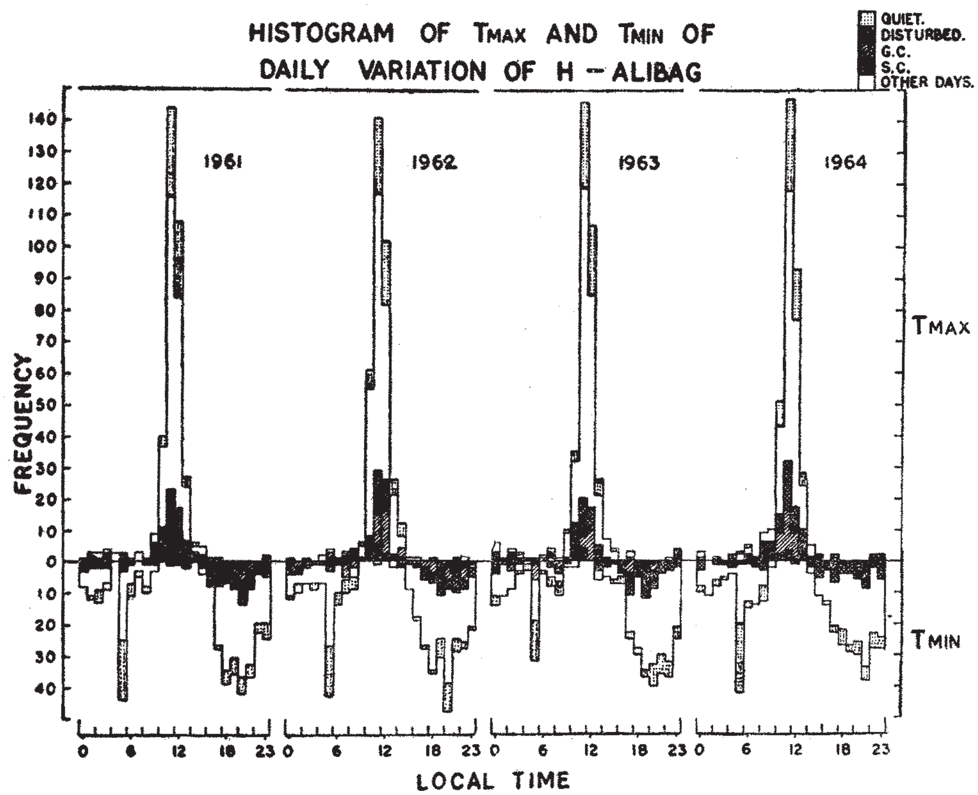

FIG 2. Histograms of the times of occurrence of maximum and minimum of the daily variation of Horizontal Force at Alibag for the years 1961, 1962, 1963 and 1964. *See* text for explanations of markings.

The histograms of $\triangle H$ during each of the four years are shown in Fig. 4. It is observed that there is a consistent shift of the histograms towards smaller values of $\triangle H$ from 1961 to 1964 approaching minimum of solar activity. The very large values of $\triangle H$ on some days during 1961 is also noticeable.

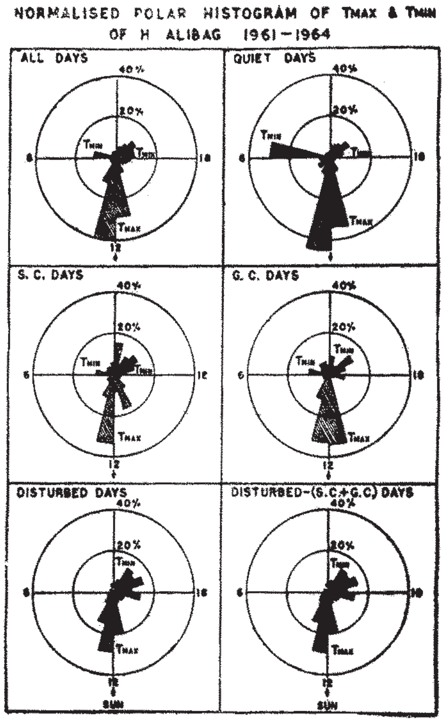

FIG. 3. Normalised polar histograms of local times of maximum and minimum of H at Alibag from year 1961 to year 1964, showing separately. (*a*) all days combined, (*b*) quiet days (*c*) days with sudden commencement storms, (*d*) days with gradual commencement storms, (*e*) disturbed days and (*f*) internationally disturbed days but during which sudden commencement and gradual commencement storms did not occur.

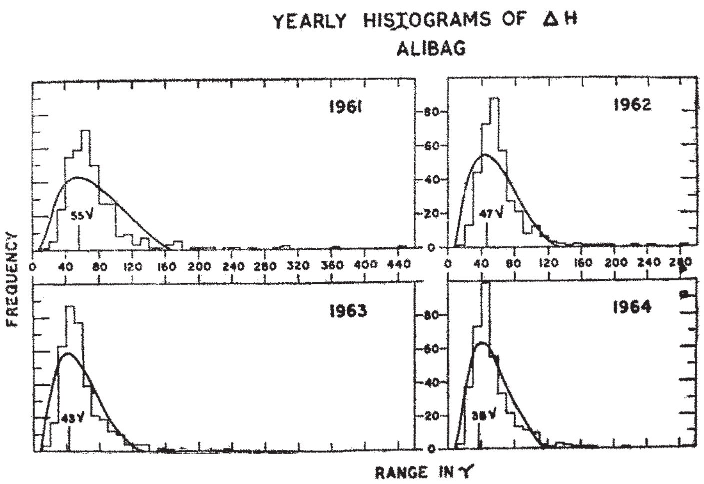

FIG. 4. Yearly histograms of ΔH for 1961, 1962, 1963 and 1964, fitted with polynomial curves.

Figure 5 shows the monthly mean $H_{min.}$ from 1961 to 1964 before and after the data have been corrected for the well-known secular change of H at Alibag, which is 26 γ/year during this period.[1]

MONTHLY MEAN H_{MIN} AT ALIBAG

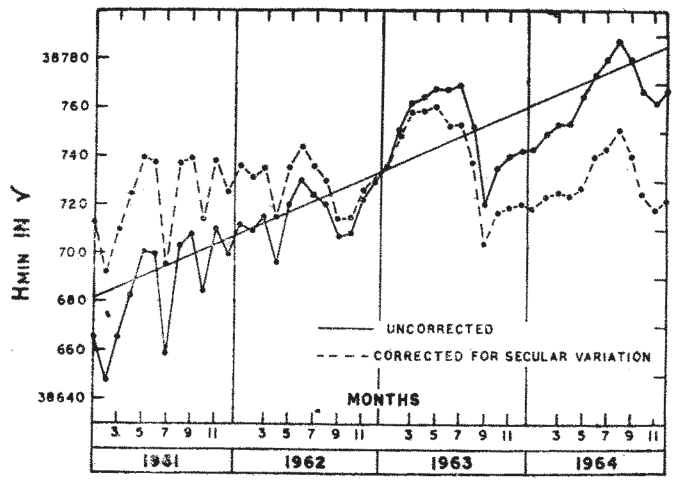

FIG. 5. Monthly mean $H_{min.}$ from 1961 to 1964 before and after the data have been corrected for secular variation.

To eliminate the influence of secular changes, of long-term changes due to the 11-year variation and of seasonal changes, we have derived $H^*_{min.}$ and $\triangle H^*$ by taking 27-day moving average of the daily values of $H_{min.}$ and $\triangle H$ and subtracting the average values from the corresponding values on the 14th day falling in the middle of the interval. The relationship of $H^*_{min.}$ and $\triangle H^*$ during each of the four years can be seen in Fig. 6 from the scatter diagrams and statistically best fit lines derived by correlation analysis. During each year, $\triangle H^*$ and $H^*_{min.}$ are negatively correlated with a coefficient of about $-0{\cdot}8 \pm 0{\cdot}02$. The points in the diagram indicated by 'X' and '$\odot$' correspond to days when sudden commencement and gradual commencement storms occurred. It would be observed that by and large there is no qualitative difference in the relationship of $\triangle H^*$ and $H^*_{min.}$ with increasing degree of geomagnetic disturbance.

The overall relationship is best brought out in Fig. 7 where data for $\triangle H^*$ and $H^*_{min.}$ for each individual day for all the four years have been included. The area of each circle is proportional to the number of days having the appropriate pair of values of $\triangle H^*$ and $H^*_{min.}$ By all standards, the relationship is remarkable. Since the correlation is negative so that with increasing $\triangle H^*$, $H^*_{min.}$ decreases, we can conclude that $H_{min.}$ is, predominantly produced by the removal of the field on the night side equivalent to $\triangle H$.

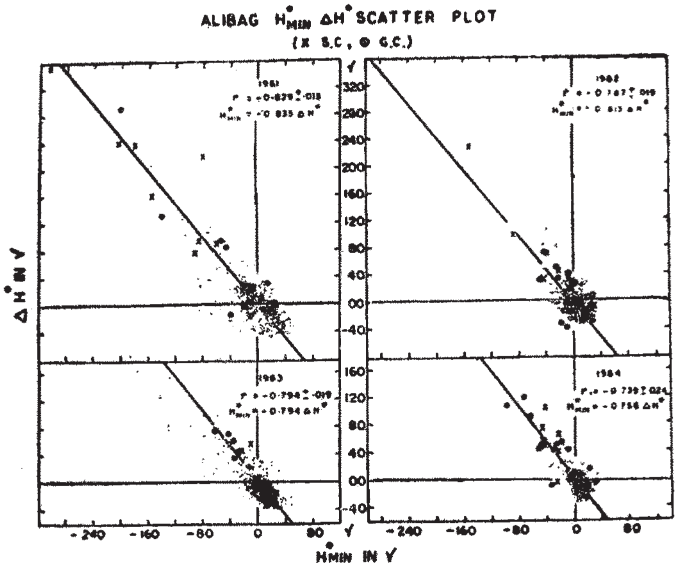

FIG. 6. Scatter plots of $H^*_{min.}$ against $\triangle H^*$ for individual years 1961 to 1964 × and ⊙ respectively indicate days on which sudden commencement and gradual commencement storms, occurred.

Figure 8 shows the scatter diagram during 1961 of $H^*_{max.}$ and $\triangle H^*$. The correlation coefficient between the two is negligible and is statistically not significant. This confirms that the midday peak in the magnetogram at Alibag is not primarily produced by the strengthening of the field on the day side due to ionospheric currents as the classical dynamo theory suggests. On the other hand, at Trivandrum on the geomagnetic equator, the magnetic effect of the electrojet current has been experimentally verified in rocket flights.[2, 3] On the average at Trivandrum (only 1100 km. south of Alibag) the daily variation has an amplitude about 1·8 times greater than the daily variation at Alibag. Since the magnetospheric effects would not differ substantially for Alibag and Trivandrum but the ionospheric electrojet effect would, we have sought confirmation of our proposition regarding the interpretation of $\triangle H$ at Alibag being negative by taking the scatter diagram of ($\triangle H$ Trivandrum$-\triangle H$ Alibag) against $\triangle H$ Alibag (Fig. 9). The correlation coefficient between the two is negligible and insignificant, clearly confirming that the basic process operative at Alibag is not directly related to the known ionospheric effect which is important at

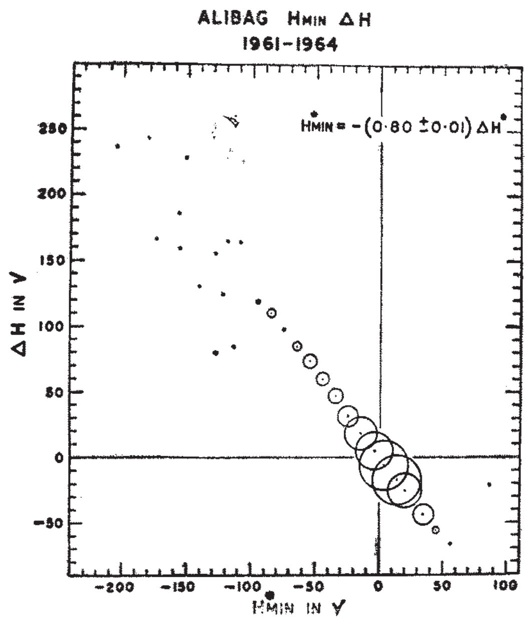

FIG. 7. H^*_{min}, ΔH^* relationship combining values for the years 1961 to 1964.

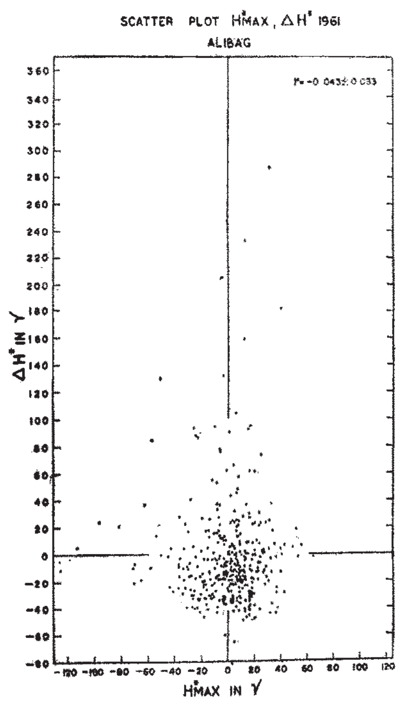

FIG. 8. Scatter diagram showing the relation between H^*_{max}, an ΔH^* for the year 1961 for Alibag.

Trivandrum. Rocket studies at middle latitudes have attempted the detection of the dynamo currents in the E region through their magnetic effects.[a, b] While the results have been partially successful, the phenomena appear variable and not directly according to what we had expected on the basis of the classical model of ionospheric current systems.

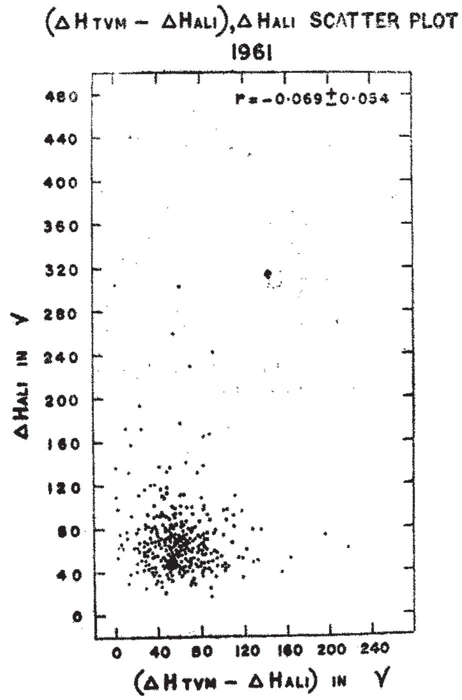

FIG. 9. Scatter diagram of (△H Trivandrum – △H Alibag) against △H Alibag for the year 1961.

CHANGES OF △H AND KINETIC ENERGY DENSITY OF INTERPLANETARY PLASMA DURING SOLAR CYCLE

During the IMP-1 period (27–11–1963 to 22–2–1964), a fairly well-established sector structure has been observed[4] in interplanetary plasma, indicating the stability of regions of solar activity.

The solar wind parameters have been experimentally measured by the M.I.T. plasma probe. Pai *et al.*[5] have reported the three hourly averages of the plasma velocity (V_s), density (N_s), flux (ϕ_s) and kinetic energy density (K.E.). From these, daily values have been obtained for each parameter. The super-position of successive 27-day values provides the average values of the solar wind parameters for each heliographic longitude at central meridian passage (C.M.P.). Similarly the values of $H_{min.}$ and $\triangle H$ have been computed and are plotted in Fig. 10 along with the values of ΣK_p.

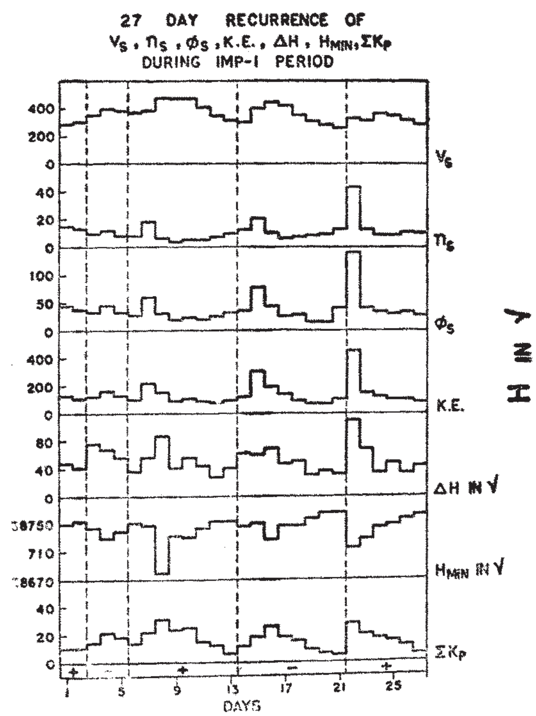

FIG. 10. 27-day recurrences during IMP–1 period of (*a*) Solar wind velocity (V_s) Km./Sec, (*b*) Solar wind number density (n_s) protons/cm.^{3}, (*c*) Solar wind flux (ϕ_s) in units of $1 \cdot 16 \times 10^7$ cm.$^{-2}$ sec.$^{-1}$, (*d*) Kinetic energy density (K.E.) in units of $8 \cdot 8 \times 10^{-11}$ ergs/cm.^{3}, (*e*) $\triangle$ H at Alibag in gammas, (*f*) $H_{min.}$ at Alibag in gammas and (*g*) Daily total of K_p (ΣK_p).

Table I indicates the correlation coefficients between the geomagnetic and the solar wind parameters. It is observed that $\triangle H$ is best correlated with K.E. and is insignificantly so with V_s. The correlation coefficient of ΣK_p is best with V_s, in agreement with the observations of Snyder *et al.*[6] However, the correlation cannot be directly related to physical models, since the equations are dimensionally not balanced. $\triangle H$ has the dimensions $M^{1/2} L^{-1/2} T^{-1}$ and therefore a meaningful physical relationship can be expressed by considering $(\triangle H)^2$ and kinetic energy density of the solar plasma, both having the same dimensions. The correlation between the two is $0 \cdot 78 \pm 0 \cdot 08$ for the 27-day superposed values for the IMP-1 period.

The scatter diagram is shown in Fig. 11. The expression connecting the two quantities is

$$\text{K.E. density} = (20 \pm 11) \times 10^{-10} + (3{\cdot}65 \pm 0{\cdot}45)\, 10^{-12} \times (\Delta H)^2 \text{ ergs/cm.}^3 \quad (1)$$

Based on expression 1 which provides a calibration of $(\Delta H)^2$ with the measured kinetic energy density of the solar plasma during the IMP-1

TABLE I

Correlation coefficients between the geomagnetic and solar wind parameters

	V_s	n_s	ϕ_s	K.E. density
ΔH	$0{\cdot}29 \pm {\cdot}18$	$0{\cdot}60 \pm {\cdot}13$	$0{\cdot}66 \pm {\cdot}11$	$0{\cdot}73 \pm {\cdot}09$
$H_{min.}$	$-0{\cdot}63 \pm {\cdot}12$	$-0{\cdot}16 \pm {\cdot}19$	$-0{\cdot}27 \pm {\cdot}18$	$-0{\cdot}40 \pm {\cdot}16$
ΣK_p	$0{\cdot}79 \pm {\cdot}07$	$0{\cdot}23 \pm {\cdot}17$	$0{\cdot}37 \pm {\cdot}17$	$0{\cdot}56 \pm {\cdot}14$

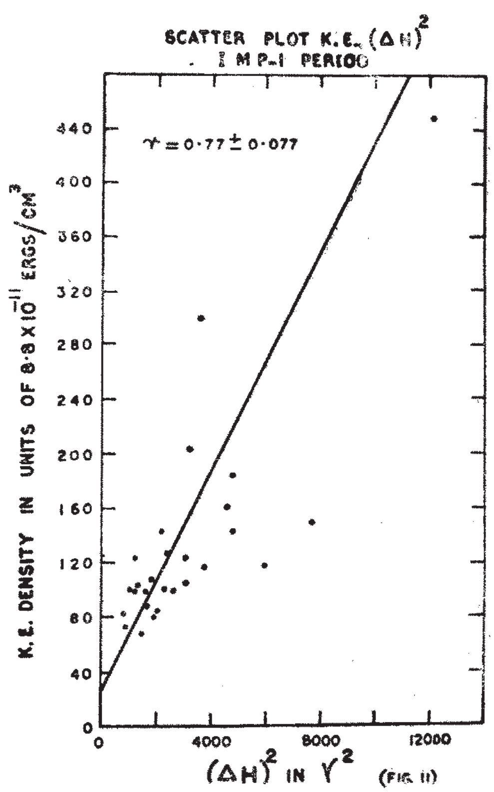

FIG. 11. Scatter plot of K.E. density of the solar wind and $(\Delta H)^2$ of Alibag.

period, we have derived the solar cycle changes of kinetic energy density from the changes of $\triangle$ H each year from 1954 to 1964. These are shown in Fig. 12 and the values of the parameters are indicated in Table II. The

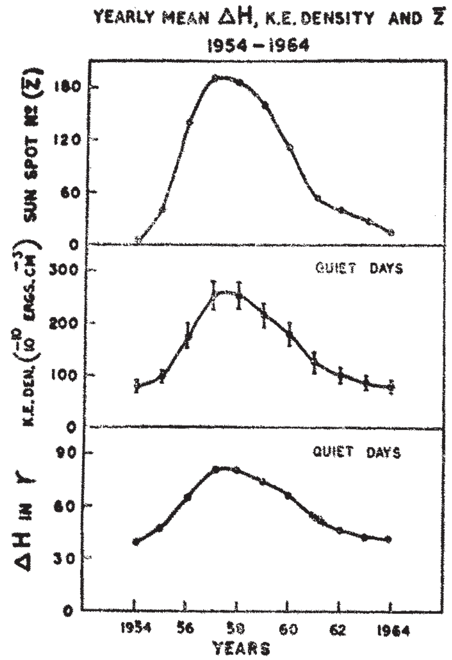

FIG. 12. Yearly mean of (1) Zurich sunspot number ($\bar{Z}$), (2) derived kinetic energy density (K.E.) of the solar wind for internationally quiet days in units of 10^{-10} ergs/cm.^{3} and (3) $\triangle$H in gammas for Alibag for the years 1954 to 1964.

derivation has been done for internationally quiet days and for all days in each year. It is observed that the derived kinetic energy density follows closely the change of the solar activity over the 11-year period as indicated by the Zurich sunspot number. We shall discuss in a separate communication the interesting implications of the differenee in the 11-year cycle change of the kinetic energy density for quiet days and for all days.

DISCUSSION

Much evidence has been accumulating recently to indicate that a simple representation of dynamo currents on a spherical ionospheric shell is inadequate to explain the observed daily changes of the magnetic field on the surface of the earth even during geomagnetically quiet days.[7–9] The fundamental character of the relationship of $\triangle H^*$ and $H^*_{min.}$ during the period of a solar cycle is best brought out in Table III,

TABLE II

K.E. density of the solar plasma for 1954 to 1964 derived from yearly mean $\triangle H$

Year	$\triangle$H quiet days gammas	$\triangle$H All days gammas	K.E. density quiet days in unit of 10^{-10} ergs/cm.^{3}	K.E. density All days in units of 10^{-10} ergs/cm.^{3}
1954	41	55	81±13	130±17
1955	46	62	97±14	168±19
1956	65	88	174±20	303±33
1957	80	95	253±28	349±38
1958	80	101	253±28	392±43
1959	73	101	215±24	392±43
1960	66	94	179±21	343±32
1961	53	74	123±16	220±25
1962	47	61	101±14	156±19
1963	42	57	84±13	139±18
1964	40	53	78±13	123±16

TABLE III

Correlation coefficients and slopes between $H^*_{\text{min.}}$ *and* $\triangle H^*$

Year	Correlation coefficient	Slope
1954	—0·61±·03	—0·620
1955	—0·60±·03	—0·630
1956	—0·72±·03	—0·730
1957	—0·88±·01	—0·880
1958	—0·80±·02	—0·797
1959	—0·79±·02	—0·800
1960	—0·83±·02	—0·850
1961	—0·83±·02	—0·835
1962	—0·79±·02	—0·813
1963	—0·79±·02	—0·794
1964	—0·74±·02	—0·756

Disregarding for the time being the small but systematic difference in the slope of the regression line during the years from 1957 to 1962 compared to the years of low solar activity 1954 to 1956 and 1963 to 1964, we note that the broad features of the $\triangle H^*$, $H^*_{min.}$ relationship are relatively constant. The results from synchronous A.T.S.-1 satellite,[10, 11] show that on the night side even at 6·6 R_e on geomagnetically quiet days the magnetic field in the anti-solar direction is less than the field in the sub-solar direction by about 25 to 30 gammas. Thus the reduction of the field on the night side is the predominant factor in the daily variation of the horizontal component of the earth's magnetie field at low latitude stations, except in the belt of $\pm$ 3° to 5° close to the geomagnetic equator where the effects of the electrojet in the ionosphere are also present. Since the latter represents an increase of field in the day time, the two factors together augment the overall daily variation that is observed at the geomagnetic equator.

Recent models explaining the shape of the magnetosphere and many of its features, particularly the tail and the neutral sheet, lead to the following:

(1) The compression of the geomagnetic field in the sub-solar direction due to the pressure of the solar plasma should produce an enhancement of H on the day side and a decrease on the night side. According to Mead's model,[12] the diurnal variation of H should be about 4 gammas, for a stand off distance of about 10 r_e. Even though the effect is connected with the kinetic energy density of the impinging plasma, this makes a minor contribution to the observed $\triangle H$ which is about an order of magnitude larger.

(2) There is a convection of the solar plasma along the sides of the magnetosheath and return through the tail[13–16] as diagrammatically visualised in Fig. 13. The computations due to Roederer[17] reveal that particles mirroring at low latitudes on the night side pseudo-trapping region (particles mirroring with less than 180° longitudinal drift for the guiding centre) are seen to abandon the magnetosphere through the boundary at 30° to 40° latitude before reaching the noon meridian (Fig. 14). This westward current which exists only for the night side decreases the horizontal field during night time for low latitude stations. At high latitudes, no trapping is possible and the daily variation due to magnetospheric drift currents is not important. At intermediate latitudes between 40° and 60° a pseudo-trapping region exists on the sunlit side but not on the night side, and in consequence there could be some reduction of the field on the day side. The state of affairs offers an alternative and a more plausible explanation

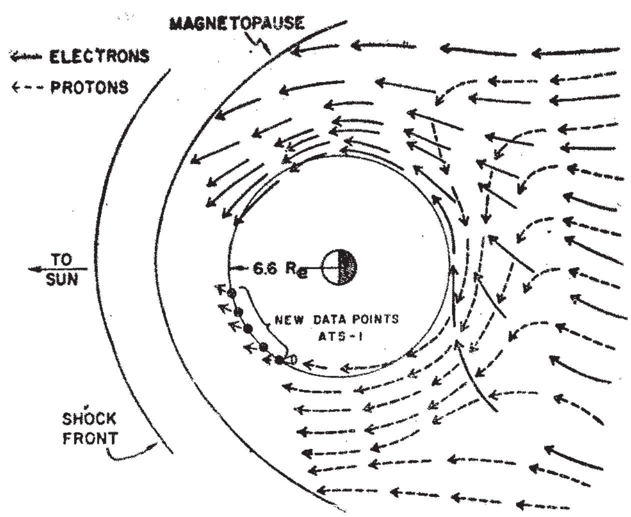

FIG. 13. A diagrammatic representation of the flow of energetic plasma through the magnetosphere in the equatorial plane, taken from J. W. Freeman, Jr., *J. Geophy. Res.*, 1968, 73, 4151–57.

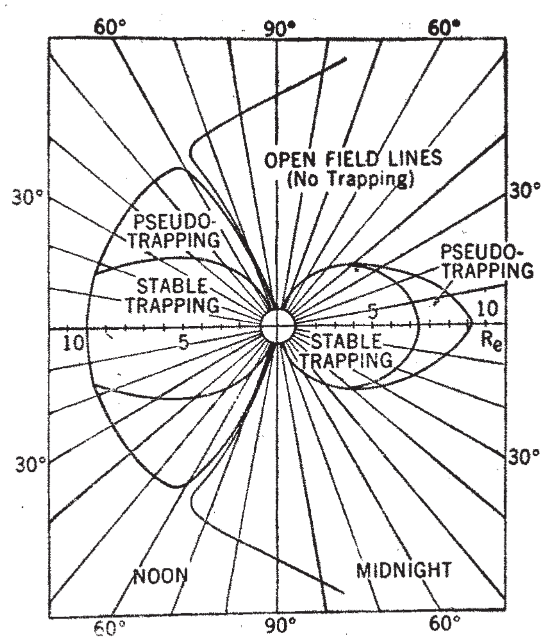

FIG. 14. Location of pseudo-trapping regions in the Mead-Williams model. J. G. Roederer, *Int. Sym. on Physics of the Magnetosphere*, Washington, D.C., September, 3–13, 1968. Particles mirroring inside these regions are unable to complete a drift around the earth.

than the classical dynamo theory of ionospheric current with foci at 40° geomagnetic latitude N and S to explain the observations, that the daily variation of the horizontal component of the magnetic field changes phase at 40° latitude.

(3) The stand off distance of the magnetopause (r_S) at the sub-solar point is inversely proportional to the sixth root of K.E. density of the solar wind. The higher the value of K.E. density, lower is the value of r_S, which means removal of more particles on the day side for low latitudes. Therefore, for days with high K.E. density, the pseudo-trapping region is pronounced and with the removal of the field on the night side large values of $\triangle$H are observed. Existing theory does not indicate the constant in the relationship between K.E. density and the magnetic field changes produced by the currents but the remarkable feature which comes out of the present analysis is that the relationship is a simple one and is given by expression (1). While the dimensions of the neutral sheet and its minimum distance from the earth are not yet derivable from the existing models of the magnetosphere, it is clear that in the -V_3 belt the minimum radial distance of the longitudinal drift of protons would be smaller than for electrons.

(4) While we suggest that $\triangle$H at low latitude stations outside the influence of the electrojet can be related to the strength of the drift currents in the pseudo-trapping region $H_{min.}$ can decrease not only due to these currents but also by those which are in the stable trapping region. Moreover, though conditions in the pseudo-trapping region can only be observed on the night side, the effects of the currents in the stable-trapping region can demonstrate themselves by lowering $H_{max.}$ and the daily mean value of H as is observed during geomagnetic storms.

(5) The most tentative aspect of the present communication is the correlation between $\triangle$H and the solar wind parameters. This is because the data for the latter were available to the authors only for 3 months. There is today extensive data concerning solar wind and this is being analysed. This will permit a confirmation of the suggestion made by us that the K.E. density can be directly related to $(\triangle H)^2$ and in consequence that the earth can be used as a plasma probe.

ACKNOWLEDGEMENTS

We are grateful to the Director of the Colaba and Alibag Observatories of the India Meteorological Department and to H. S. Bridge and the Plasma Group at M.I.T. Cambridge for the basic data on which the present study is based. We are also grateful to the Department of Atomic Energy for support.

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CHARACTERISTICS OF COSMIC RAY FLUCTUATIONS IN THE FREQUENCY RANGE OF 10^{-6} TO 4.15×10^{-3} CYCLES PER SECOND

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We have investigated the frequency dependence of the power spectrum of the μ meson intensity recorded at Chacaltaya (Bolivia) for periods ranging from 7 days to 4 minutes. Two sets of meson data of record length 27 days from 24 November to 20 December 1965 and 22 February to 20 March 1966, are analysed. The corresponding pressure records for these two sets are also subjected to similar analysis. Different regions of the frequency spectrum show different values of exponent for a power law fit. Comparison is made with the spectrum of the interplanetary field reported by JOKIPII and COLEMAN [1].

Introduction

Extensive investigations have been carried out in the past concerning modulation of cosmic ray intensity pertaining to periods from 11 years to diurnal and semi-diurnal variations. Attempts were made by several workers to extend the investigations to periods of a few minutes [2, 3], but the counting rates of the mu meson detectors used in the investigations were too low (10^5 per min in the results reported by TORIZUKA and WADA [2], and 4×10^4 per min by PATEL and MAEDA [3]) to lead to any conclusive evidence regarding the presence of short period fluctuations. Recently, DHANJU and SARABHAI [4] analysed data from a giant mu meson detector scintillator forming a part of the Bolivian Air Shower Experiment, and have obtained a counting rate of 10^6 per minute. Using methods of power spectrum analysis they were able to establish for the first time the presence of prominent frequencies of 18 and 25 cycles per hour in the average of 487 three hourly samples calculated from the mu meson data of Chacaltaya and covering the period from Nov. 1965 to March 1966. The average amplitude of these oscillations is of the order of about 0.04%. For each three hourly interval variability in the occurrence of prominent peaks was observed but averaged towards the above mentioned frequencies when large number of samples were superposed. It was also established that there was a correspondence between the peaks observed in the power spectrum of the Pioneer VI measurements of the interplanetary field and peaks in the meson intensity.

Comparison with K_p, the daily character figure for planetary disturbance indicated that when K_p is low the average power density for the frequency range of 6 to 30 cycles per hour is large with relatively no pronounced peaks. But during periods of high K_p, there is a reduction of the average power and appearance of pronounced peaks. This meant that during quiet periods the entire range of frequencies is excited but for periods that are not relatively quiet, the power is decreased but certain frequencies become prominent.

Thus, with the present status of our knowledge regarding short period fluctuations, it is now possible to investigate the relative properties of the entire spectrum of frequencies ranging from periods of a few days to a few minutes. We determine for the above mentioned period range the frequency dependence of the power spectrum of the mu meson intensity recorded at Chacaltaya.

Calculation of spectra

For the calculation of single spectrum the data used have record length of 27 days with a sampling rate of 2 minutes. In order to achieve the spectral range of 10^{-6} to 4.15×10^{-3} cycles per second a lag of 2500 is used for 19440 data points

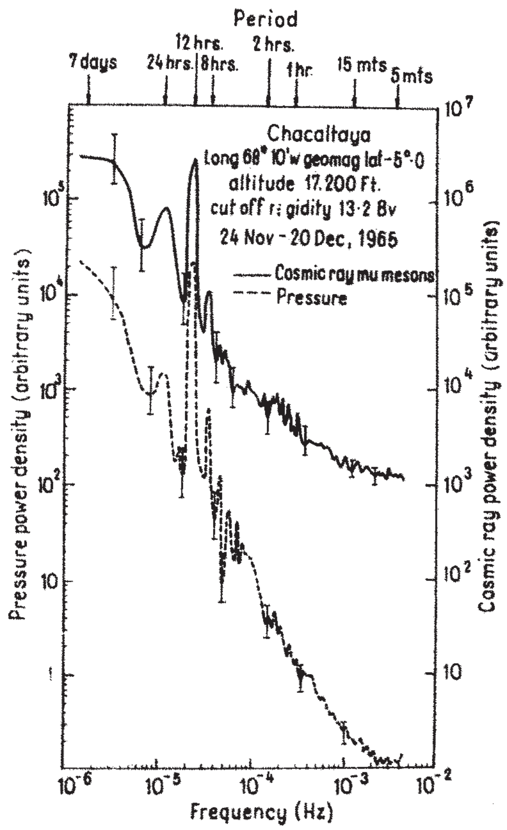

Fig. 1. The plot of spectral density estimates calculated for the frequency range from 10^{-6} to 4.15×10^{-3} cycles per second from records of cosmic rays and pressure at Chacaltaya for the interval from Nov. 24 to Dec. 20, 1965

of the 27 day set. The usual methods of Blackman and Tukey [5] for the calculation of the spectrum are used.

Fig. 1 shows the plot of the spectral density estimates of cosmic rays for the record interval from November 24 to December 20, 1965. The lower plot shows the estimates calculated for the same record length of atmospheric pressure at Chacaltaya. Prominent peaks are at 24 hour, 12 hour and 8 hour periods.

We take the general trend of the spectrum, and calculate the power law fit.

The 90% confidence band is shown in the figure by error marks for the estimates that follow the general trend. The log slope is precise to about ± 0.1. For the power law fit expressed by $P(f) \sim f^{-\alpha}$, the calculation of the exponent value α, we take points that lie within the error bars. The best fit calculated for these values leads to the value of α.

We find that in general the spectra are steep in the beginning but are relatively flat towards the high frequency end. For cosmic rays in the frequency region 4×10^{-6} to 1.5×10^{-4} CPS, $P(f) \sim f^{-1.6}$, and in the region 1.5×10^{-4} to 4.15×10^{-3}, the ex-

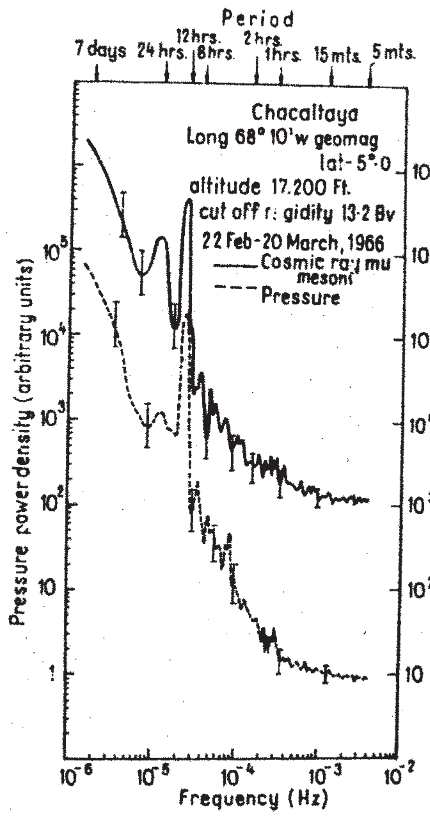

Fig. 2. The plot of spectral density estimates calculated for the frequency range from 10^{-6} to 4.15×10^{-3} cycles per second from records of cosmic rays and pressure at Chacaltaya for the interval from Feb. 22 to March 20, 1966

ponent value is -0.5. For the pressure spectrum the exponent value is -1.9 in the frequency region 3×10^{-6} to 5×10^{-4} CPS and reduces to a value of -1.1 in the region 5×10^{-4} to 4.15×10^{-3}.

Fig. 2 shows the spectral density estimate for cosmic rays and pressure for 27 days record length from February 22 to March 20, 1966. Calculations for the exponent values are carried out in the same way as described earlier. For cosmic rays in the frequency region 1.6×10^{-6} to 9×10^{-5}, the exponent value is -1.9, and for the range from 9×10^{-5} to 4.15×10^{-3}, it reduces to -0.34. For the pressure spectrum, the exponent value of -1.9 is observed in the part ranging from 1.6×10^{-6} to 3.6×10^{-4} CPS. The value reduces to -0.2 in the range from 3.6×10^{-4} to 4.15×10^{-3}.

Comparison of spectra

We have made a comparison of the cosmic ray spectra described above with the spectra of the interplanetary field given by JOKIPII and COLEMAN [1] for the field measurements carried out aboard Mariner IV. The results are described in Table 1.

Table 1

Period investigated	Parameter	Frequency range (Hz)	Exponent α	Remarks
24 Nov.	Cosmic rays	4×10^{-6}—1.5×10^{-4}	1.6 ± 0.1	
20 Dec.		1.5×10^{-4}—4.15×10^{-3}	0.5 ± 0.1	
1965	Pressure	3×10^{-6}—5×10^{-4}	1.9 ± 0.1	
		5×10^{-4}—4.15×10^{-3}	1.1 ± 0.1	
22 Feb.	Cosmic rays	1.6×10^{-6}—9×10^{-5}	1.9 ± 0.1	
20 Mar.		9×10^{-5}—4.15×10^{-3}	0.34 ± 0.1	
1966	Pressure	1.6×10^{-6}—3.6×10^{-4}	1.9 ± 0.1	
		3.6×10^{-4}—4.15×10^{-3}	0.2 ± 0.1	
29 Nov. 30 Dec. 1964	Interplanetary field	3×10^{-5}—5×10^{-3}	1.5 ± 0.2	From JOKIPII and COLEMAN [1]

The comparison of spectra of cosmic rays with the interplanetary field spectrum, shows similarity in the steepness of the slope up to frequencies of 10^{-4} CPS. At higher frequencies the cosmic ray spectra flattens whereas the interplanetary spectrum does not. The value of ΣK_p averaged for the period Nov. 24 to Dec. 20, 1965 is 10 and for the period 22 Feb. to 20 Mar., 1966 is 14.

*

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Short–Period Fluctuations of Cosmic Ray Intensity at the Geomagnetic Equator and their Solar and Terrestrial Relationship

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By using power spectrum analysis on the μ meson intensity records of a high counting rate instrument (10^6 counts/min) operated at Chacaltaya, Bolivia, it has been possible to identify the presence of cosmic ray fluctuations of 15 to 19 and 25 to 28 cycles per hour (cph). These frequencies were found at a 99% level of significance in the average of 1034 three–hour samples extending from November 1965 to June 1966. Comparison with Pioneer 6 measurements (Ness et al., 1966) indicates that the magnetosheath field, at a distance of about 10 earth radii (R_E), and the interplanetary magnetic field show peaks in spectral density that correspond closely (though not identically) with peaks in muon intensity. It is most plausible that these cosmic ray fluctuations are caused by the fluctuations of geo–magnetic field corresponding to an amplitude of about 20γ in the dipole magnetic field. Magnetic field measurements conducted in the magnetosphere by Explorer 12 (Patel and Cahill, 1964) show similar oscillations. Recent observations by ATS 1 confirm the presence of magnetic oscillations of similar frequencies at about 6 R_E. These frequencies are also found in the geomagnetic micropulsations observed at the surface of the earth. The integrated power of cosmic ray oscillations in the frequency range of 6 to 30 cph has been studied at various periods, and its solar–terrestrial relationship is examined. The association of observed frequencies in cosmic rays with frequencies in the solar photosphere and the interplanetary magnetic field, as well as the resonance frequencies of the magnetosphere, are discussed.

We have earlier reported [Dhanju and Sarabhai, 1967] the presence of prominent peaks at 18 and 25 cph in the power spectrum analysis of the μ meson intensity re–corded with a high counting rate meson monitor (10^6 counts/min) forming a part of the Bolivian Air Shower Joint Experiment at Chacaltaya, Bolivia, at an altitude of 17,200 ft, longitude 68°10'w, geomagnetic latitude —5.0°.

The data are subjected to power–spectrum analysis following the well–known method given by Blackman and Tukey [1958] with a spectral window of 1 to 30 cph and an analysis period of 3 hours usisng counts integrated over 1–min intervals. The power density estimates are calculated from the values that are deviations from the average of the 3–hour periods interval. Successive 3–hours periods in the time inter–val from November 1965 to March 1966 were analyzed. The analyses have now been extended to cover a further period from April to June 1966. Periods when the appa–ratus was defective have been omitted, however. As well as investigating prominent peaks in the power–spectrum analysis, we have now also studied the integrated power in the spectral band from 6 to 30 cph. Moreover, the solar–terrestrial rela–tionships of the occurrence of short–period fluctuations in the stated range of fre–quencies are also studied.

Peaks of spectral density estimates of μ–meson intensity. Figure 1 shows the superposed cosmic ray spectral density estimates. Significance of peaks in the power spectrum is determined by applying the chi square test in relation to a smooth poly–

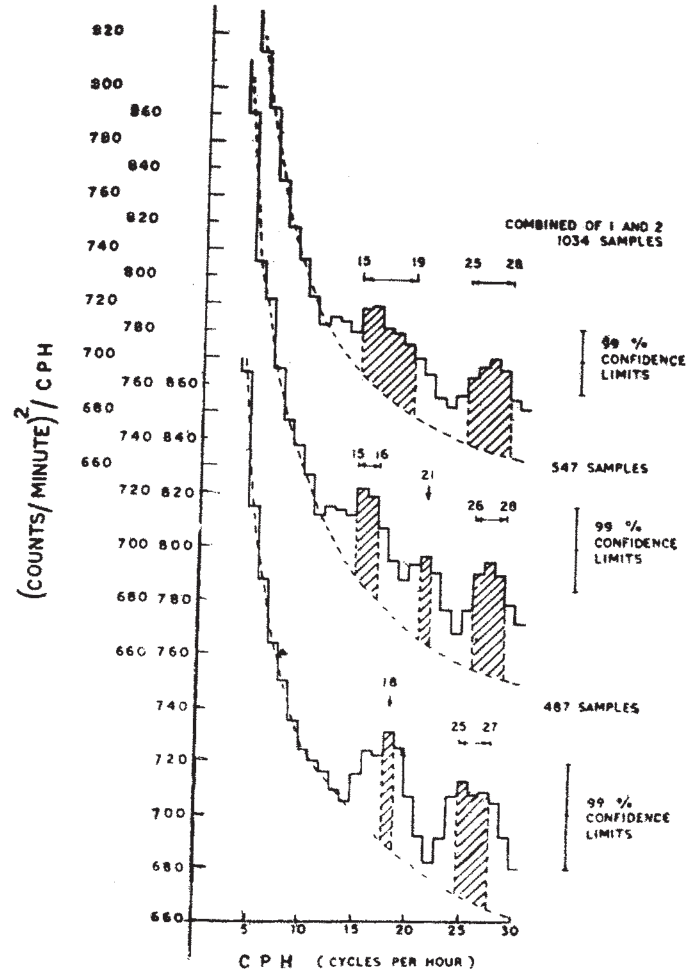

Fig. 1. Superposed cosmic ray spectral density estimates of 487, (November 21, 1965, to March 15, 1966); 547 (March 16, 1966, to June 15, 1966); and combined 1034 (November 21, 1965, to June 15, 1966) 3-hour samples in the frequency range 1 to 30 cph.

nomial fitted to the spectral frequencies in the range from 5 to 14 cph. in which there is no evidence that peaks occur. The polynomial is identical for all the sets. The cosmic ray μ meson intensity has on the average a variation of about $0.035 \pm 0.0005\%$ at the frequencies corresponding to the prominent peaks [Dhanju, 1968].

The local time dependence of the occurrence of significant peaks at particular frequencies is found by obtaining 8 sets of average spectral frequency estimates, having superposed 3-hour samples of similar timing, that are spaced as 0–3, 3–6, . . . 21–24 hours. No statistically significant variation of the average spectral density related to local time is observed. In this regard, therefore, our remarks in an earlier communication [Dhanju and Sarabhai, 1967], based on the analysis of partial data, does not hold when all the data are analyzed.

Comparison of cosmic ray frequencies with the frequencies found in magnetic field measurements by Pioneer 6, Range 1–30 cph. Ness et al. [1966] have detected certain frequencies in the magnetic field fluctuations in the magnetosheath and in the interplanetary space recorded by Pioneer 6 during its outward journey. The data of the magnetic measurements for the 3-hour intervals 1400 to 1700 hours, when the spacecraft was inside the magnetosheath, and 1715 to 2015 hours, when it was outside the bow shock in interplanetary space, have been subjected to power spectrum analysis by Ness et al. [1966]. For the same 3-hour intervals from 1400 to 1700 hours and 1715 to 2015 hours UT on December 16, 1965, the cosmic ray data are also subjected to power spectrum analysis, and spectral densities are calculated. Although mostly there is no 1 to 1 correspondence, cosmic rays, as well as the interplanetary and magnetosheath magnetic fields, have prominent frequencies in the same range that are statistically significant.

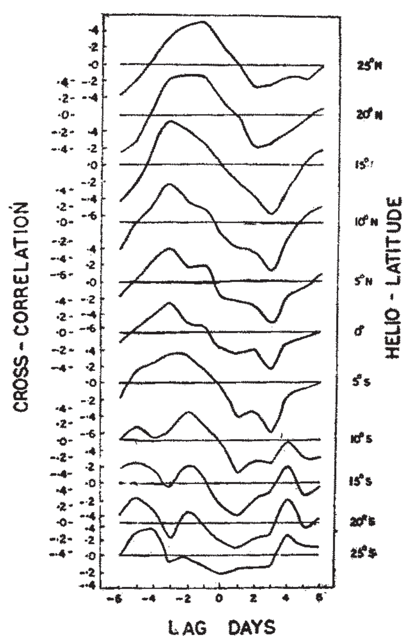

Fig. 2. Cross-correlation between 5303-A intensity for every 5° helio-latitude from 25°S to 25°N and 27-day recurrent 6 to 30 cph average cosmic ray per cent amplitude (solar rotation number 1810 to 1818).

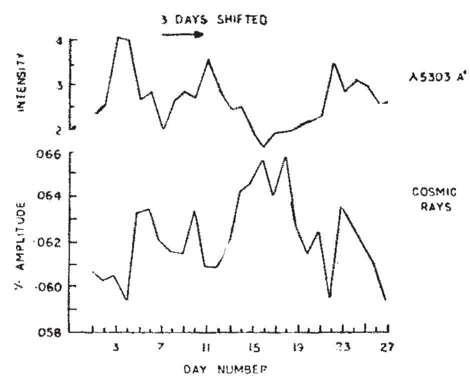

Fig. 3. The 27-day pattern of the per cent average amplitude of 6 to 30 cph and λ5303-A intensity averaged from 5°S to 15°N helio-latitude., shifted by 3 days (solar rotation number 1810 to 1818).

The average spectral power density estimates from 6 to 30 cph and coronal green lines intensity (λ5303 A). It has been observed that many types of cosmic ray variations measured on the earth correlate well with the intensity of the coronal green line λ5303 A [Pai and Sarabhai, 1963; Gnevyshev and Ol, 1966; Sarabhai and Subramanian, 1966]. Because many terrestrial phenomena related to solar activity have a 27-day recurrence tendency, the correlation between λ5303-A intensity and cosmic ray variations for the frequency range of 6 to 30 cph is studied on this basis. The per cent amplitude for 6- to 30-cph range for the solar rotations number 1810 to 1818 are superposed. The λ5303-A intensity at CMP meridian is at east and west limbs 7 days earlier and later, respectively, as described by Pai and Sarabhai [1963]. Cross correlations are computed between the averaged coronal intensity for each 5° helio-latitude and per cent amplitude for 6 to 30 cph. The process is carried out for lags of +6 to—6 days. Figure 2 shows the values of cross correlation. We have a cross correlation of —0.64 with a lag of 3 days for the coronal intensity (λ5303A) averaged for helio-latitudes from 5°S to 15°N. The 27-day pattern for the average per cent intensity and the coronal intensity 5°S to 15°N, displaced by 3 days, is shown in Figure 3. It may be noted that during the period under study the sun was more active north of the solar equator than south of it.

Relation of cosmic ray power spectrum to interplanetary conditions near the earth. For the purpose of this study we have considered the modulation of galactic cosmic ray intensity, averaged over 24 hours, and the planetary index of geomagnetic disturbance Kp as criteria for distinguishing between disturbed and quiet interplanetary conditions. The daily mean cosmic ray intensity is from the Deep River Neutron Monitor. Two types of analyses have been conducted. In the first, days are classified in three groups on the basis of deviations ΔI of the daily mean intensity from 27-day moving average values as follows :

Condition	Group	ΔI in %
Large depression	A	$\Delta I \leqslant -1.0$
Quiet	B	$+1.0 > \Delta I > -1.0$
Large rise	C	$\Delta I \geqslant +1.0$

In the second, attention is confined to cosmic ray decreases, and days are classified into two groups according to the magnitude of the decrease δI on one day compared to the daily mean intensity on the previous day. A fast change is recognised when $\delta I \leqslant -0.5\%$. For slow change, the cumulative δI of 3 successive days has a value more than $\pm 0.5\%$ for any particular day. Days on which a fast cosmic ray change occurs are designated as group F, and as group S when a slow change occurs.

Finally, using Kp, the daily character figure of planetary disturbances, we consider three groups as follows :

Condition	Group	Criteria
Quiet	P	Σ Kp 0 to 7
Semi-disturbed	Q	Σ Kp 8 to 23
Disturbed	R	Σ Kp 24 or higher

The power density estimates are calculated for periods each of 3-hour duration with 1-min data values. The deviations subjected to the analysis are from each of the 3-hour averages. The spectral density estimates for the range 6 to 30 cph are normalized on the basis of the average value of cosmic ray intensity during each 3-hour period. The spectral density estimates for the number of samples in each type of epoch are superposed. The normalized average power, the prominent peaks in the superposed spectral estimates, and their levels of significances are shown in Table 1.

The conclusions that emerge from this analysis are : (a) The average power is large (greater than 700 $\pm$ 2 (counts/min)^2/cph) for geomagnetically quiet days (group P) and for slow cosmic ray changes (group S). The situation on days on which the cosmic ray intensity is not greater than the 27-day average by more than $\pm 1.0\%$ (group B) is similar. Simultaneously, there is a general absence of peaks in the spectral estimates at levels of significance greater than 95%. (b) The average power is small (less than 700 $\pm$ 2 (counts/minute)^2/cph) for geomagnetically disturbed days (group R) and for fast cosmic ray changes (group F). The situation on days when the cosmic ray intensity is larger than the 27-day average by more than $+1.0\%$ (group C) is similar. In general, the spectral estimates show peaks at 95% level of significance.

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A STUDY OF THE LONG-TERM MODULATION OF GALACTIC COSMIC RAY INTENSITY

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Physical Research Laboratory, Ahmedabad, India

(*Received in final form* 16 *July* 1969)

Abstract—It is shown that the 11-yr variation of the galactic cosmic-ray intensity is linearly

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Abstract—It is shown that the 11-yr variation of the galactic cosmic-ray intensity is linearly related to the λ5303 coronal intensity close to the solar equator ($\pm 5°$ or $\pm 10°$). The available data on the temperature of the inner corona is used to calculate the annual average solar wind velocity at low heliolatitudes ($\pm 5°$) for each year during the period 1957–1967. The 11-yr variation of the computed velocity from the solar data is linearly related to the variation of cosmic-ray intensity. In terms of the theory of diffusion-convection, the empirical results are used to estimate the cosmic-ray intensity in the nearby interstellar space and hence the residual modulation at solar minimum. The following are the important conclusions:

(1) The size of the modulating region (R) varies with solar cycle such that for a given rigidity P, $R - r/K =$ const. where $r = 1$ a.u. and K is the isotropic diffusion coefficient.

(2) The residual modulation of the cosmic-ray intensity is roughly proportional to P^{-1}.

(3) The modulating parameter η for 1965 is found to be slightly higher than the upper limit of 1 GV set by Gloeckler and Jokipii (1967).

1. INTRODUCTION

The present investigation attempts to relate the conditions in the solar corona with the solar wind parameters and the electromagnetic state of the interplanetary space relevant to the 11-yr modulation of the intensity of the galactic cosmic rays observed at the Earth.

The broad features of the 11-yr modulation of galactic cosmic rays are consistent with the diffusion–convection model first proposed by Parker (1958, 1963) and extended by Dorman (1963), Axford (1965) and Parker (1965). This model describes the depression of cosmic-ray intensity in terms of a balance between inward diffusion and outward convection of cosmic-ray particles by irregularities in the interplanetary magnetic field carried outward by the solar wind. According to this model the density of cosmic-ray particles with magnetic rigidity P and velocity $C\beta$ observed at a heliocentric distance r at time t is given by

$$U(r, t, P, \beta) = U_0(R, P, \beta) \exp\left[-\int_r^R \frac{V}{K}\,\mathrm{d}r\right] \qquad (1)$$

where V is the solar wind velocity and K is the isotropic diffusion coefficient. R is the heliocentric distance beyond which $V = 0$ and/or $K = \infty$ and the cosmic-ray density corresponds to the unmodulated interstellar density U_0.

Recent measurements of the cosmic ray gradients (O'Gallagher and Simpson, 1967; O'Gallagher, 1967) clearly indicate that even at solar minimum in 1965 there was a residual solar modulation of the galactic cosmic-rays. Direct measurements of the amount of residual modulation have not been made and one must, therefore, use indirect arguments to deduce this quantity. In the present communication we suggest a new empirical approach to this problem by relating the observed cosmic ray intensity at the Earth to the solar wind velocity. We first show in Section 2 that the 11-yr variation of the galactic cosmic-ray intensity is linearly related to λ5303 coronal intensity close to the solar equator ($\pm 5°$ or $\pm 10°$). In Sections 3 and 4, the available data on the temperature of the inner corona (Billings and Hatt, 1968) are used to calculate the 11-yr variation of the solar wind velocity at low heliolatitudes ($\pm 5°$) for different values of the polytrope index α close to 1·1 (Parker, 1963). In

Section 5, we establish an empirical relationship between the 11-yr variation of the cosmic-ray intensity and the solar wind velocity. In Section 6, we estimate the cosmic-ray density in the nearby interstellar space by extrapolating this empirical relation to zero solar wind velocity. The residual modulation at solar minimum in 1965 is estimated for different mean primary rigidities and the modulating parameter η for 1965 is calculated and compared with previous estimates.

2. SOLAR ACTIVITY RELEVANT TO 11-YR MODULATION OF COSMIC RAY INTENSITY

Many features of the 11-yr modulation of the galactic cosmic-rays are now well known. There is not only a change of intensity but also a change of energy spectrum of variation. Observationally, if the change of intensity is plotted against any parameter of solar activity related to the whole Sun, such as sunspot number or the integrated coronal intensity, one observes the well-known 'hysteresis', viz., that for the same level of solar activity during ascending phase and the descending phase of the solar cycle, the cosmic ray intensity is different (Simpson, 1963). Quenby (1966) has, however, pointed out that consideration of sunspot number close to the solar equator ($\sim \pm 10°$) substantially reduces the difficulty.

Evidence has accumulated over the years that the more appropriate parameter relevant to the modulation of galactic cosmic-ray intensity is the coronal intensity $\lambda 5303$ rather than the sunspot number. This is not surprising since the solar wind, which influences the electromagnetic state of the interplanetary space, is related to the excitation of the solar corona. Correlations between 27-day recurrent changes of cosmic-ray intensity and the regions of enhanced $\lambda 5303$ emission in the solar corona have been reported by Simpson *et al.* (1952). Similar correlations were also observed by Pai and Sarabhai (1963). Recent work by Simpson and Wang (1967) has shown that by using $\lambda 5303$ ($\pm 30°$) intensity, the time-lag between the cosmic-ray intensity maximum and solar activity minimum reduces to ~ 1 or 2 months. Assuming that the time-lag Δt is related to the dimension of the modulating region R by $R = V \times \Delta t$ where V is the solar wind velocity, this gives $R \sim 7$ a.u. in 1965 which agrees well with the value of R derived from the measurements of the radial gradient of cosmic rays (O'Gallagher, 1967). Hatton *et al.* (1968) have shown that $\lambda 5303$ ($\pm 22{\cdot}5°$) is best correlated with the 11-yr variation of cosmic-ray intensity without any lag.

The present authors have examined the relationship of the 11-yr modulation of galactic cosmic-rays with annual mean $\lambda 5303$ intensity at each 5° heliolatitude North and South of the solar equator during the period 1957–1967. The coronal intensity data, used for the present analysis, have been obtained from the solar maps of the Fraunhofer Institute. From 1956 to 1965, the $\lambda 5303$ intensity was expressed in the solar maps by a 5-step scale. From January 1966 onwards, this was changed to a 9-step scale. For the purpose of intercomparison, the 9-step scale has been converted to the older 5-step scale for the years 1966 and 1967. Figure 1 illustrates the individual relationship of the annual mean coronal intensity with the annual mean neutron intensity at Deep River. It can be clearly seen from this figure that hysteresis loops form only for helio-latitudes above 10° and are almost absent at lower latitudes. The hysteresis is more pronounced for the Northern Hemisphere of the Sun than for the Southern Hemisphere. It should be noted that there was a marked North–South asymmetry in the $\lambda 5303$ intensity during the last solar cycle and the activity of the new solar cycle started more vigorously in the Northern Hemisphere. The N–S asymmetry can be very clearly seen from Fig. 2 where the yearly average $\lambda 5303$ intensity is plotted as a function of heliolatitude for the period 1957–1967. Note that during 1957, the activity in the Southern Hemisphere was more than that in the Northern.

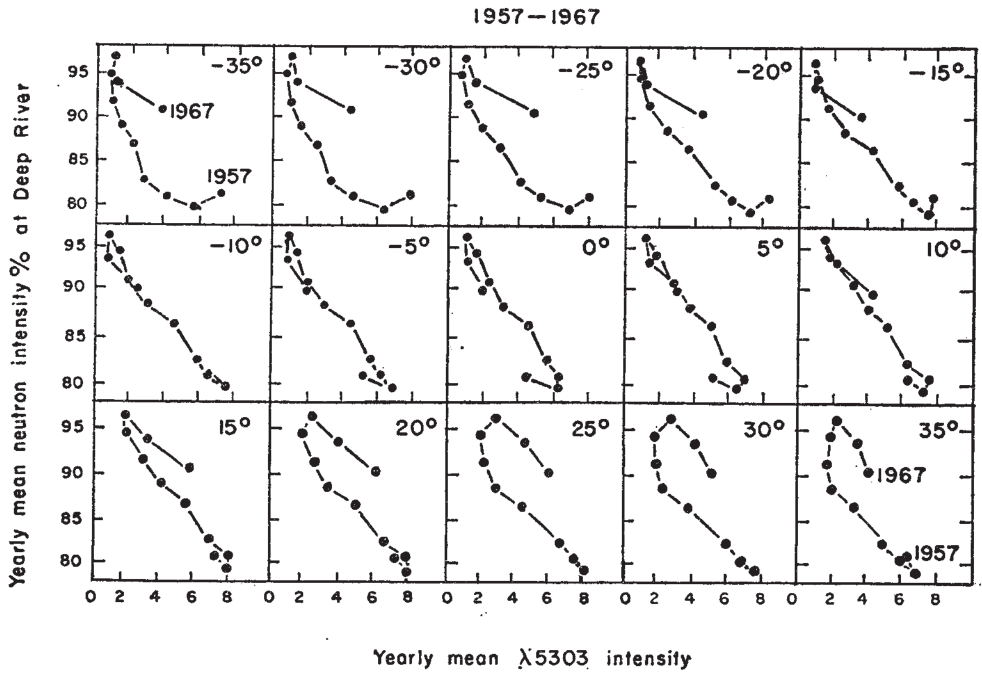

Fig. 1. Regression plot of yearly mean neutron intensity at Deep River (1957–1967) against yearly mean λ5303 intensity at each heliolatitude from −35° to +35°.

We conclude from these observations that for the 11-yr modulation of galactic cosmic-rays, which occurs over a region of radial distance of at least 5–10 a.u. from the Sun, the coronal activity mainly in the solar equatorial region ±5° or ±10° is relevant.

3. 11-YR CHANGE OF SOLAR WIND VELOCITY AT LOW HELIOLATITUDES

Since measurements of solar wind velocity in interplanetary space are available only for limited periods of time, it is valuable to employ some alternative method to estimate the solar wind velocity for the past solar cycle. According to Parker (1963), the solar wind velocity at large distances from the Sun should be proportional to the square root of the temperature at the base of the solar corona. The solar wind velocity is given by

$$V^2(r) \approx V_0^2 + \frac{4KT_0}{M}\left(\frac{\alpha}{\alpha - 1}\right) - \frac{2GM_\odot}{a} \tag{2}$$

where V_0 = expansion velocity at the base of the solar corona
K = boltzmann constant
M = mass of a proton
α = polytrope index ($\alpha > 1{\cdot}0$)
T_0 = temperature at the base of the corona
G = universal gravitational constant
$M_\odot$ = mass of the Sun
a = radius of the Sun.

V_0, the expansion velocity at the base of the solar corona is of the order of 1 km/sec or

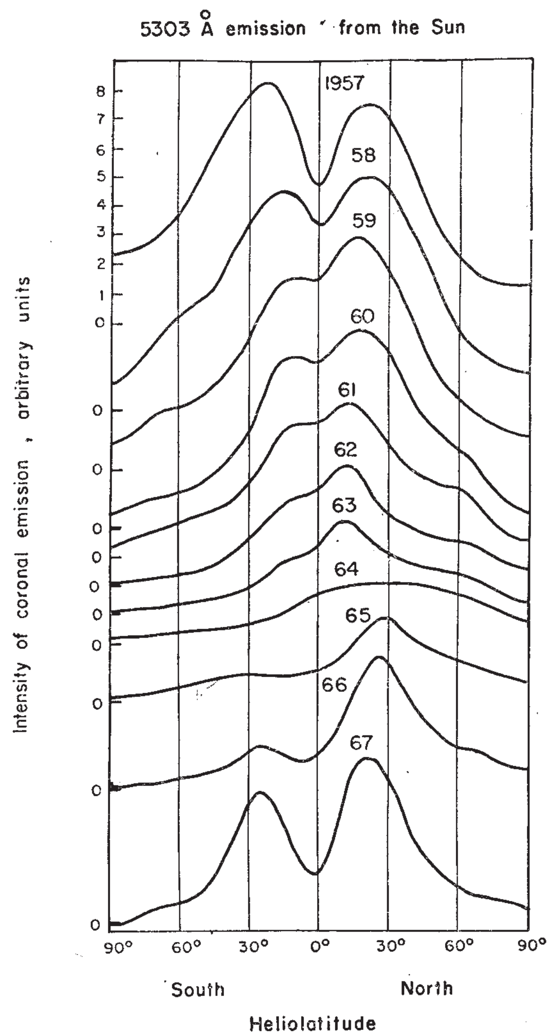

FIG. 2. YEARLY MEAN λ5303 INTENSITY PLOTTED AS A FUNCTION OF HELIOLATITUDE FOR THE PERIOD 1957–1967.

less (Parker, 1963) and therefore can be neglected for all practical purposes. The theoretical limit of the polytrope index α is from 1·0 (for an isothermal corona) to 5/3 (for an adiabatic corona). Parker (1963) has, however, pointed out that the observed temperature gradient, of the order of 3°K/km in the lower corona, indicates that coronal heating is sufficient to maintain α in the vicinity of 1·1. Thus assuming different values of α close to 1·1, we can calculate the solar wind velocity from Equation (2) if T_0 is known.

A rough estimate of the temperature in the inner corona has been made by Billings and Hatt (1968) from the ratio of the intensities of green (λ5303) and red (λ6374) coronal emission lines. The temperature is estimated with and without the consideration of yellow (λ5694) line emission. For the present analysis we have used only T_0 (with yellow). The temperature data is available for each Carrington rotation from 1956 to 1963. This temperature is, however, averaged for the entire Sun. In order to calculate solar wind velocity at low heliolatitudes we require to know the coronal temperature at these latitudes.

In order to accomplish this, we first examine the correlation of λ5303 intensity with the coronal temperature, both averaged over the whole Sun. The temperature data have been kindly supplied to us by Dr. D. E. Billings. Figure 3 shows a scatter plot using half-yearly values for the period 1957–1963. This gives a high positive correlation ($r = 0{\cdot}94$). The regression line is given by

$$T_0 = C\lambda + D \tag{3}$$

where $C = 0{\cdot}18 \times 10^6$ and
$D = 1{\cdot}03 \times 10^6$.

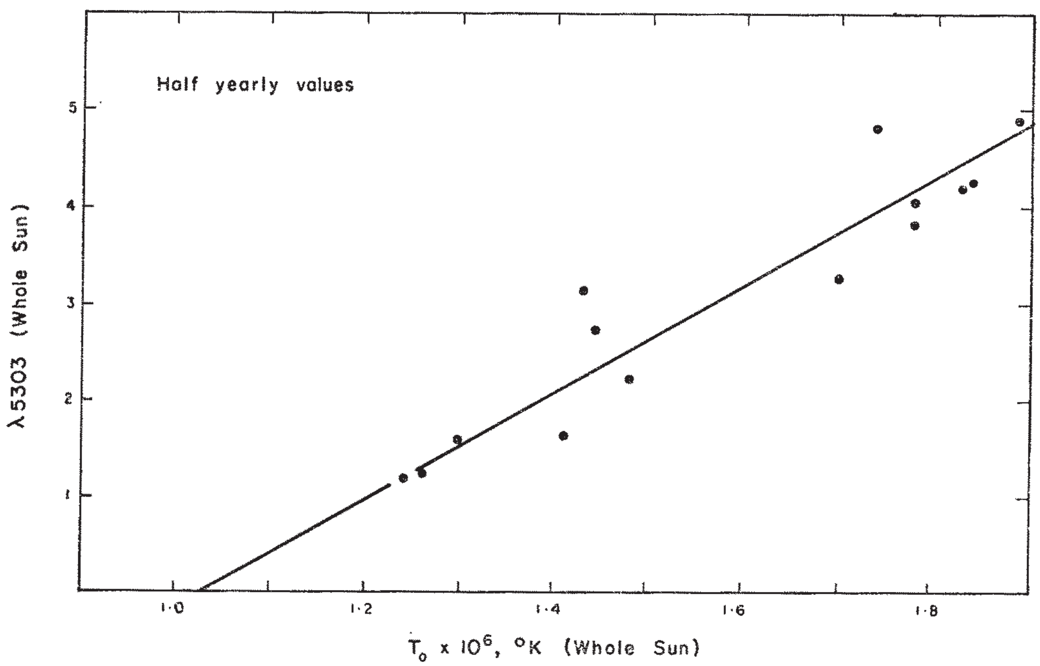

FIG. 3. SCATTER PLOT OF HALF-YEARLY AVERAGE λ5303 INTENSITY AND T_0, THE TEMPERATURE IN THE LOWER CORONA, BOTH AVERAGED FOR THE WHOLE SUN.

We assume that the above relationship which holds for the whole Sun, is applicable for individual latitude θ through the following relation:

$$T_0(\theta) = C\lambda(\theta) + D. \tag{4}$$

Substituting yearly mean $\lambda(\pm 5°)$ in Equation (4), we obtain T_0 $(\pm 5°)$ for the period (1957–1967) as indicated in Table 2.

4. EFFECT OF VARIATION OF THE POLYTROPE INDEX α ON THE SOLAR WIND VELOCITY

It follows from Equation (2) that by increasing the value of α, the solar wind velocity would decrease. Parker (1963) has shown that for a given value of α, there is a range of coronal temperatures for which steady coronal expansion is possible. The maximum and minimum temperatures are given by

$$T_{\text{max.}} = \frac{8 \times 10^6}{S\alpha} \tag{5}$$

$$T_{\text{min.}} = \frac{8 \times 10^6}{\alpha/\alpha - 1} \tag{6}$$

where $S = 2$ for radial expansion. The minimum annual average coronal temperature at $\pm 5°$, which occurs in 1965, is $1{\cdot}21 \times 10^6$ °K. Taking $T_{\text{min.}} = 1{\cdot}21 \times 10^6$ °K, we have from Equation (6)

$$\frac{\alpha}{\alpha - 1} = \frac{8 \times 10^6}{1{\cdot}21 \times 10^6} = 6{\cdot}61.$$

This gives $\alpha = 1{\cdot}18$. For this value of α and $T_0 = 1{\cdot}21 \times 10^6$ °K the solar wind velocity would be zero. Thus α should be less than 1·18 during 1965.

Having found the upper limit of α we now try to fix a range of α which would give reasonable values of solar wind velocities. For this purpose, we make use of the experimentally observed solar wind velocities. If we assume that the solar wind observed by the space probes originated at low heliolatitudes ($\pm 5°$), the effective value of α can be obtained by substituting the average value of the observed solar wind velocity and the average value of T_0 ($\pm 5°$), as obtained from λ ($\pm 5°$), in Equation (2). Using the mean solar wind velocity observed on Mariner-2, IMP-1 and Vela 2 Space-crafts we have deduced the effective values of α which are shown in Table 1. As can be seen from this table, α ranges from 1·10 to 1·14. All these values of α refer to periods characterised by low or medium solar activity. Since we do not have any measurement of solar wind velocity during high solar activity periods, we cannot decide whether α changes with solar activity or not. We have therefore considered a range of values of α from 1·09 to 1·13 to calculate the solar wind velocity. Without a specific basis to postulate the change of α with solar cycle, we have assumed a constant α and on this basis Table 2 shows yearly average values of λ ($\pm 5°$), T_0 ($\pm 5°$) and corresponding solar wind velocities calculated for different values of α. It can be seen that by increasing α, the solar wind velocity decreases as expected. The range in V, (i.e. $V_{\text{max.}} - V_{\text{min.}}$) however, remains constant and is equal to about 320 km/sec for each value of α, as it is dependent only on the range of coronal temperature which is the same for all values of α.

This range of solar wind velocity represents the slow variation in the steady component of the solar wind from solar maximum to solar minimum and does not include the effect of transient increases due to solar flares. Another important question is the choice of the polytrope index α, since, as we have seen, a slight variation in α changes the solar wind velocity drastically. It is also not known whether α varies during a solar cycle or more precisely with the change in coronal temperature and density. A comparison of the experimentally observed range at sunspot maximum during the present solar cycle and the minimum in 1964 would permit us to judge, when such data is available, whether there is evidence for change of the polytrope index with the solar cycle.

5. CORRELATION OF THE 11-YR VARIATION OF THE COSMIC-RAY INTENSITY WITH SOLAR WIND VELOCITY

According to the diffusion-convection model we can write the modulated cosmic-ray intensity N in terms of the unmodulated intensity N_0 in the nearby interstellar space as

$$\log_e N(r, t, P, \beta) = \log_e N_0(R, P, \beta) - V(t)\left[\frac{R - r}{K}\right]. \tag{7}$$

TABLE 1

Instrument	Reference	Mean solar wind velocity (km/sec)	Mean λ ($\pm 5°$)	Mean T_0 ($\pm 5°$) ($\times 10^6$ °K)	α
Mariner—2 (Sept.–Dec. 1962)	Snyder *et al.* (1963)	504	3·24	1·59	1·11
IMP—1 (Dec. 1963–Feb. 1964)	Wolfe *et al.* (1966)	378	2·27	1·44	1·13
—do—.	Pai *et al.* (1967)	360	2·27	1·44	1·14
Vela—2 July 1964–July 1965	Coon (1968)	420	1·27	1·26	1·10

TABLE 2. TABLE SHOWING YEARLY AVERAGE λ ($\pm 5°$), T_0 ($\pm 5°$) AND SOLAR WIND VELOCITY (IN km/sec) FOR DIFFERENT VALUES OF α

Year	λ ($\pm 5°$)	T_0 ($\pm 5°$) ($\times 10^6$ °K)	Solar wind velocity (km/sec) $\alpha = 1·09$	$\alpha = 1·10$	$\alpha = 1·11$	$\alpha = 1·12$	$\alpha = 1·13$	$\alpha = 1·14$
1957	5·0	1·93	711	659	614	573	536	502
1958	6·6	2·22	789	735	688	646	609	575
1959	6·6	2·22	789	735	688	646	609	575
1960	5·8	2·07	749	697	651	609	572	539
1961	4·7	1·88	697	646	600	559	522	489
1962	3·3	1·62	618	568	532	482	445	411
1963	2·3	1·44	556	507	462	421	383	347
1964	1·6	1·32	511	462	416	374	335	297
1965	1·0	1·21	466	416	370	326	284	242
1966	1·1	1·23	475	425	379	335	294	253
1967	2·3	1·44	556	507	462	421	383	347

For the measurements at the Earth r = const. (1 a.u.), while t varies. Thus for given r, P and β, the long-term variation of cosmic-ray intensity is a function of the long-term variation of V, R and K. We do not know how R and K vary with time, but the time variation in V for the period 1957–1967 has been estimated in Section 4 for different assumed values of the polytrope index α. If $\log_e N(r, t, P, \beta)$ is linearly related to $V(t)$, the ratio $R - r/K$ would be the slope of the regression line given by (7) while the intercept on the $\log_e N$ axis is $\log_e N_0(R, P, \beta)$ which represents the cosmic-ray intensity for $V = 0$, i.e. a condition of zero modulation.

We now examine the correlations of $\log_e N$ vs. $V(t)$ using the long-term variation of cosmic-ray intensity, measured by different cosmic-ray detectors as listed in Table 3. These detectors measure the integral cosmic-ray intensity above a threshold rigidity determined by either the atmospheric cut-off or the geomagnetic cut-off. The mean rigidity of response for each detector is also given in the table. Kane *et al.* (1966), have shown that the mean rigidity of response of an ion-chamber at the top of the atmosphere at high latitude, such as at Thule, is $\sim$2·5 GV at solar minimum and $\sim$3·5 GV at solar maximum.

Figures 4(a) and (b) show scatter plots of ($\log_e N$) vs. (V) for the yearly mean neutron intensities at Deep River and Mt. Norikura, using yearly mean solar wind velocity for α = 1·10. Figure 5 is a similar scatter plot for the yearly mean ion-chamber intensity at the top of

TABLE 3

Detector	Cut-off rigidity (GV)	Mean rigidity of response (GV)	Investigator
Thule ion chamber (Balloon data)	0·5 (Atmospheric)	~2·5 (solar min.) ~3·5 (solar max.)	H. V. Neher and H. R. Anderson
Deep River Neutron Monitor	1·02 (Geomagnetic)	~10	J. F. Steljes and H. Carmichael
Mt. Norikura Neutron Monitor	11·39 (Geomagnetic)	~25	Y. Miyazaki

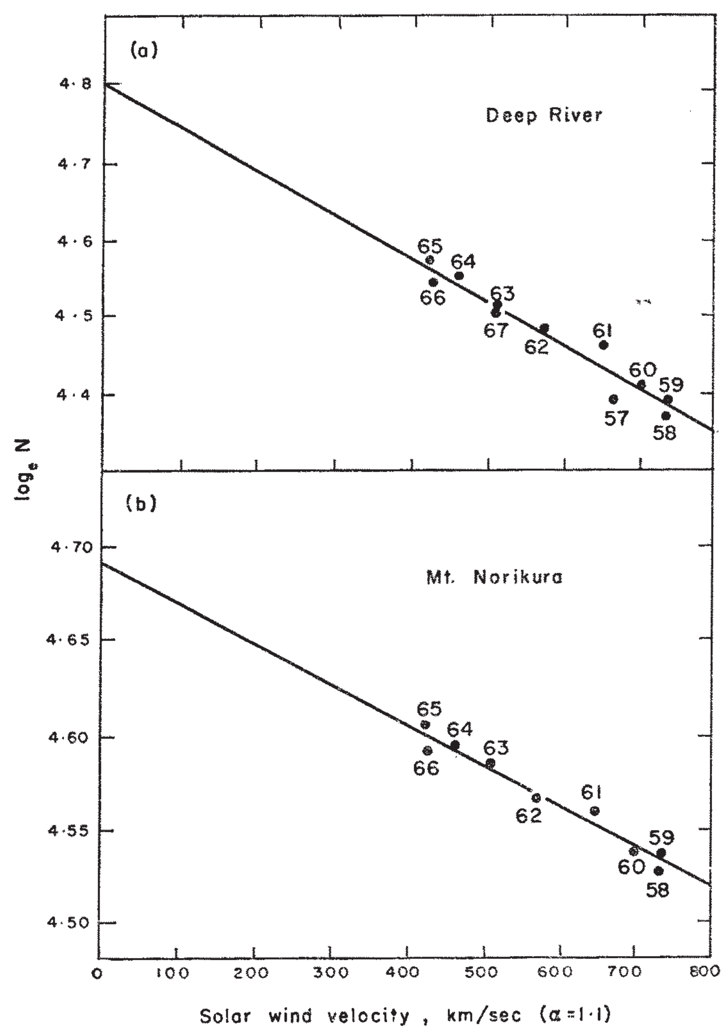

FIG. 4. CORRELATION OF YEARLY AVERAGE SOLAR WIND VELOCITY FOR $\alpha = 1{\cdot}10$ WITH $\log_e N$ FOR (a) YEARLY MEAN NEUTRON INTENSITY AT DEEP RIVER FOR THE PERIOD 1957–1967 AND (b) YEARLY MEAN NEUTRON INTENSITY AT MT. NORIKURA FOR THE PERIOD 1958–1966.

the atmosphere at Thule (these data have been read from Fig. 3 of the paper by Neher and Anderson, 1966). High negative correlations are quite evident in all the three cases, indicating that, on the average, $\log_e N$ and V ($\pm 5°$) are linearly related.

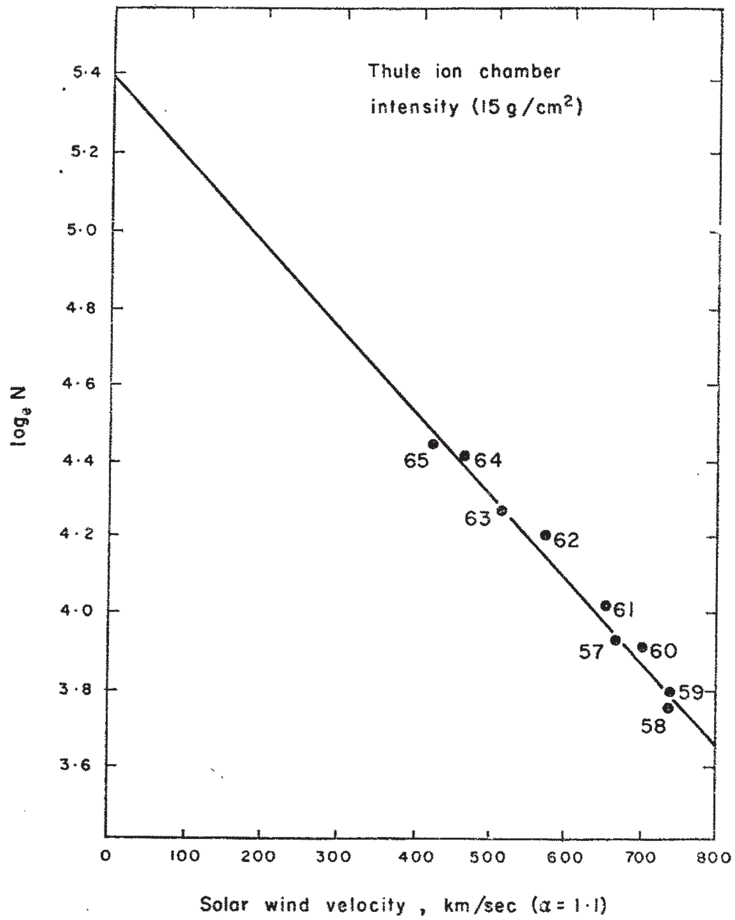

Fig. 5. Correlation of yearly average solar wind velocity for $\alpha = 1{\cdot}10$ with $\log_e N$ for the ion-chamber intensity at the top of the atmosphere over Thule (Neher and Anderson, 1966).

The slope in the $\log_e N$ vs. V plot should be an inverse function of rigidity. This is indeed seen from Fig. 6, where the slope (change in $\log_e N$ for each 100 km/sec increase in V) is plotted as a function of mean rigidity for $\alpha = 1{\cdot}10$. The slope is given by $-0{\cdot}75\ P^{-1{\cdot}1}$ where P is the mean rigidity in GV. Thus for a given mean rigidity, the ratio $R - r/K$ is, on the average, a constant.

If it is assumed that R does not vary appreciably with solar activity, it follows that the isotropic diffusion coefficient K for a given rigidity should, on the average, be nearly constant, which is unlikely. On the other hand, if both R and K vary, then it follows that when

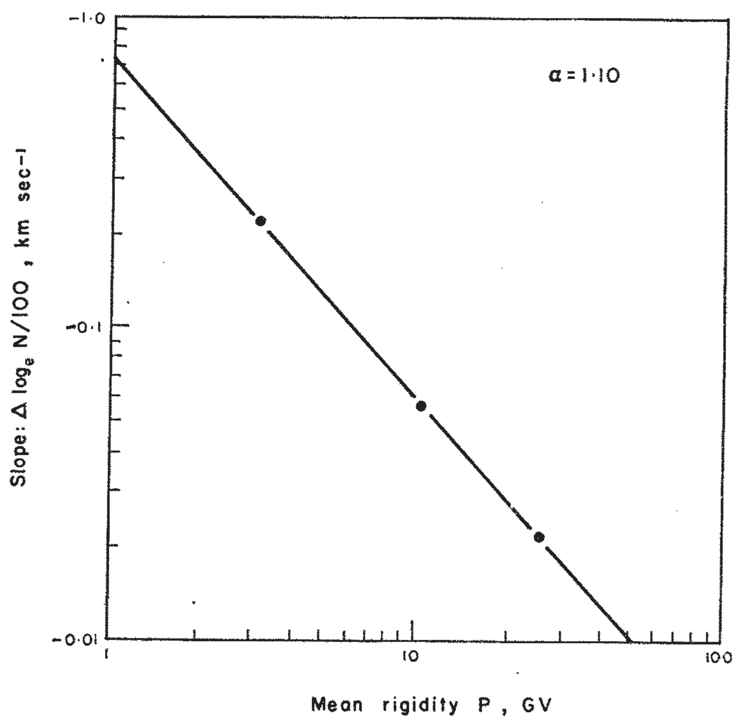

FIG. 6. THE SLOPE (CHANGE IN $\log_e N$ FOR EACH 100 km/sec INCREASE IN V) IS PLOTTED AS A FUNCTION OF MEAN RIGIDITY FOR $\alpha = 1{\cdot}10$.

K increases from solar maximum to solar minimum, R should also increase simultaneously to maintain this ratio constant. This means that the modulating region should be smallest at solar maximum and largest at solar minimum. This is surprising at first sight but probably implies that the outer boundary of the modulating region is determined by the existence beyond it of a power spectrum of irregularities in the interplanetary magnetic field such that nearly isotropic diffusion of cosmic-rays within the relevant energy spectrum is possible. This would imply that beyond the boundary, diffusion parallel and perpendicular to the interplanetary field lines are comparable. Sarabhai and Subramanian (1966) have suggested that at high sunspot activity this could well be the case due to interaction of solar wind of high and low velocity from a number of discrete regions on the spinning Sun.

6. ESTIMATION OF RESIDUAL MODULATION IN 1965

If we assume that the regression line in the $\log_e N$ vs. V plot can be extrapolated to zero wind velocity, we can obtain $N_0(R, P, \beta)$, which is the cosmic-ray intensity in the nearby interstellar space. This would directly give us the residual modulation of the cosmic-ray intensity at the solar minimum in 1965. Table 4 gives the average residual modulation in 1965, corresponding to the three detectors for different values of α. In Fig. 7, we have plotted the average residual modulation in 1965, as a function of $P\beta$, for the lowest and highest value of the polytrope index. It can be seen that the residual modulation is roughly proportional to $(P\beta)^{-1}$. However, since $\beta \approx 1$ for all the three detectors, it is not possible to distinguish a $(P\beta)^{-1}$ dependence from a $(P)^{-1}$ dependence. To compare the residual modulation obtained by the above method with other estimates, we compute the modulating

TABLE 4. AVERAGE RESIDUAL MODULATION (1965) IN PER CENT FOR DIFFERENT VALUES OF α

Detector	$\alpha = 1{\cdot}09$	$\alpha = 1{\cdot}10$	$\alpha = 1{\cdot}11$	$\alpha = 1{\cdot}12$	$\alpha = 1{\cdot}13$
Thule ion-chamber	155	134	115	96	79
Deep River neutron monitor	28	25	22	19	16
Mt. Norikura neutron monitor	10	9	8	7	6

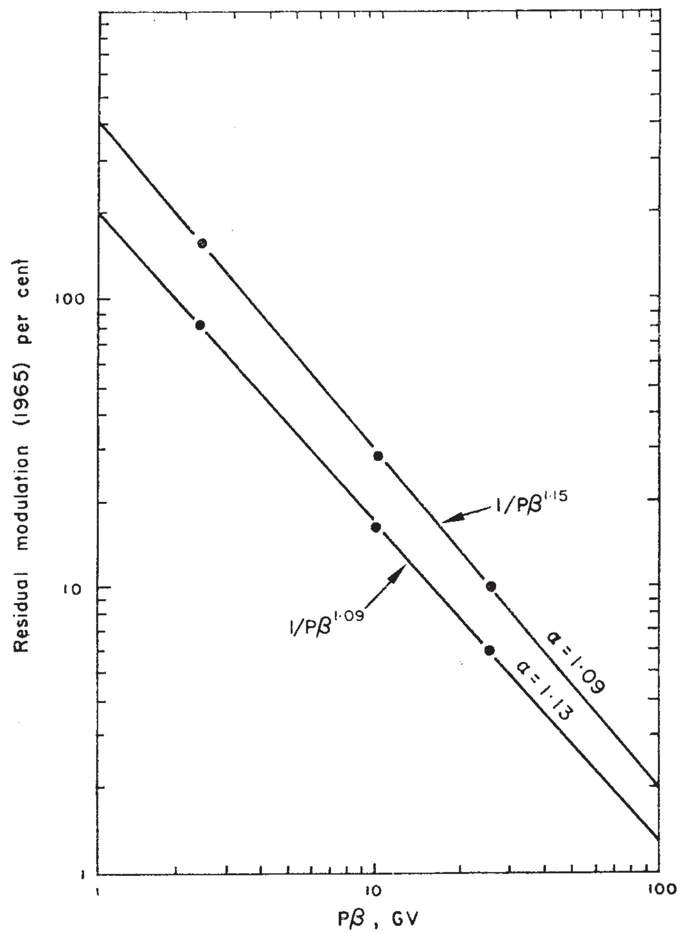

FIG. 7. AVERAGE RESIDUAL MODULATION IN PER CENT AT SOLAR MINIMUM IN 1965 PLOTTED AS A FUNCTION OF $P\beta$ FOR THE LOWEST AND THE HIGHEST VALUES OF α.

parameter η as defined by the following equation (Gloeckler and Jokipii, 1966).

$$N(r, t, P, \beta) = N_0(R, P, \beta) \exp\left[-\frac{\eta(r, t)}{P\beta}\right]. \tag{8}$$

Table 5 shows the average values of η in 1965, corresponding to the three detectors for different values of α. This shows that η decreases as α is increased. For the range of α from 1·09 to 1·13 the mean η changes from about 2·5 GV to 1·5 GV. For a given value of

α, the η values for the three detectors are nearly constant, indicating that the mean rigidities of response used for the three detectors are approximately correct.

TABLE 5. AVERAGE MODULATING PARAMETER η(GV) IN 1965 FOR DIFFERENT VALUES OF α

Detector	$\alpha = 1·09$	$\alpha = 1·10$	$\alpha = 1·11$	$\alpha = 1·12$	$\alpha = 1·13$
Thule ion-chamber	2·48	2·26	2·05	1·81	1·57
Deep River neutron monitor	2·54	2·29	2·04	1·78	1·52
Mt. Norikura neutron monitor	2·41	2·18	1·95	1·71	1·48
Mean η	2·48	2·24	2·01	1·77	1·52

Previous estimates of η have been made by several workers. Silberberg (1966) found that η was about 2·9 GV in 1963, while Biswas *et al.* (1967) obtained a value of $\eta = 0·6$ GV in 1965 from the observed energy dependence of the [$He^3/He^3 + He^4$] ratio. Gloeckler and Jokipii (1967) demodulated the observed cosmic-ray spectrum at solar minimum in 1965, using different values of η and found that for $\eta \sim 1$ GV the interstellar cosmic-ray energy density was about 1 eV/cm^3, which is the upper limit if the cosmic-rays are to be contained by a reasonable galactic magnetic field of about 10^{-5} G. Thus it was concluded that the value of η in 1965 should be $\leqslant 1$ GV. However the lowest value of η obtained from the present estimate is $\sim$1·5 GV for $\alpha = 1·13$.

The value of η can be further reduced by increasing α beyond 1·13. However, this would reduce the solar wind velocity to considerably low values which may seem to be unreasonable. Another way to reduce the residual modulation would be to increase the range of V from solar maximum to solar minimum. This can be done by allowing α to vary over the solar cycle such that it is minimum for periods of maximum solar activity and vice versa. Since we do not have any knowledge about the variation of α over a solar cycle, we consider a rather arbitrary variation of α as shown in Table 6. The corresponding solar wind velocities and average η for each year, calculated from yearly mean neutron intensity at Deep River, are also shown in the table. The solar wind velocity now ranges from about 790 km/sec in 1958 and 1959, to 325 km/sec in 1965, while the average value of η in 1965 is 1·3 GV which is closer to the value estimated by Gloeckler and Jokipii (1967).

TABLE 6. ARBITRARY VARIATION OF α AND CORRESPONDING SOLAR WIND VELOCITY AND AVERAGE η FOR EACH YEAR

Year	α	V (km/sec)	η (GV)
1957	1·10	659	3·1
1958	1·09	789	3·3
1959	1·09	789	3·1
1960	1·10	697	2·9
1961	1·10	646	2·4
1962	1·11	532	2·2
1963	1·11	462	1.9
1964	1·12	374	1·5
1965	1·12	326	1·3
1966	1·11	379	1·6
1967	1·11	462	2·0

7. DISCUSSION AND CONCLUSIONS

The empirical relationship established between the 11-yr variation of the cosmic-ray intensity and the average λ5303 intensity at low heliolatitudes ($\pm 5°$ or $\pm 10°$) allows us to draw the following important conclusions:

(1) The diffusion-convection process producing the 11-yr modulation of cosmic rays measured on the Earth, is largely governed by interplanetary conditions along the plane of the ecliptic and the solar activity close to the solar equator. We must conclude, therefore, that diffusion in the region relevant to the modulation is largely anisotropic and occurs along the spiralling magnetic field lines.

(2). Assuming a polytrope index α which is constant during a solar cycle, we can derive from the empirical relationship between λ5303 intensity and cosmic-ray intensity, a new relationship relating solar wind velocity and cosmic-ray intensity.

(3) As discussed in Section 5, the empirical relationship implies that for a given mean rigidity, the ratio $R - r/K$ is, on this average, a constant. When K increases from solar maximum to solar minimum, as is plausible, it follows that R should be minimum at solar maximum and vice versa. This is in conformity with the suggestion made by Sarabhai and Subramanian (1966) that the boundary of the modulating region is related to the interaction of fast and slow solar wind from a number of active regions on the spinning Sun, producing a distribution of magnetic field irregularities beyond a radial distance R such that diffusion parallel and perpendicular to magnetic field are almost equal.

(4) By extrapolating the empirical relationship between cosmic-ray intensity and solar wind velocity to zero solar wind velocity we have obtained the residual modulation at solar minimum in 1965. The rigidity dependence of the residual modulation so obtained is roughly proportional to P^{-1} which is similar to the rigidity dependence of the 11-yr modulation of the galactic cosmic-ray intensity.

The residual modulation as expressed by the modulating parameter η is an inverse function of the polytrope index α. For the range of α from 1·09 to 1·13 the mean η for 1965 changes from about 2·5 GV to 1·5 GV. However, the upper limit of η in 1965 should be about 1 GV only (Gloeckler and Jokipii, 1967). Thus the residual modulation estimated from the present empirical relationship is higher than the theoretical upper limit. It is not reasonable to assume an $\alpha > 1{\cdot}13$, since this would result in solar wind velocities being less than the observed values at minimum of solar activity.

If α is allowed to vary throughout the solar cycle such that it is minimum during maximum solar activity and vice-versa, then for an arbitrary variation of α, as shown in Table 6, the value of η in 1965 can be about 1·3 GV, which reduces the discrepancy. However, merely from this, it is not possible to conclude that the polytrope index does vary in this manner during a solar cycle.

The present analysis which has attempted to put together theoretical concepts with experimental observations of the modulation of galactic cosmic-rays, of solar wind in interplanetary space and of the excitation of the solar corona, provides not only a broad confirmation of the self-consistency of the basic theoretical ideas but further insights regarding the parameters which are involved in the various processes. The most important amongst these are the polytrope index in the solar corona and the variation of the size of the modulating region with solar cycle of activity. There are still difficulties in reconciling the estimated residual modulation with a reasonable estimate of the energy density of interstellar cosmic-rays. However, it remains to be seen whether, with more accurate measurements of solar wind velocity and intensity of galactic cosmic-rays in interplanetary space, the empirical relationships which have been derived in the present paper can be modified to narrow the discrepancy.

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Daily Variation of the Geomagnetic Field at the Dip Equator

THE range ΔH_A of the daily variation of the horizontal component of the geomagnetic field at Alibag (A), a low latitude station outside the influence of the equatorial electrojet, is largely caused by weakening of the ambient field on the night side rather than an enhancement on the day side[1-3]. The effect may be caused by magnetospheric drift currents which, being more than 30,000 km above the surface of the Earth, would produce almost identical effects at Alibag and Trivandrum (T), situated on the dip equator 1,100 km south of Alibag, if differences in the induced field arising from local ground conditions are ignored. On the other hand, the well known enhancement of ΔH at the dip equator is caused by the influence of the equatorial electrojet. Consequently $\Delta H_T - H_A$ must be related to purely ionospheric currents.

We examine here the validity of these assumptions particularly because they contradict the dynamo theory, which suggests that the contribution of ionospheric currents should predominate at both stations on days which are not geomagnetically disturbed. We also estimate the relative contributions of the two processes at Trivandrum and at Alibag.

Fig. 1 shows the normalized histograms of $\Delta H_T - \Delta H_A$ for different ranges of ΔH_A for the years 1962, 1963, 1964 and for all the three years combined. On a day-to-day basis, ΔH_A is more or less independent of the purely ionospheric contribution $\Delta H_T - \Delta H_A$. Similarly, as shown in Table 1, ΔH_A is independent of the changes of F region ionospheric electron density related to the midday mean value of f_0F_2 over Kodaikanal, which is also close to the dip equator. Thus ΔH_A does not track the changes in the ionosphere.

Since January 1964, regular measurements of the electron drifts in the E and F regions of the ionosphere have

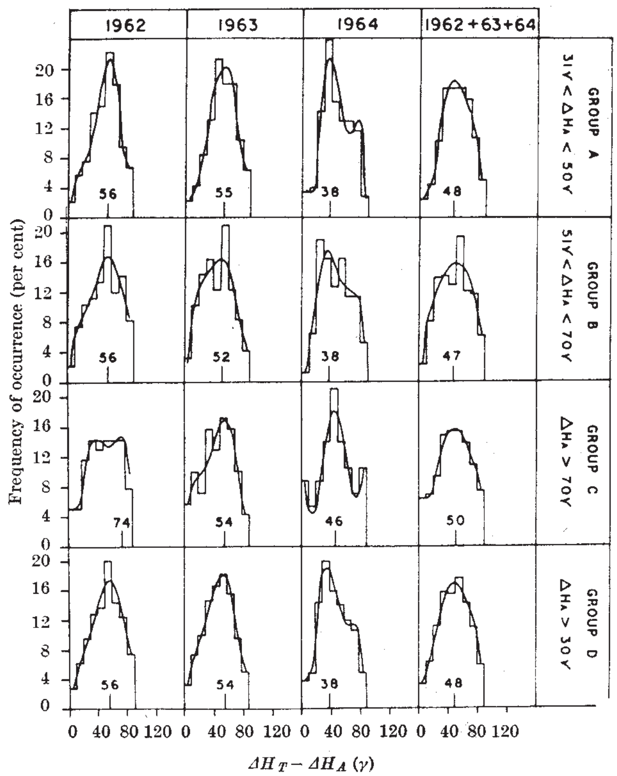

Fig. 1. The normalized histograms of ($\Delta H_T - \Delta H_A$) for different ranges of ΔH_A for the years 1962, 1963, 1964 and for all the three years combined.

been made at Thumba, near Trivandrum, by recording the fading of radio reflexions at three spaced aerials. The drift was always to the west during the day. The mean drift speed between 1100 and 1300 h correlates well with $\Delta H_T - \Delta H_A$ shown in Fig. 2. Rocketborne magnetometers have measured the magnetic field of the electrojet current in the E region[4]. R. Raghava Rao (private communication) has shown, using current density derived from similar measurements and simultaneously observed electron density, that the average electron velocity is comparable with the drift velocities measured by the spaced aerial technique. A linear relationship between the drift speed in the E region and $\Delta H_T - \Delta H_A$ is therefore consistent with the interpretation that the drift velocity measured by the spaced aerial technique is proportional to the electron drift velocity in the electro-jet

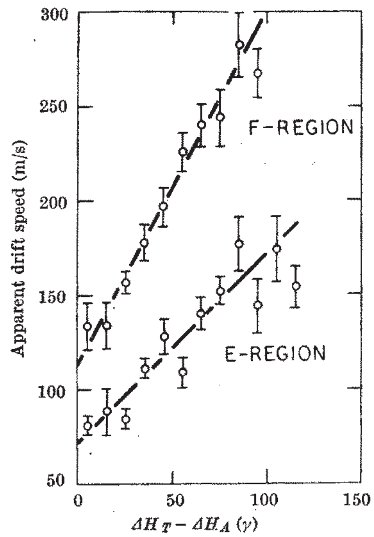

Fig. 2. The relation showing the mean westward apparent drift speed during midday hours (1100–1300 h) for different values of $\Delta H_T - \Delta H_A$.

and that moreover the latter, at noon, can be deduced from $\Delta H_T - \Delta H_A$, which is derived exclusively from ground measurements.

Electron and ion currents in the F region would produce equal and oppositely directed magnetic effects, and therefore the correlation of $\Delta H_T - \Delta H_A$ with F region electron drifts indicates that the latter are themselves correlated with the E region drifts. Comparing the magnetograms from Tamale (dip 1° 14′) and Legon (dip 10° 11′), Osborne[5] has argued that the electrojet cannot be a simple enhancement of the normal current in a belt of high conductivity. Moreover, Osborne and Skinner[6] have also shown a correlation between the electrojet strength and the F region drifts. The conclusions of these authors are therefore consistent with ours.

According to the dynamo theory, the mean current density $J = \overline{\Sigma}' \cdot E$, where $\overline{\Sigma}'$ is the height integrated conductivity and E is the primary electric field. The derived values of $\overline{\Sigma}'$ for E region at 0°, 30°, 60° and 90° dip latitudes[7] enable a smooth curve to be drawn to express the variation of conductivity with latitudes. For this, the ratio of conductivities at Trivandrum and Alibag is derived as

$$\frac{7{\cdot}58 \times 10^{-8}}{2{\cdot}61 \times 10^{-8}} = 2{\cdot}9$$

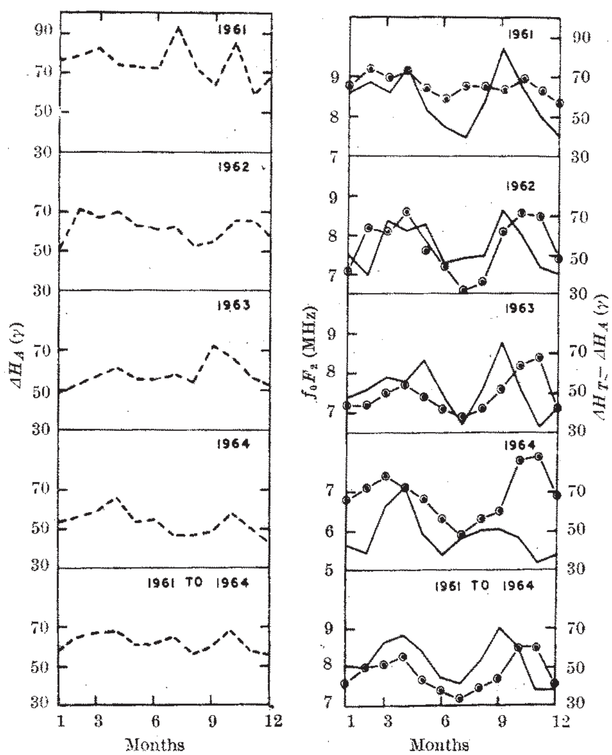

Fig. 3. The monthly mean values of ΔH_A, $\Delta H_T - \Delta H_A$ and f_0F_2 at Kodaikanal for the years 1961, 1962, 1963, 1964 and for all the four years combined. - - - -, ΔH_A; ——— $\Delta H_T - \Delta H_A$; ●—●, f_0F_2.

Table 1 shows that the average ionospheric contribution at Trivandrum is about 50γ. Consequently, the average ionospheric contribution to ΔH_A would be $50/2{\cdot}9 \approx 17\gamma$.

The monthly mean values of $\Delta H_T - \Delta H_A$ and ΔH_A are shown in Fig. 3 separately for the years 1961, 1962, 1963 and 1964, and for the four years all together, along with the midday mean values of f_0F_2 at Kodaikanal, which is also close to the dip equator. $\Delta H_T - \Delta H_A$, which is purely a result of ionospheric currents, shows clear equinoctial maxima. Drifts at Thumba also exhibit equinoctial maxima[8]. In contrast with the purely ionospheric effect, ΔH_A has no consistent seasonal variation.

Table 1

ΔH_A range	Mean ΔH_T–ΔH_A (γ)	Mean midday f_0F_2 (MHz)	Number of days
31 to 50 γ	50	7·3	319
51 to 70 γ	51	7·6	314
71 γ and above	49	7·7	292
31 γ and above	50	7·6	925

According to Hones and Bergeson[9], a radial electric field generated by the wobbling of the Earth's magnetic axis in the magnetosphere, distorted by the solar wind, should cause charged particles to experience net energy changes over a number of revolutions around the Earth. From this theory, an explanation for the enhancement of the equatorial electrojet at equinoxes can be visualized. Assuming that the kinetic energy density of the solar wind, which compresses the magnetosphere in the sub-solar direction, is constant over a period of one year, the Earth's magnetic axis is more nearly perpendicular to the solar wind flow at equinoxes than at solstices. The compression of the magnetosphere and the radial electric field produced in the ionosphere is therefore a maximum during equinoctial months. This effect should be more pronounced at the equator than at higher latitudes.

We conclude that the contribution to ΔH_T at Trivandrum, which can unambiguously be attributed to an ionospheric current, remains largely unaffected by the magnetospheric contribution at both Trivandrum and Alibag. This supports the contention that two independent processes are operating. While at Trivandrum the ionospheric contribution is similar in magnitude to the magnetospheric contribution on a normal day, at Alibag the ionospheric contribution is only about a third of the magnetospheric effect. Moreover, our results support the view that drift velocities measured by the technique of spaced aerials are related to the velocity of electrons in the electrojet.

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MORPHOLOGY OF THE GEOMAGNETIC FIELD VARIATIONS AND A STUDY OF THE INTERPLANETARY MAGNETIC FIELD FLUCTUATIONS IN RELATION TO THE DAILY VARIATION OF THE GEOMAGNETIC FIELD AT LOW LATITUDES

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(Received 6 January, 1971)

Abstract. It is suggested that ΔH, the daily variation of the horizontal component of H at a low latitude station outside the influence of the equatorial electrojet is caused by (1) the dynamo current, mainly at the ionospheric E-region, (2) the surface currents at the magnetopause, and (3) the tail currents, the eccentric ring current and the partial ring current in the magnetosphere. Analysis of data from Honolulu and Guam confirms the contention that ΔH is largely due to a reduction of the field on the night side, suggesting a major contribution from magnetospheric currents. The study of the variability of H at different hours related to day-to-day changes of the daily variation, confirms the view that there are two independent processes contributing to ΔH even during quiet days and that the variance, due to both the factors, is larger during years of high solar activity than when the Sun is quiet. From the study of the observed interplanetary magnetic field parameters from satellites IMP-1, IMP-3 and Explorer-33, it is shown that σB_z, the fluctuation of the north-south component of the interplanetary magnetic field is linearly correlated with ΔH. The relationship between the two remains relatively unaltered during the solar cycle from 1963-64 (IMP-1) through 1965 (IMP-3) to 1967-68 (Explorer-33).

In the light of the experimental evidence, it is shown that the time dependent azimuthal electric field in the magnetosphere and the azimuthal asymmetry of the outer magnetosphere play a very important part in populating the inner shells of the magnetosphere. These enhance the eccentric and the partial ring currents, and the tail currents, lowering H during night time and contributing to an increase in ΔH. 66% of the variance of $(\Delta H)^2$ can be attributed to changes in KE density and $(\sigma B_z)^2$ of the interplanetary plasma. This leaves 34% of the variance of $(\Delta H)^2$ attributable to other causes such as ionospheric currents. The experimentally observed shift of the time of minimum of H, from dawn hours during quiet days to dusk hours during disturbed days, is explained as a consequence of the drift motion of charged particles injected form the tail of the distorted magnetosphere in the presence of a corotational electric field and geomagnetic field gradients.

1. Introduction

If we wish to use geomagnetic field changes to probe interplanetary plasma, we should have an appreciation of the various current systems in the ionosphere, magnetosphere and at the magnetopause, which could affect the unperturbed geomagnetic field. Evidence has been presented (Sarabhai and Nair, 1969a, b, c and d and Nair *et al.*, 1970) which indicates that the daily variation of the geomagnetic field at a low latitude station away from the influence of the equatorial electrojet, is dominated by current systems outside the ionosphere. Moreover it has been shown that the kinetic energy density of interplanetary plasma in the neighbourhood of the Earth is related to this effect. In the present communication, we furnish further experimental evidence in support of this view and new data which connects the non-ionospheric contribution

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with the variance of the component of the interplanetary magnetic field parallel to the geomagnetic dipole.

To make credible the proposition that the observed geomagnetic effect is significantly related to magnetospheric currents, it is necessary to demonstrate that experimental observations and theoretical studies of the drifts of particles in the magnetosphere provide an overall view which is consistent with our assumption. Some direct observational evidence is available with respect to the currents in the ionosphere and the magnetosphere. Moreover, from theoretical studies one can now infer the existence of currents in the magnetosphere due to the convection of the plasma driven as a result of reconnection of interplanetary and geomagnetic field lines (Dungey, 1961); due to the viscous interaction of the interplanetary plasma with the magnetosphere

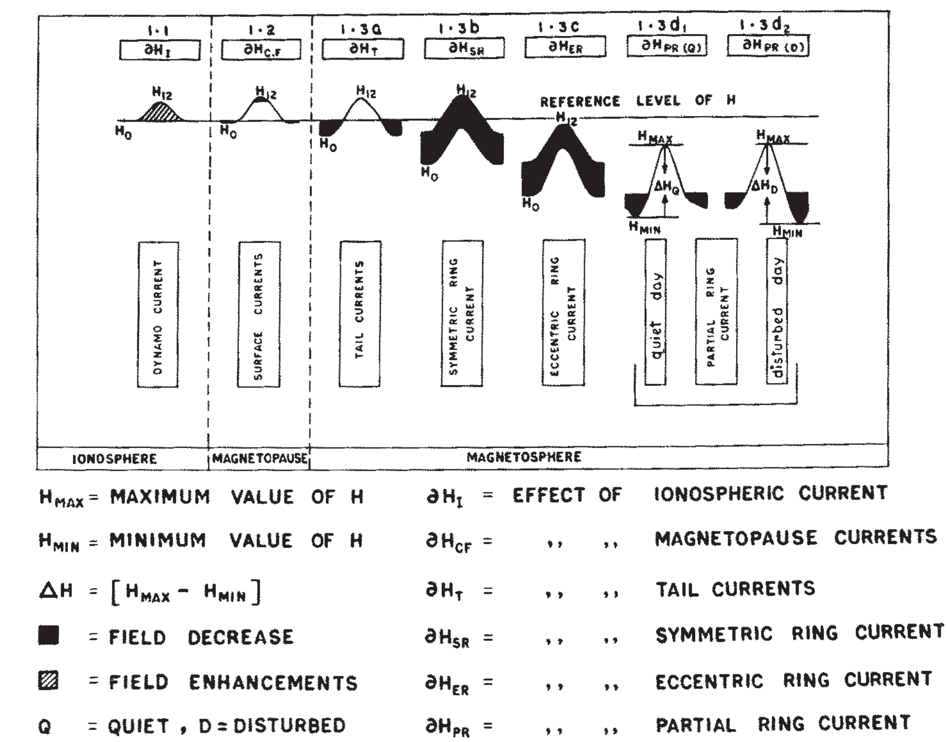

Fig. 1. Hypothetical representation of the development of ΔH for a low latitude station away from the effects of the equatorial electrojet, from various sources.

(Axford and Hines, 1961); and due to gradient and curvature of the field lines in the magnetosphere.

The dynamo theory suggests that the currents in the ionosphere occur in the *E*-region due to thermal winds and electric fields. The effects of the currents in the magnetosphere and the ionosphere, and their progressive contributions to the unperturbed geomagnetic field at a low latitude station such as Alibag can be conceptually and diagrammatically depicted as shown in Figure 1 (Sarabhai and Nair, 1969d). For the time being we neglect the effects due to the induced Earth currents. The darkened portions indicate the contribution of ΔH, due to decreases, and the hatched portions due to enhancements. H represents the assumed value of the surface unperturbed dipole field as would obtain if the sources of electromagnetic and particle radiations from the Sun were cut off. The different effects can be summarized as follows. It is suggested that the various processes are all operative on each day, though their relative importance varies depending on solar, terrestrial and interplanetary conditions in the neighbourhood of the Earth.

1.1. Dynamo current

The effect of the ionospheric current in the equatorial electrojet has been measured with rocket-borne magnetometers (Maynard and Cahill, 1965; Sastry, 1968). Moreover, Nair *et al.*, (1970) have demonstrated the high correlation between the *E*-region ionospheric drift velocities of electrons at Trivandrum (dip equator) and the differences between the daily range, of the H component of the geomagnetic field at Trivandrum and Alibag. It has been estimated that on an average day the ionospheric contribution to ΔH at Alibag represents a day time increase of about 17 γ, while at Trivandrum it is about 50 γ. This effect is shown in the Figure as ∂H_I.

1.2. Magnetopause currents

According to Mead (1964) the effect of the surface currents on the magnetopause due to the quiet day corpuscular flux of the solar wind would give rise to an increase of nearly 2 γ on the day side and a reduction by the same magnitude during night time at the surface of the Earth. This is shown in the Figure as ∂H_{CF}.

1.3. Magnetospheric currents

a. *The Tail Currents*

Siscoe and Cummings (1969) have reported that an increase in the tangential stress at the magnetopause which is associated with an increase in kinetic energy density of the solar wind, should increase the magnetic energy stored in the tail. In consequence the tail radius should increase and the inner edge of the neutral sheet should move closer to the earth. The effect of the neutral sheet and the θ type current system in the tail is equivalent to a small magnetic dipole, of opposite magnetic moment to that of the main geomagnetic field (Axford *et al.*, 1965; Williams and Mead, 1965). This should cause a decrease in the field during night time shown as ∂H_T.

b. *The Symmetric Ring Current*

There should be at all times and even during quiet periods a field reduction due to a symmetric westward ring current which is mainly situated at 3.5 Earth radii. From the observed values of particle drifts in the magnetosphere, Schield (1969a, b) has estimated that the quiet day ring current would have a magnetic moment of 0.21 M_E, resulting in a decrease of 28.4 γ at the surface of the Earth at the equator. This is shown as ∂H_{SR}.

c. *The Eccentric Ring Current*

The contours of constant field magnitude in the equatorial plane have been constructed by Fairfield (1968), using the data from the satellites IMP-1, 2 and 3. The contours of constant B, with $B < 150\,\gamma$ are not symmetrical in the equatorial plane and they are nearer to the Earth in the anti-solar direction compared to the subsolar direction. This is due to compression of the magnetic field by the solar wind on the dayside. The eccentricity of the constant B contours is enhanced when the solar wind pressure is more. Moreover, Kavanagh *et al.* (1968) have worked out the energy contours in the outer magnetosphere for protons and electrons, which are nearer to the Earth in the night side compared to the dayside. Thus particles which conserve the first adiabatic invariant and do not change their energy within the period of their drift around the Earth, have to drift along contours of constant B, forming a westward eccentric ring current which is nearer to the Earth on the night side compared to the dayside. In consequence the decrease of H during night time is more than during day time. This effect is shown as ∂H_{ER}.

Nakada and Mead (1965) have examined the diffusion of protons in the outer radiation belt due to violation of the third adiabatic invariant, when the kinetic energy of the solar wind increases in time short compared to the longitudinal drift period of these trapped particles. The net effect is an inward displacement and acceleration of particles. The above mechanism enhances the eccentric ring current, which in turn enhances the range and lowers the level of H for equatorial stations.

d. *Partial Ring Current*

The nature of the partial ring currents can be understood in terms of the inward drift of particles from the tail. The computations due to Roederer (1969) reveal that particles mirroring at low latitudes, on the night side, are seen to abandon the magnetosphere, before reaching the noon side. Anderson (1965) and Anderson and Ness (1966) have reported experimental evidence relating to partial trapping zones, called the cusp region. During geomagnetically disturbed days, as explained by Freeman and Maguire (1967) and Cummings *et al.* (1968) protons drift closer to the Earth than electrons, even though in the tail they have the same energy. Moreover in the process, the energy of protons is increased through betatron acceleration. Therefore the currents produced by the protons which drift towards dusk are stronger than those produced by electrons (Kavanagh *et al.*, 1968), and we can expect a minimum value of H in the late evening, as is observed.

Extending these considerations we describe in Section 4.3 of the present communication a unified interpretation of the experimentally observed (Sarabhai and Nair, 1969b) occurrence of $T_{\min}$ of H at dawn side for quiet days and dusk side for disturbed days.

2.1. Confirmation of observations from Alibag with observations from Honolulu and Guam

We have earlier examined the relationship of ΔH, the daily range of H, with $H_{\min}$ and $H_{\max}$, the minimum and maximum values respectively of H, attained each day for a low latitude station such as Alibag and at a station at the dip equator such as Trivandrum. We have concluded that outside the effects of the equatorial electroject, there is a significant negative correlation between ΔH and $H_{\min}$. This was interpreted by us as signifying that ΔH at Alibag is largely due to the reduction of the field on the night side. In terms of the nomenclature we have used in Section 1 of the present communication, the experimental evidence suggests that ∂H_I which represents an increase during day time is smaller than the decreases of H during night time due to the combined contributions of ∂H_{ER}, ∂H_{PR} and ∂H_T. Note that ∂H_{CF} gives equal contributions on the day and the night side.

In order to confirm the experimental results from the analysis of data from Alibag, we have examined data from the magnetic observatories at Honolulu and Guam

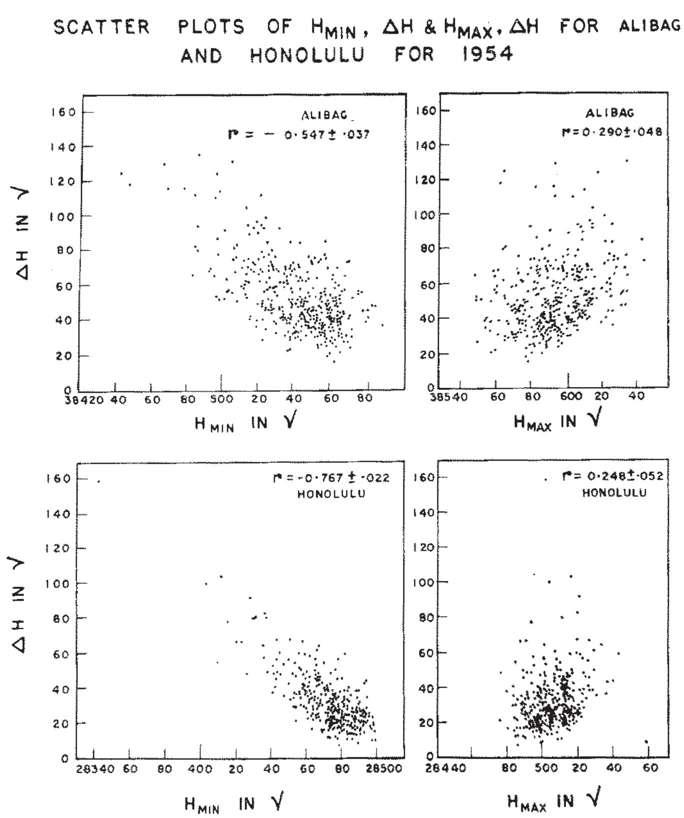

Fig. 2. Scatter diagram showing the relationship between $H_{\min}$, ΔH and $H_{\max}$, ΔH for Alibag and Honolulu for the year 1954.

which, like Alibag, are low latitude stations outside the effect of the equatorial electrojet. Figure 2 shows the scatter diagrams of ΔH against H_{min} and ΔH against H_{max} for Alibag (geomagnetic latitude 9.5° N) and for Honolulu (geomagnetic latitude 21.1° N) for the year 1954 and Figure 3 that for Alibag and for Guam (geomagnetic

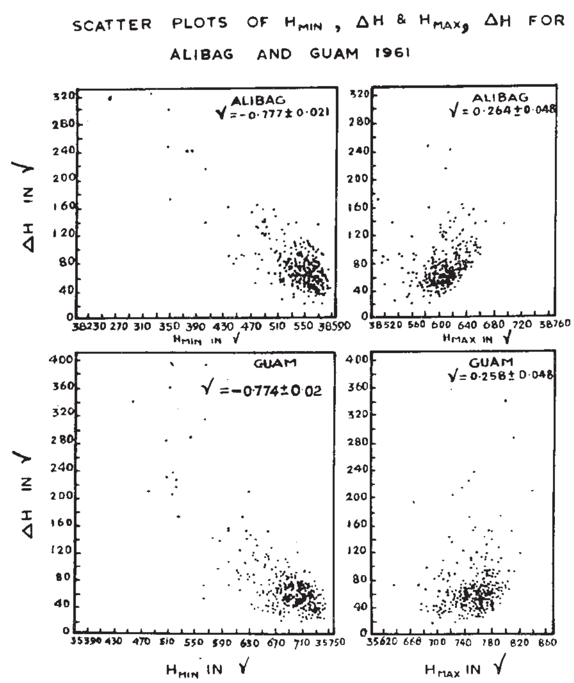

Fig. 3. Scatter diagram showing the relationship between H_{min}, ΔH and H_{max}, ΔH for Alibag and Guam for the year 1961.

latitude 4.0° N) for the year 1961. In our earlier work we noted the effect of the secular variation of H in reducing the correlation between ΔH and H_{min}. To eliminate the influence of secular changes, of long term changes due to the 11-yr variation and seasonal changes, we have derived H^*_{min} and ΔH^* by taking 27-day moving average of the daily values of H_{min} and of ΔH, and subtracting the average values from the corresponding values on the 14th day falling in the middle of the interval. The overall relationship of H^*_{min}, ΔH^* for each individual day for the years 1963 to 1967 for Honolulu is brought out in Figure 4. Here the area of each circle is proportional to the number of days having the appropriate pairs of values of H^*_{min} and ΔH^*. By all standards, the relationship between H^*_{min} and ΔH^* is remarkable at Honolulu, just as we observed earlier at Alibag (Sarabhai and Nair, 1969c).

2.2. The slowly varying component of ΔH at Alibag

In deriving ΔH^* we have subtracted $\overline{\Delta H}$, the 27 day moving average, from the value of ΔH on each day. The eleven year variation of $\overline{\Delta H}$ for Alibag is shown in Figure 5,

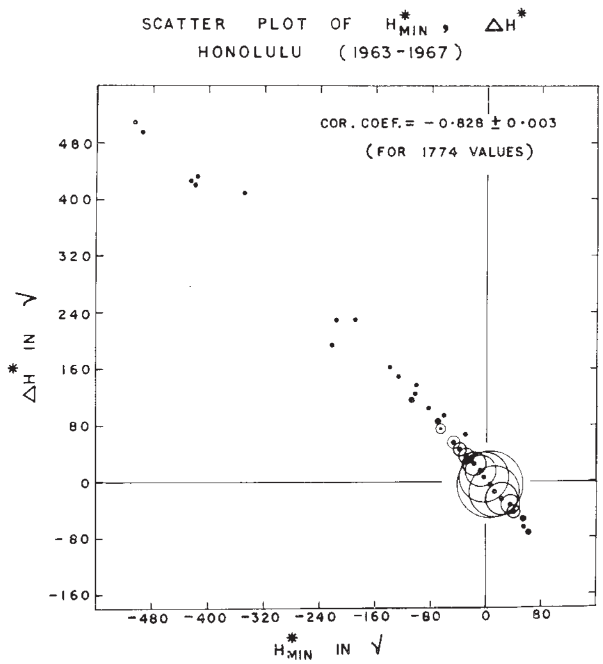

Fig. 4. The overall relationship of H^*_{min} and ΔH^* for Honolulu for the period 1963 to 1967.

where the normalised yearly histograms are plotted for individual years 1954 to 1964 and also for all the eleven years combined.

$\overline{\Delta H}$ has a minimum value of 40 γ even during years of low solar activity. On the other hand during years of low solar activity there are days when ΔH is as low as 20 γ. The earlier observation of Nair *et al.* (1970), that the ionospheric contribution is about 17 γ at Alibag is consistent with the present evidence. A noteworthy feature seen in Figure 5 is that during the years of high solar activity, not only is the mean $\overline{\Delta H}$ about double of what it is at low sunspot activity, but the spread of $\overline{\Delta H}$ during a particular year is also larger.

2.3. Variability of H at different hours related to day-to-day changes of the daily variation

In the introductory section, we have identified the ionosphere, the magnetopause and the magnetosphere as three regions from where currents of drifts can contribute to the observed daily variation of H at a low latitude station. The contribution from magnetopause currents is small compared to the contributions from the other two and in consequence we can confine attention to ionospheric and magnetospheric current systems. For a station like Trivandrum, which is at the dip equator, ΔH is controlled mainly by dynamo electrojet currents and in consequence the variability of the currents would exhibit itself through a large variance of hourly H from one day to another during day time hours only. But at a low latitude station outside the effect of the

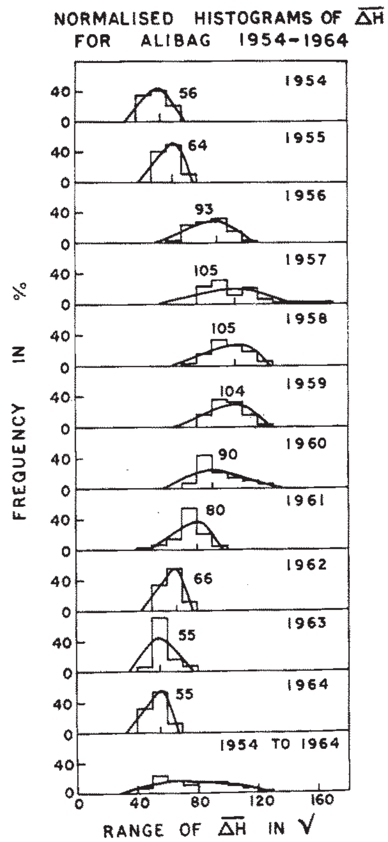

Fig. 5. The normalised yearly histograms of $\overline{\Delta H}$ for Alibag for individual years 1954 to 1964 and also for all the eleven years combined, showing the eleven year variation of $\overline{\Delta H}$ for Alibag.

equatorial electrojet the situation would be quite different if ΔH is controlled largely by the magnetospheric drifts which are effective during day as well as night hours, contributing a variance from day-to-day which is insensitive to local time.

In order to confirm the view that there are two independent processes contributing to ΔH even during quiet days, we have studied variations with local time of the variance of H_T^r and H_A^r, the rth hour values of H for Trivandrum and Alibag for internationally quiet days during high and low solar active periods. Figure 6 shows the local time dependence of the variances $(\sigma H_T^r)^2$ and $(\sigma H_A^r)^2$ for the years 1958 to 1960 and for 1962 to 1964.

We observe that (1) the variance at Alibag is insensitive to local time while at Trivandrum it is much larger during day time than at night, as expected; (2) the variance at night at each station is of the same magnitude indicating a common source for both stations during night; (3) variance due to both factors is larger during years of high solar activity than when the Sun is quiet.

3.1. Interplanetary magnetic field fluctuations and the enhancement of ΔH

Falthammar (1968) has suggested that the azimuthal electric field fluctuations in the outer magnetosphere play a very important part in populating the cusp region in a distorted magnetosphere. The azimuthal electric field fluctuations are themselves expected to be caused by the fluctuations of the transverse component of the interplanetary magnetic field. In this section we test this mechanism by studying the correlations of interplanetary magnetic field parameters with ΔH_A. We are thankful to N. F. Ness for the interplanetary magnetic field data from magnetometers on board IMP-1 and IMP-3 satellites. The data consists of hourly averages of the magnitude of the interplanetary magnetic field B, and σB_x, σB_y and σB_z, the standard deviations of B_x, B_y and B_z, of the field components along X, Y and Z directions, derived from 5.46 min values. From these, daily values have been computed for each parameter.

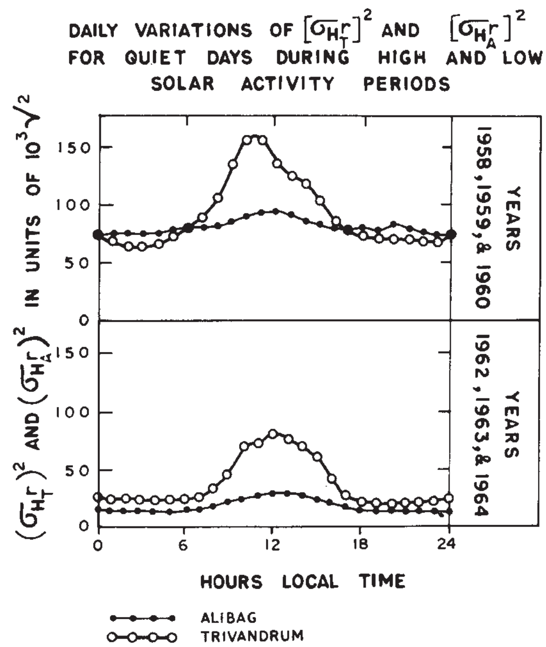

Fig. 6. Daily variations fo $(\sigma H_T{}^r)^2$ and $(\sigma H_A{}^r)^2$ for the years 1958, 1959 and 1960 combined and 1962, 1963 and 1964 combined.

During IMP-1 period (27-11-1963 to 15-2-1965) a fairly well established sector structure has been observed (Wilcox and Ness, 1964) in the interplanetary plasma, indicating the stability of the regions of activity. We have derived, by superposition of successive 27-day values, the avergae B, σB_x, σB_y and σB_z for each heliographic longitude at central meridian passage (CMP). Similarly, the values of V_s, the solar wind velocity; the kinetic energy density of the solar wind (KE density); ΔH_A, the daily range of H, at Alibag and $\sum K_p$, the daily sum of K_p have been computed. Figure 7 shows the average 27-day patterns of these parameters. Table I shows the correlation coefficients between geomagnetic and interplanetary parameters. It can be seen that σB_z and KE density are well correlated with ΔH_A. Note that V_s is well correlated with $\sum K_p$ but only poorly so with ΔH_A.

Figure 8 shows the scatter diagram of the average 27-day values of ΔH_A and σB_z during IMP-1 and IMP-3 periods combined. The correlation between ΔH_A and σB_z is

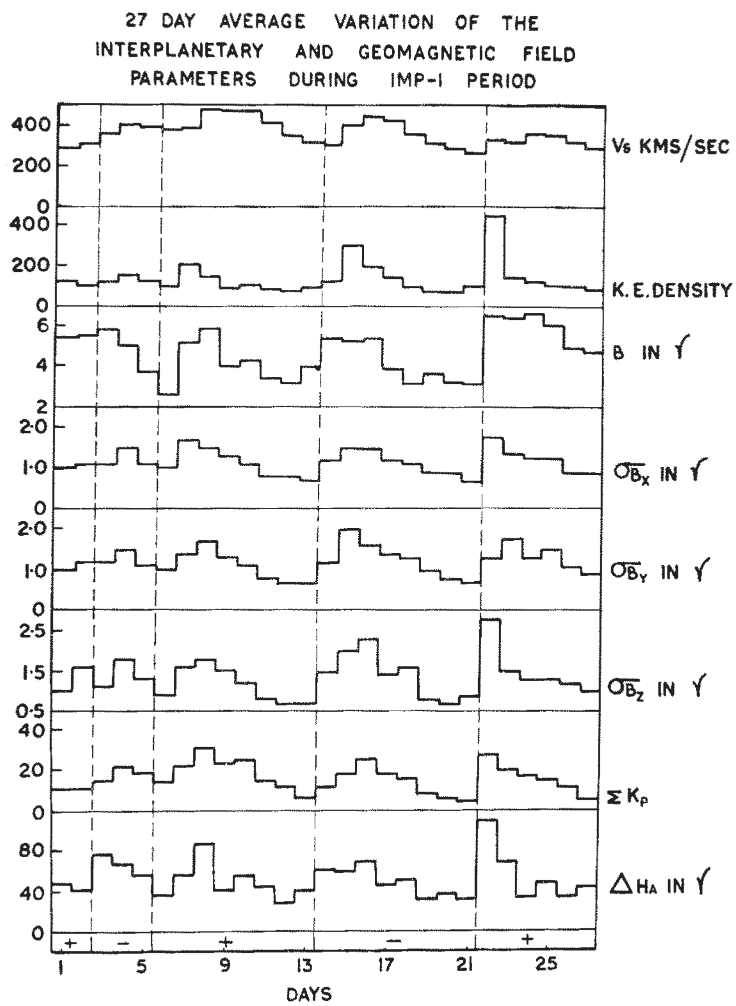

Fig. 7. The 27-day recurrence during IMP-1 period of (a) solar wind velocity (V_s) Km/sec. (b) kinetic energy density in units of 8.8×10^{-11} ergs/cm^3 (c) The modulus of the interplanetary magnetic field (B) in gammas, (d) standard deviation of the component of B along the Sun-Earth direction, (σB_x) in gammas (e) Standard deviation of the component of B perpendicular to the Sun-Earth line but in the plane of the ecliptic, (σB_y) in gammas, (f) Standard deviation of B in a direction prarallel to the Earth's magnetic axis but perpendicular to the ecliptic plane (σB_z) in gammas, (g) daily total of K_p (ΣK_p) and (h) ΔH at Alibag (ΔH_A) in gammas.

TABLE I

Correlations between interplanetary parameters and geomagnetic field parameters during IMP-1 period (for 27-day average pattern)

	ΔH_A	ΣK_p
B	0.60 ± 0.13	0.42 ± 0.16
σB_x	0.56 ± 0.13	0.67 ± 0.11
σB_y	0.57 ± 0.13	0.69 ± 0.10
σB_z	0.77 ± 0.08	0.74 ± 0.09
V_s	0.29 ± 0.18	0.79 ± 0.07
KE density	0.73 ± 0.09	0.56 ± 0.14

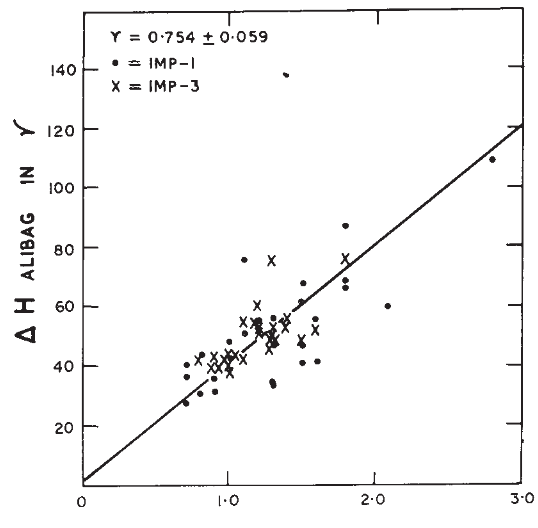

Fig. 8. The scatter diagram showing the average 27-day values of ΔH Alibag (ΔH_A) and σB_z during IMP-1 and IMP-3 periods (combined).

0.75 ± 0.06 suggesting that there is a statistically significant relation between the two. It can be seen that the relation holds good in the same way for the two different periods. 27-11-1963 to 15-2-1964 and 1-6-1965 to 26-1-1966.

In order to confirm the relation between σB_z and ΔH_A, we have also conducted the analysis for the years 1967 and 1968. The interplanetary magnetic field data from Ames magnetometer on Explorer-33 in the solar magnetospheric coordinate system used in the present work, were generously made available to us by C. P. Sonett. The primary data consists of hourly averages of B, B_x, B_y and B_z. We have computed the daily values of $\sigma B_z'$ for days when there is no break in the data, using the relation –

$$\sigma B_z' (\text{daily}) = \sqrt{\frac{1}{24} \sum_{0}^{23} (B_{zi} - \bar{B}_z)^2} . \quad (1)$$

It has been noted that during 1967 and 1968 the 27-day recurrence of interplanetary magnetic field strength was poor. Consequently, averaging data according to synodic rotation, suppresses detailed information. However, since data are available for 382 days it is meaningful to group the days into different sets according to ΔH_A values at intervals of 10 γ. Figure 9 shows the scatter plot of the mean values of ΔH_A and σB_z for different sets. The area of each circle is proportional to the number of days having appropriate pairs of values of ΔH_A and σB_z. The solid line in Figure 9 corresponds

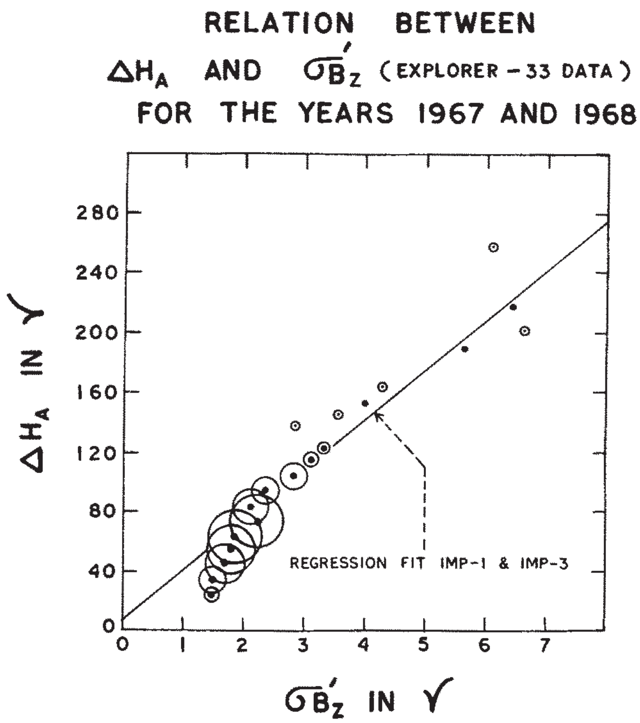

Fig. 9. The scatter plot of the mean values of ΔH_A and σB_z for groups of days selected according to ΔH_A at intervals of 10 γ. The area of each circle is proportional to the number of days having appropriate pairs of values of ΔH_A and σB_z. The solid line corresponds to the regression between ΔH_A and σB_z during IMP-1 and IMP-3 periods.

to the regression between ΔH_A and σB_z for IMP-1 and IMP-3 (Figure 8). It is remarkable that the relationship between ΔH_A and σB_z remains relatively unaltered during the solar cycle from 1963–64 (IMP-1) through 1965 (IMP-3) to 1967–68 (Explorer-33).

3.2. The relative contributions of the observed KE density of the solar wind and σB_z to ΔH_A and the relation between σB_z and KE density

We have shown earlier that during the IMP-1 period the KE density is correlated with $(\Delta H_A)^2$. Data for density and velocity of interplanetary plasma from IMP-3 and Explorer-33 are not available to the authors, but during the IMP-1 period it is possible to study the relative contributions of the KE density and σB_z of interplanetary plasma and other causes such as ionospheric currents, to ΔH_A. We have accordingly computed the multiple correlation of the average 27-day values for $(\Delta H_A)^2$, observed kinetic energy density of the solar wind and the variance of B_z for the IMP-1 period. The values of KE density used in the present analysis are those reported by Pai *et al.* (1967). While 61% of the variation in $(\Delta H_A)^2$ is attributable to changes in KE density alone and 58% only to $(\sigma B_z)^2$, 66% can be explained by referring to both KE density and $(\sigma B_z)^2$. This leaves 34% of the variance of $(\Delta H_A)^2$ attributable to other causes such as ionospheric currents. This is consistent with our estimate that on an average, a third of the observed amplitude of ΔH_A is due to ionospheric currents.

Apart from an effect due to ∂H_{CF} of about 4 γ as computed by Mead (1964), Nakada and Mead (1965) have pointed out the effect of an enhancement of solar wind pressure at the magnetopause in augmenting the symmetric as well as the asymmetric ring currents. According to Roederer and Schulz (1969) the azimuthal asymmetry of the Earth's magnetosphere enables pitch-angle scattering to violate the third adiabatic invariant of trapped particles, thereby causing radial diffusion. The radial diffusion coefficient

$$D_L \sim R_s^{-8} L^{10} \left(\frac{\mu_0}{\tau}\right) \tag{2}$$

where R_s is the stand-off distance to the magnetopause given by

$$R_s = \left[\frac{B_0^2}{4\pi n m v^2}\right]^{1/6} \tag{3}$$

B_0 is the field strength at the Earth's surface, $\frac{1}{2} n\, m\, v^2$ is the KE density of the solar wind, L is the McIlwain parameter,

$$\mu_0 = \cos \alpha_0 \tag{4}$$

where α_0 is the equatorial pitch angle at the night meridian and τ is the life time of the particle against pitch angle scattering.

From Equation (2) and (3) it can be seen that

$$D_L \sim \left[\frac{4\pi n m v^2}{B_0^2}\right]^{4/3} L^{10} \frac{\mu_0}{\tau}. \tag{5}$$

Thus

$$D_L \alpha\, (\text{KE density})^{4/3}. \tag{6}$$

The enhancement of the KE density of the solar wind thus enriches the inner shells of the magnetosphere and thereby promotes partial, eccentric and symmetric ring currents. In consequence there should be a depression of H as well as an enhancement of ΔH through lowering of $H_{\min}$.

Thus the experimental results of the present study linking ΔH_A with KE density as well as with σB_z are qualitatively consistent with recent theories on the dynamics of the magnetosphere in relation to the electromagnetic conditions of interplanetary plasma.

Figure 10 shows the scatter plot of the 27-day values of the KE density of the observed solar wind with $(\sigma B_z)^2$ during the IMP-1 period. The correlation between KE

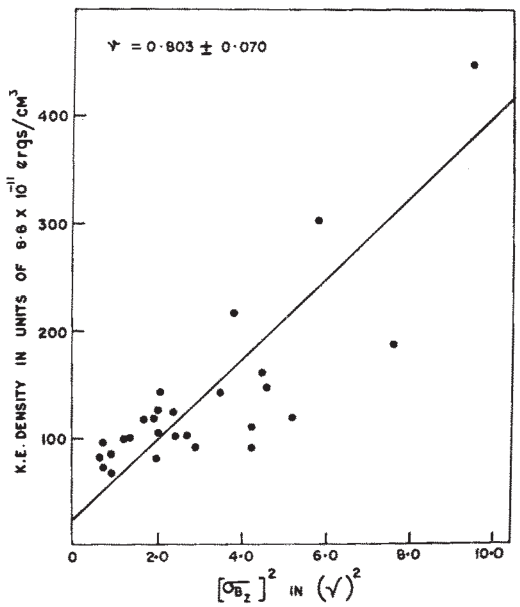

Fig. 10. The scatter diagram of the average 27-day variation of the kinetic energy density of the solar wind and $(\sigma B_z)^2$ the variance of the north-south component of B in the solarmagnetospheric coordinate system during IMP-1 period.

density and $(\sigma B_z)^2$ is 0.80 ± 0.07. This is not surprising since an increase in KE density due to enhancement of solar wind velocity must simultaneously result in a compression of the plasma in interplanetary space and a change in the interplanetary magnetic field. In this connection Sarabhai (1963) and Dessler and Fejer (1963) have earlier examined the situation when a fast solar wind overtakes a slow solar wind.

2. Discussions

2.1. We have proposed in Section 1, a conceptual representation of the effects of various processes contributing to the daily variation of H at a low latitude station. It is suggested that these processes are all operative on each day, though their relative importance varies depending on the solar terrestrial conditions.

Bhargava and Yacob (1970) using data from Alibag for a period of 37 yr have computed the variation in the mean daily horizontal intensity (after removing the effects of secular variation) and daily range, as a function of magnetic activity. They have shown that for very quiet days ($A_p \sim 0$) to moderately disturbed days, the horizontal intensity decreases linearly, but the daily range increases with increase in the level of geomagnetic disturbances. They have pointed out that this is inconsistent with the dynamo theory and that a depression of the field during night time is necessary to account for the above, as suggested by Sarabhai and Nair (1969b).

2.2. In one of our earlier communications (Nair *et al.*, 1970) we have estimated that on an average day the ionospheric contribution to ΔH_A represents a day time enhancement of 17 γ in a total range of 50 ν. Moreover, in Section 3.2 of the present communication we have given experimental evidence to show that the combined contributions from KE density and $(\sigma B_z)^2$ amount to $\frac{2}{3}$ of ΔH_A. Recently Olson (1970) has reported that the calculations done with models of the magnetopause, asymmetric ring, and neutral sheet current systems show that they all produce variations in the Earth's surface magnetic field similar to the observed *Sq* patterns and that, after giving allowance for the induced Earth currents, the combined fields of these three non-ionospheric current systems account for more than 10 γ to the *Sq* variations. He has concluded that "because of the large observed fluctuations in solar wind parameters (which determine the strengths of these currents), it is suggested that magnetospheric currents may make a significant contribution on the day-to-day variability in S_q." Olson has ignored the effect of the partial ring current, the existence of which is now well accepted (Fejer, 1961; Kavanagh *et al.*, 1968; Chen, 1970; Schield *et al.*, 1969; Cummings, 1966; and Freeman and Maguire, 1967). The relative effects of an eccentric ring current should be more during quiet days than what Olson has quoted. We therefore do not regard Olson's estimate as contradicting our suggestion.

2.3. The experimentally observed shift of $T_{\min}$ of H, from dawn hours during quiet days to dusk hours during disturbed days is a feature of great interest. It can be understood as follows:

The drift paths of charged particles, in the equatorial plane of the Earth's dipole field with convective electric field and corotational electric field superimposed have been computed by Kavanagh *et al.* (1968), Chen (1970) and Wolf (1970).

The drift velocity of charged particles, V_d would be the same as a pure $\mathbf{E}\times\mathbf{B}$ drift in an equivalent electric field, E_{eq} where

$$E_{eq} = -\nabla\Phi \tag{7}$$

$$\Phi = -\frac{1}{C}\,\Omega M_E\,\frac{\sin^2\theta}{R} - E_0 R\sin\varphi + \frac{\mu M_E}{qR^3}. \tag{8}$$

In Equation 8, the first term $(1/C\Omega M_E \sin^2\theta/R) = K/R$ represents the potential due to corotation of the plasma with the geomagnetic field, the second term $(E_0 R\sin\varphi)$ is the potential due to a convective electric field and the third term $\mu M_E/qR^3$ is the potential due to the geomagnetic field gradient. M_E and Ω are the magnetic moment and angular velocity of the Earth, θ and R are the colatitude and radial distance defining the position of the particle, φ is the azimuthal angle measured counter-clockwise from the solar direction, μ and q are the magnetic moment and charge of the particle and

$$V_d = C\frac{\mathbf{B} \times \nabla\phi}{B^2} \tag{9}$$

$$= \Omega\left(R - \frac{R^3}{K} E_0 \sin\varphi - \frac{3\mu M_E}{qKR}\right)\hat{e}_\varphi + \left(\frac{\Omega R^3}{K} E_0 \cos\varphi\right)\hat{e}_R . \tag{10}$$

The first term on the right hand side of Equation 10 represents the azimuthal component, $V_d(\varphi)$ and the second term represents the radial component, $V_d(R)$ of V_d. At 0000 hr local time, $\varphi = 180°$ and

$$V_d(\varphi) = \Omega\left[R - \frac{3\mu M_E}{qKR}\right]. \tag{11}$$

For electrons q is $-v_e$, but for protons it is $+v_e$. Thus the azimuthal drift for electrons is eastward irrespective of their energy, while for protons the azimuthal drift is eastward when

$$\mu < \frac{|q|\ KR^2}{3M_E}$$

and westward when

$$\mu > \frac{|q|\ KR^2}{3M_E}.$$

At a radial distance R from the centre of the Earth, protons would have a critical energy E_{pc}, above which the charge and energy dependent magnetic gradient drift predominates over the charge and energy independent electric field drift.

$$E_{(PC)} = \mu_{(PC)} \cdot B_{(R)} = \frac{\Omega\,|q|\ R^2 B(R)}{3C} \tag{12}$$

where $B(R)$ is the magnetic field strength at R, for $\theta = 90°$ in Equation (8), that is at the equator. Figure 11 shows the variation of E_{pc} with R.

The westward ring currents due to the drifts of protons and electrons in such a situation have different characteristics depending on the value of $E_{pc}(R)$. Moreover, Kavanagh *et al.* (1968) have shown that the forbidden region for the drift of protons is nearest to the Earth at 1800 hr, while for electrons it is nearest at 0600 hr local time.

During geomagnetically quiet days, the energy of protons injected from the tail of the magnetosphere must be less than E_{pc} and in consequence protons as well as electrons drift eastward. The azimuthal component of the drift speed for electrons is more than that for protons, as a result of which relative motion of electrons with respect to protons is set up constituting a westward ring current, which is nearer to the earth on the morning side. The magnetic effect at the ground due to this asymmetric ring current is a decrease of the field during morning hours.

During geomagnetically disturbed days, the energy of protons injected from the tail of the magnetosphere must be more than E_{pc}. Electrons drift eastward and protons

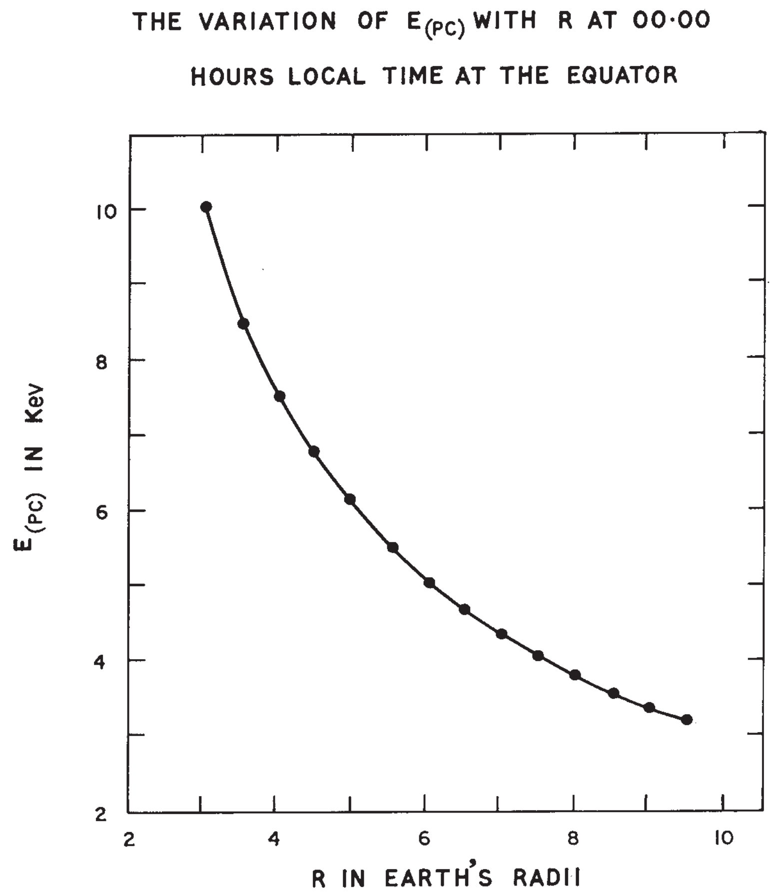

Fig. 11. Calculated values of E_{pc} with radial distance R at 00 00 hr local time at the equator.

drift westward constituting a strong westward ring current which is nearer to the earth on the dusk side. This is so because, for protons and electrons of the same energy in the tail, protons can drift closer to the earth than electrons (Kavanagh *et al.*, 1968). The geomagnetic field depression at the ground due to this asymmetric ring current is more on the dusk side compared to the dawn side.

2.4. Our observations have indicated, as described in Section 3.1, that σB_z and KE density are well correlated with ΔH_A, while V_s and σB_z are correlated with $\sum K_p$. However the correlation of V_s with ΔH_A is poor. The relationship of ΔH_A with σB_z and KE density has been explained by us, in Sections 1, 3.1 and 3.2, as due to the time dependent azimuthal electric field in the magnetosphere and the azimuthal asymmetry of the outer magnetosphere.

The relationship of V_s and σB_z with $\sum K_p$ can be explained in the light of the interaction of the solar wind with the magnetosphere. In Dungey's unshielded magnetospheric model, is is assumed that the interplanetary magnetic field has a southward component. In the presence of the interplanetary magnetic field the solar wind is associated with an electric field.

$$\mathbf{E} = -\frac{1}{C}(\mathbf{V} \times \mathbf{B}) \tag{13}$$

when observed in a frame fixed to the magnetosphere. This electric field is "thought to enter the magnetosphere" (Obayashi and Nishida, 1968). The fluctuation of the east-west component of the electric field in the magnetosphere, σE_{ym} would be high when V_s or σB_z or both are high. σE_{ym} promotes convection of plasma from the tail of the magnetosphere. Through the above process the auroral electrojet strength becomes enhanced, which should result in the enhancement of $\sum K_p$. This is so because K_p is based on magnetic records from 12 selected observatories lying between 47.7° and 62.5° geomagnetic latitudes.

Acknowledgements

We are grateful to Dr C. P. Sonett for making available to us the unpublished interplanetary magnetic field data from satellite Explorer-33. Thanks are to Dr B. N. Bhargava, Director of Alibag and Colaba Observatories for supplying unpublished magnetic data from Alibag; to Dr N. F. Ness and to the Director World Data Centre-A (Rockets and Satellites) GSFC, Greenbelt for supplying interplanetary magnetic field data from satellites IMP-1 and IMP-3; and to Dr H. S. Bridge for supplying plasma data from IMP-1. We are deeply grateful to Professor E. N. Parker for stimulating discussions. Thanks are due to Drs C.-G. Fälthammar, R. Pratap and A. C. Das for useful comments. Financial support from the Department of Atomic Energy is also gratefully acknowledged.

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Music & Noise

VIKRAM A. SARABHAI

Physical Research Laboratory, Ahmedabad 9

THE subject of this symposium falls squarely in the field of my own research, and the research which my collaborators and I have been doing for the last 20-25 years, partly at the Physical Research Laboratory, Ahmedabad, and partly at the Massachusetts Institute of Technology, Cambridge, USA. I want to take the opportunity in this inaugural talk to convey to you what appears to me to be the most interesting aspects of the phenomena that we are going to discuss for the next four days.

I started my career in research by studying a narrow field in cosmic radiation. It was the experimental detection of the polarization of mesons. One of the problems that I encountered in those days was to get reproducible results. From day to day I went on seeing certain changes occurring, and these were a great nuisance. Counting rates were very low, and we started taking readings every half an hour. Of course, what we were seeing was not an experimental error. There was a pronounced semidiurnal wave in the meson intensity which we could see in our observations. I immediately rushed to my meteorologist friend Dr Basu. I saw the pressure charts and there was a clear anti-correlation between the semidiurnal wave of pressure and the cosmic ray intensity.

The study led me to the problems of the oscillations of the atmosphere. Problems of variations of the geomagnetic field, solar activity and the interplanetary magnetic field opened up. This symposium covers the broad spectrum of all these related phenomena and theory.

Those of us who have been studying geophysical parameters are deeply struck by the fluctuations in these parameters that take place all the time. We, therefore, ask ourselves the question: What are these fluctuations due to? The accuracy of the best magnetic observations is extremely good, being of the order of 1-2 γ. But still we observe fluctuations of 5-10 γ. If these are not due to observational errors, then what is the noise in these experiments? In fact, this is not noise, but signatures of very important phenomena occurring at various levels, not only in the atmosphere, ionosphere and magnetosphere, but also in the interplanetary space, connected with solar activity. So the central theme of all those working in this field is to understand the meaning of these signatures.

Until relatively recently we had all inferences from a network of earth-bound stations. However, the advent of space research has assisted our tasks greatly. We have been able to make measurements in three-dimensional space, and it is this which has enriched our horizon. We are now able to understand these signatures, and interpret them in a definite way. The consequences are rather great, because we can almost throw away the spacecraft and do a great deal of interpretation of what happens in interplanetary space and the magnetosphere from the data collected from the surface of the earth.

In my talk, I shall discuss two different aspects. First, how to interpret the signatures that we see in cosmic rays and magnetic field fluctuations; and second, what they add up to.

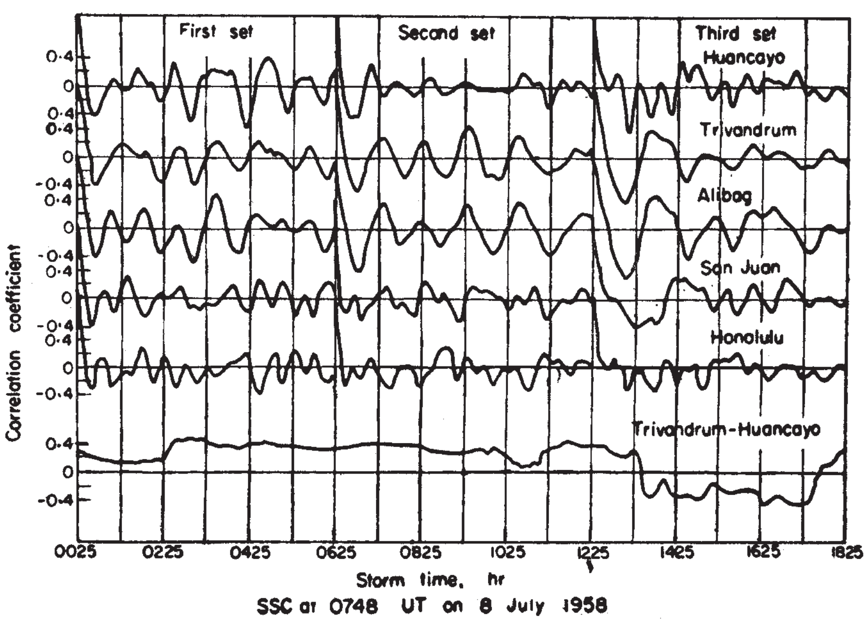

Fig. 1 — Autocorrelation coefficients of sets of 72 five-minute values at five stations and the cross-correlation of successive 72 pairs of Trivandrum and Huancayo five-minute values [Storm of 8 July 1958] (ref. 1)

It is well known that during geomagnetic storms there is a very significant up and down movement in the magnetometer traces. Fig. 1 shows the analysis of the cross-correlation coefficients of 72 successive five-minute values of H, the horizontal intensity of the earth's magnetic field, at Huancayo, Trivandrum, Alibag, San Juan and Honolulu. This analysis enables us to test the simultaneity and worldwide nature of long-period fluctuations[1]. From an analysis of the horizontal intensity of the earth's magnetic field at Huancayo, during 36 storms in 1958, it has been shown in Fig. 2(a) that there are periodic fluctuations with a most probable period of 40-50 min. During quiet periods, fluctuations are either absent or have irregular periods. The periodic fluctuations occur during sudden commencement, as well as during gradual commencement storms. On the assumption that the periodic fluctuations are due to large-scale inhomogeneities in the solar plasma impinging on the magnetosphere, we calculated the average scale length of the inhomogeneities in the plasma to be 0·02 astronomical units (a.u.).

Meanwhile, we conducted[2] cosmic ray studies at Ahmedabad using east- and west-pointing telescopes, inclined 45° to the zenith. Fig. 3 shows on a polar histogram that during 1957-58 there were many days when the daily variation at Ahmedabad was consistent with an anisotropy of primary radiation.

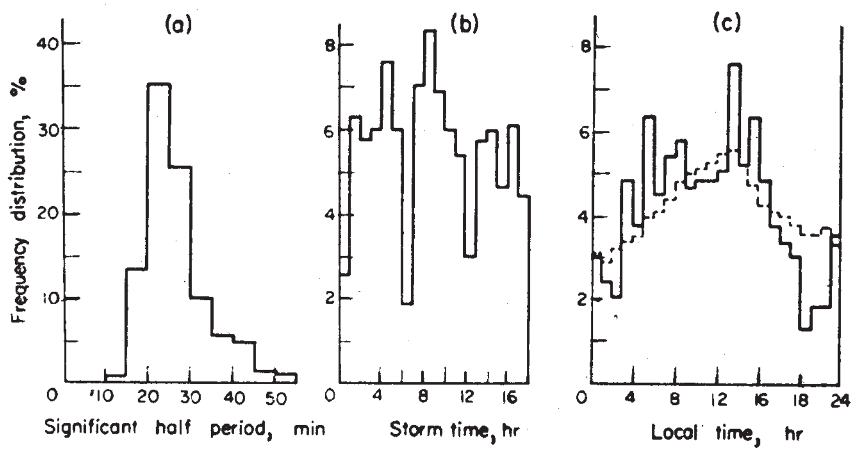

Fig. 2 — (a) Frequency distribution of the period of the significant half intervals in the autocorrelation plots for 36 storms at Huancayo in 1958; (b) frequency distribution of the time of occurrence of the significant half periods in storm time; and (c) continuous curve shows the frequency distribution of the time of occurrence of the significant half periods in Huancayo local time, and dashed curve shows the frequency distribution of the number of hours for which data are used for autocorrelation analysis (ref. 1)

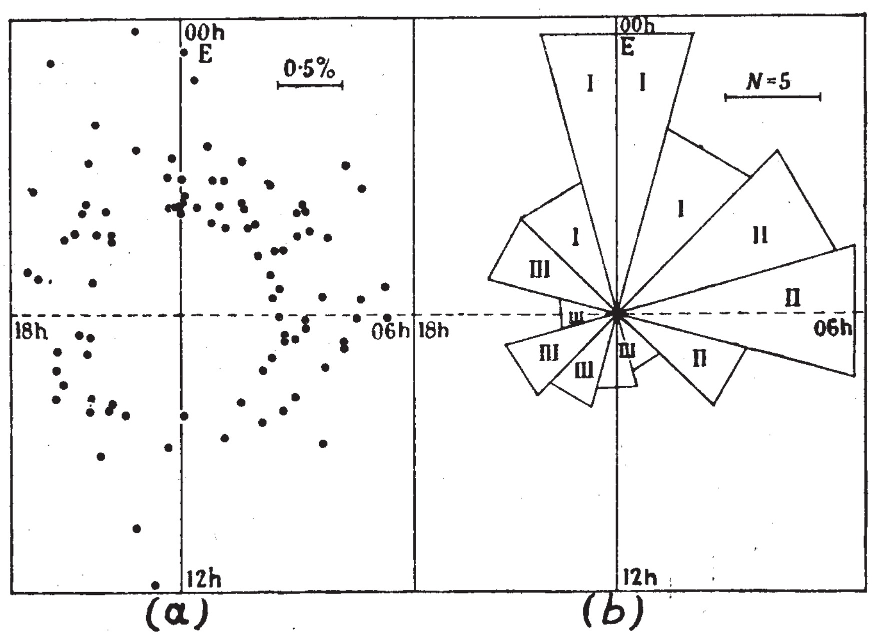

Fig. 3 — (a) Distribution of diurnal component of daily variation for west relative to that for east, assumed to be along 00·00 h direction, on individual days when the amplitudes of variation for east and west are simultaneously significant at the 2σ level; and (b) harmonic dial representation of the histogram of occurrence of the diurnal maximum for west relative to that for east, assumed to be along the 00·00 h direction, on individual days when both east and west have significant amplitudes (ref. 2)

However, there were a significant number of days (group I) when the daily variation appeared to have been caused by a local source of non-meteorological origin in the direction of the sun.

One of the handicaps that we had in the above experiment was the low counting rate. But, in the last 3-4 years, Kargathra[3] has been working at the Physical Research Laboratory, Ahmedabad, with large-area scintillation telescopes, which are measuring cosmic ray intensity along east, west, north, south and vertical directions. The set-up consists of eight scintillation detectors, each having an area of 4 sq m. The geometry of half the section is shown in Fig. 4.

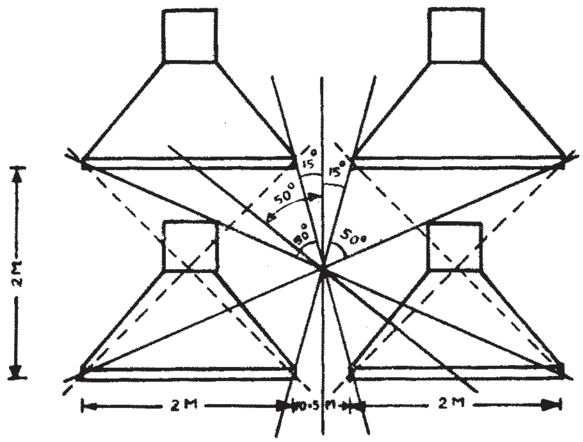

Fig. 4 — Schematic diagram of four scintillation counters forming two vertical and two inclined telescopes (ref. 3)

In Fig. 5 the asymptotic cones of acceptance for each telescope are shown. Except for the north, all the other telescopes scan the ecliptic plane. The north telescope registers cosmic ray intensity away from the plane of the ecliptic. Due to the high mean energy of response and the direction of viewing away from the plane of the ecliptic, the north telescope effectively scans high heliolatitudes. Thus, with this unit, we should be able to study the electromagnetic state of the interplanetary space, and the manner in which it changes, even at higher heliolatitudes. There are a few other observations like comet tails, which give us information about what is happening in the solar system away from the plane of the ecliptic.

These experiments also provide an important method of interpreting the earlier results of Rao and Sarabhai[2] where we have pointed out evidence for a local source of modulation like an electric field in the magnetosphere.

Thus we see that cosmic ray studies could give us a very good understanding of interplanetary and magnetospheric changes. Simultaneously with all this work, my collaborator Dhanju and I set up a cosmic ray experiment at Chacaltaya in Bolivia. This is a very high altitude observatory and a great thing about it was that it had a very big meson detecting system put up by MIT, USA, and a group of Japanese observatories. With a very high counting rate of about a million per minute, we could study short-period variations of periodicity of a

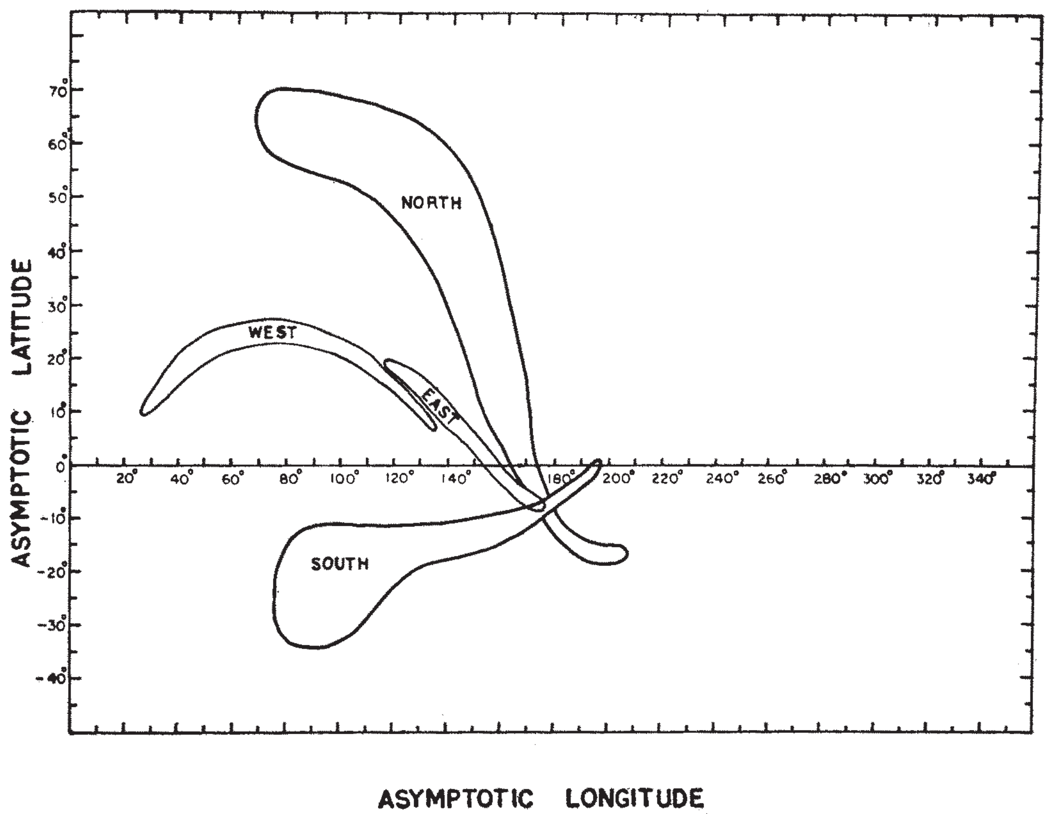

Fig. 5 — Asymptotic cones of acceptance for east, west, north and south telescopes at Ahmedabad

few minutes with great accuracy. One of the results we obtained was that in the dynamical range of 1-30 cycles per hour we get peaks around about 18 cycles and 25-26 cycles, as shown in Fig. 6 (ref. 4). These peaks which are seen in fluctuations of cosmic ray intensity are at about the same frequency as the peaks in the dynamical spectral range as observed in the magnetosphere and interplanetary space with satellites. There is, therefore, a complete correspondence of the type of spectral changes in interplanetary space, magnetosphere and cosmic rays.

Recently, Sarabhai and Nair[5-7] have studied in detail the daily variation of the horizontal component of the geomagnetic field for low latitude stations, away from the effects of the equatorial electrojet. Fig. 7 shows a typical magnetogram at Alibag (geomagnetic latitude, 9·5°N). It can be seen that H attains its maximum value around 1100 hrs local time, and minimum value between 1800 and 0600 hrs local time. Let us denote ΔH as the daily range of H defined by $(H_{max}-H_{min})$ and let T_{max} and T_{min} denote the times at which maxima and minima of H occur during 24 hr. Fig. 8 shows the normalized histograms of T_{max} and T_{min} separately for (a) all days combined, (b) quiet days, (c) days with sudden commencement storms, (d) days with gradual commencement storms, (e) disturbed days, and (f) internationally disturbed days, but during which sudden commencement and

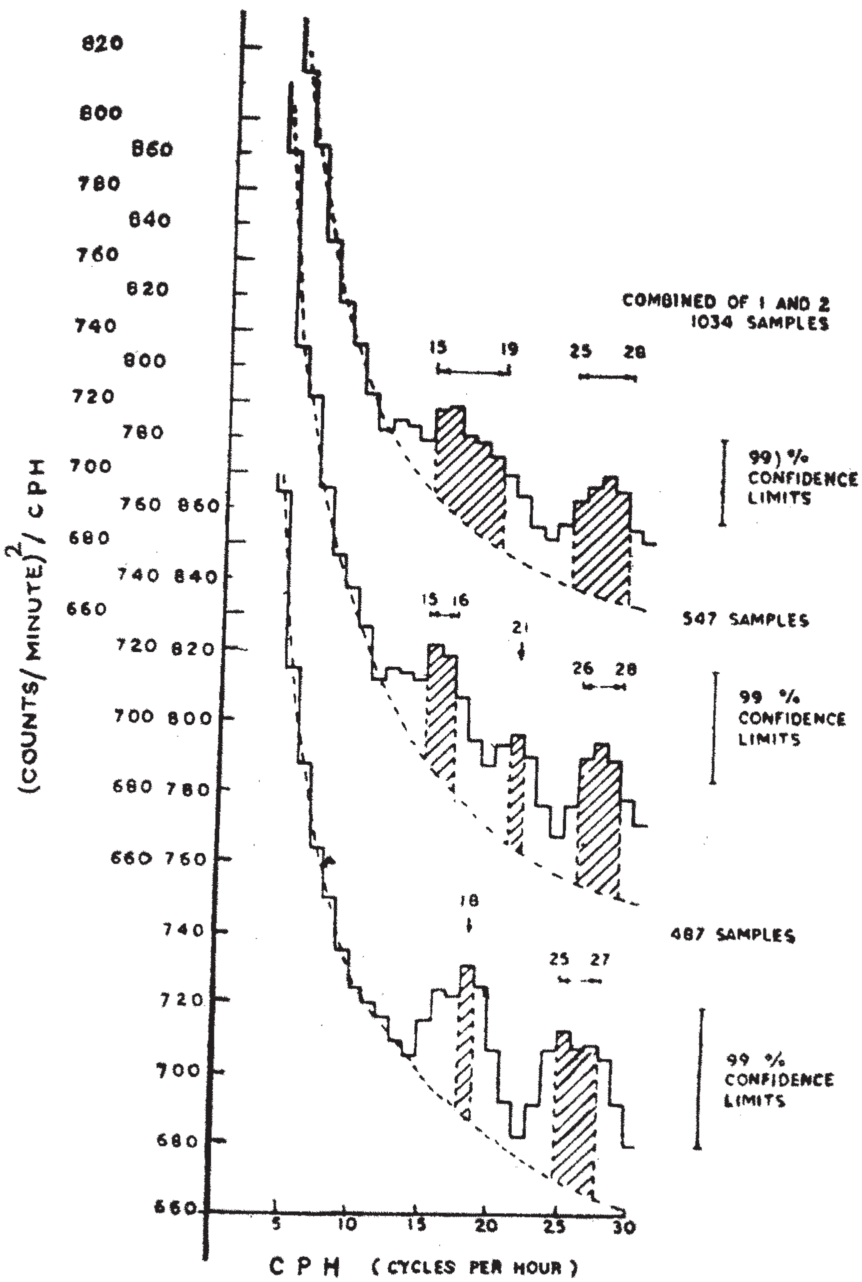

Fig. 6 — Superposed cosmic ray spectral density estimates of 487 (21 November 1965-15 March 1966), 547 (16 March 1966-15 June 1966), and combined 1034 (21 November 1965-15 June 1966) 3 hr samples in the frequency range 1-30 cph (ref. 4)

gradual commencement storms did not occur. T_{max} histograms are relatively unaffected by the degree of geomagnetic disturbance. However, T_{min} occurs at 0500 hrs significantly more often on geomagnetically quiet days than on all other groups of days. The almost complete absence of T_{min} between 0200 and 0600 hrs on disturbed days is also noteworthy.

We have been interested in verifying whether ΔH represents an increase of H on the dayside over a base level of H_{min} or alternatively it is a decrease of H on the nightside from a base level of H_{max}. In the former case, we should have a positive correlation between ΔH and H_{max}, with poor correlation between ΔH and H_{min}. On the other hand, in the latter case, we should get a negative correlation between ΔH and H_{min} and a poor correlation between ΔH and H_{max}. The classical view was that ΔH is due to an enhancement of H during day-time, due to ionospheric E-region currents. If the classical picture is right, then the maximum value of H should increase as ΔH increases. We have earlier examined the relationship of ΔH with H_{min} and H_{max} for a low latitude station, such as Alibag and a station at the dip equator, such as Trivandrum. We have concluded that outside the effects of the equatorial electrojet, there is a significant negative correlation between ΔH and H_{min}. This was interpreted by us as signifying that ΔH at Alibag is largely due to the reduction of the field on the nightside.

In order to confirm the experimental results from an analysis of the data from Alibag, we have examined data from the magnetic observatories at Honolulu and Guam, which like Alibag are low latitude stations outside the effect of the equatorial electrojet. In our earlier work we have noted the effect of the secular variation of H in reducing the correlation between ΔH and H_{min}. To eliminate the influence of secular changes, of long-term changes due to the 11-year variation, and seasonal changes, we have derived H^*_{min} and ΔH^* by taking 27-day moving average of the daily values of H_{min} and of ΔH, and subtracting the average values from the corresponding values on the 14th day falling in the middle of the interval. The overall relationship of H^*_{min}, ΔH^* for each individual day for the years 1963-67 for Honolulu is brought out in Fig. 9. Here the area of each circle is proportional to the

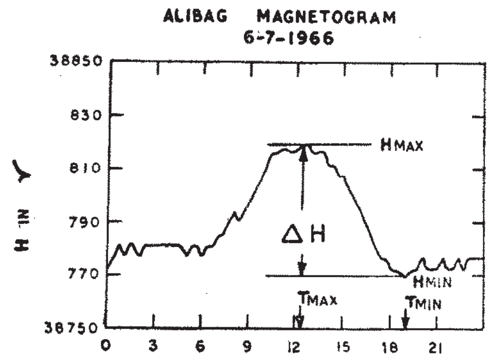

Fig. 7 — A typical magnetogram at Alibag (ref. 5)

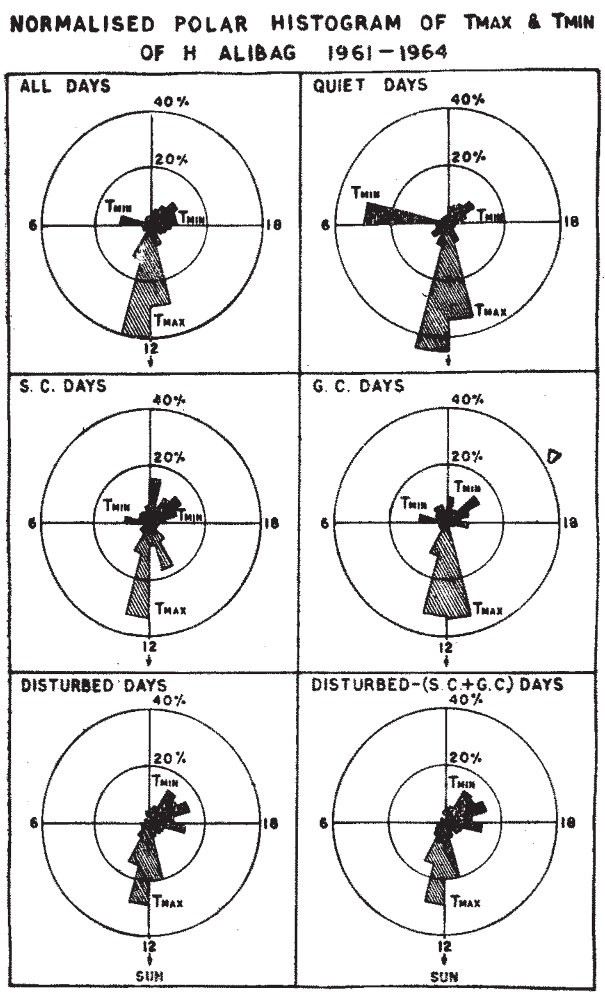

Fig. 8 — Polar histograms of local time of maximum and minimum of H at Alibag (ref. 5)

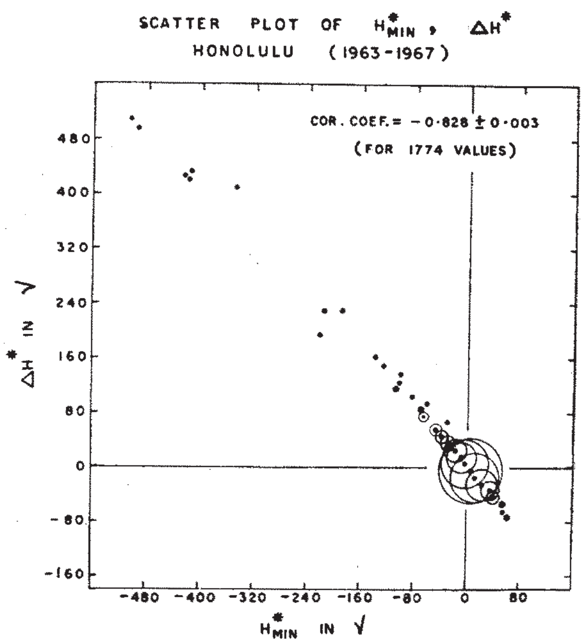

Fig. 9 — Overall relationship of H^*_{min} and ΔH^* (ref. 7)

number of days having the appropriate pairs of values of H^*_{min} and ΔH^*. By all standards, the relationship between H^*_{min} and ΔH^* is remarkable at Honolulu, just as we observed earlier at Alibag.

Bhargava and Yacob[8], using data from Alibag for a period of 37 years (1932-69), have computed the variation in the mean daily horizontal intensity $\bar{H}$ (after removing the effects of secular variation) and mean daily range ΔH as functions of magnetic activity. This is shown in Fig. 10. It can be seen that for very quiet days ($A_P \sim 0$) to moderately disturbed days, the horizontal intensity decreases linearly, but the daily range increases with increase in the level of geomagnetic disturbances. They have pointed out that this is inconsistent with the dynamo theory and that a depression of the field during night-time is necessary to account for the above, as suggested by Sarabhai and Nair[5,6].

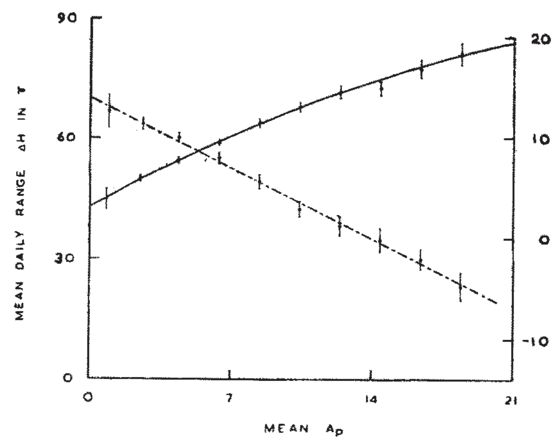

Fig. 10 — Variation in mean horizontal intensity and daily range with A_P (ref. 8)

Then we ask ourselves the question: " If indeed the phenomenon is so different from the classical picture, then what is really happening? " The existence of electrojet currents has been confirmed by observations made with rockets. If there is something occurring at night, which produces the night decrease in H, then this must be in the magnetosphere, because E-region currents are very weak during night. Since the magnetospheric currents would be located at distances exceeding about 30,000 km above the surface of the earth, their effect must be almost identical at Alibag (A) and at Trivandrum (T), 1100 km south of Alibag, but situated at the dip equator (neglecting differences in the induced field arising from local ground conditions). On the other hand, the well-known enhancement of ΔH at the dip equator is caused by the influence of the equatorial electrojet. In consequence, $(\Delta H_T - \Delta H_A)$ must be related to purely ionospheric currents.

Fig. 11 shows the normalized histograms of $(\Delta H_T - \Delta H_A)$ for different ranges of ΔH_A for the years 1962, 1963 and 1964 and for all the three years combined[9]. It is observed that on a day-to-day basis, ΔH_A is more or less independent of the purely ionospheric contribution, namely $(\Delta H_T - \Delta H_A)$. Thus ΔH_A does not track the changes in the ionospheric currents. Fig. 12 shows the local time

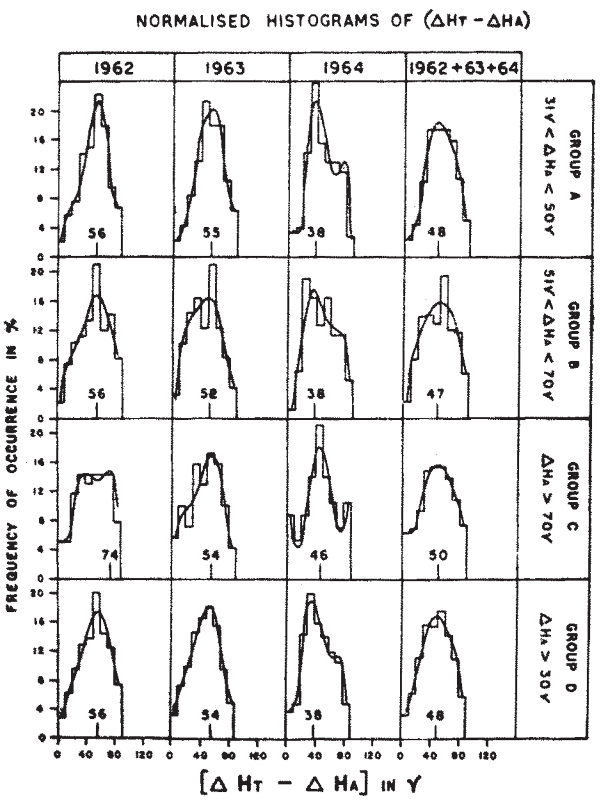

Fig. 11 — Histograms of $(\Delta H_T - \Delta H_A)$ for different ranges of ΔH_A (ref. 9)

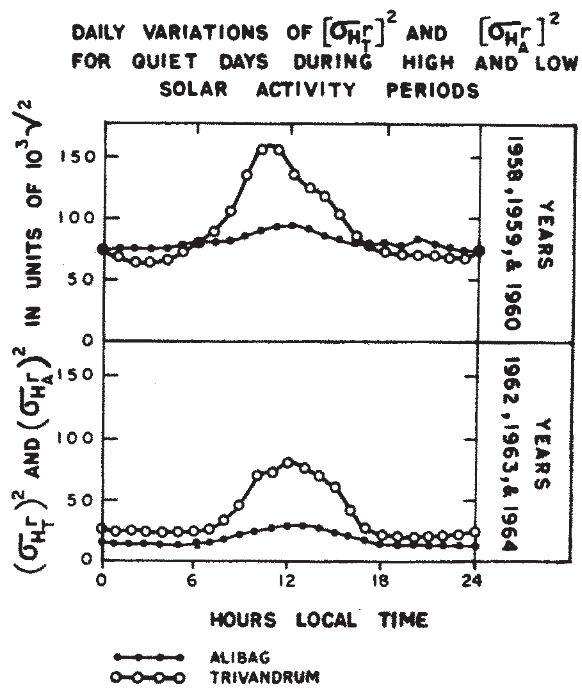

Fig. 12 — Daily variations of the variance of H at Trivandrum and Alibag (ref. 7)

dependence of the variance of H for Trivandrum and Alibag for the years 1958-60 and 1962-64. Here we find that during night-time the variances for hourly values of H at Alibag and Trivandrum are the same. But during day-time, the additional dynamo effects are much larger at Trivandrum than at Alibag. So that, here we are observing two superimposed effects, one of which is the magnetospheric effect. Fig. 13 shows a linear relationship that exists between the drift speeds of the ionospheric inhomogeneities in the E- and F-regions measured by spaced aerial technique at Thumba during midday hours and $(\Delta H_T - \Delta H_A)$ (ref. 9). Figs. 14 and 15 show the geomagnetic field strength measured by ATS-1 spacecraft in equatorial synchronous orbit at 6·6 R_e for five quiet days of

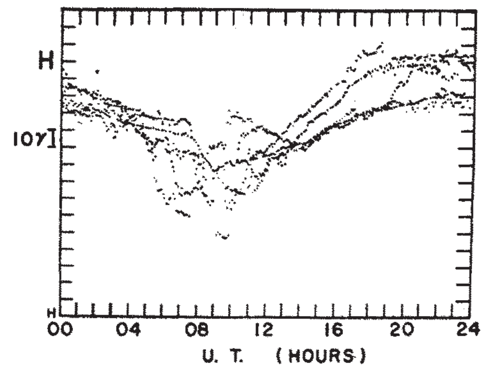

Fig. 15 — Daily variation of H for disturbed days at 6·6 R_e (ref. 10)

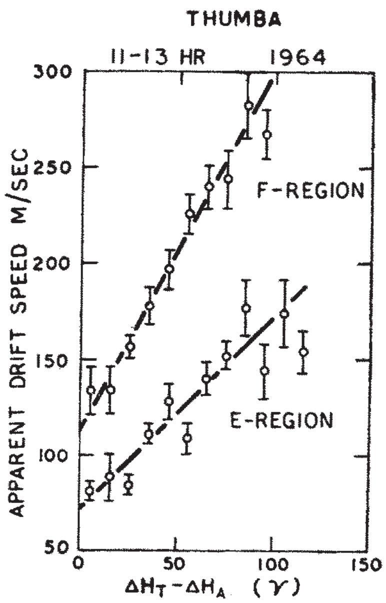

Fig. 13 — Westward drift speed during midday hours for different values of $(\Delta H_T - \Delta H_A)$ (ref. 9)

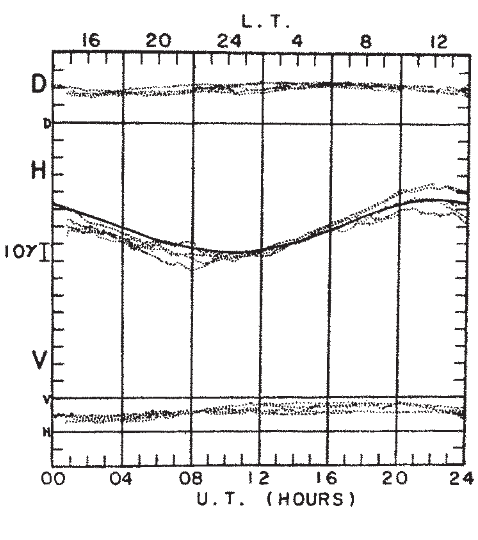

Fig. 14 — Daily variation of H for quiet days at 6·6 R_e (ref. 10)

January 1967, and for five disturbed days of December 1966 and January 1967, as reported by Cummings and Barfield[10]. Their results show that on the nightside, even at 6·6 R_e on geomagnetically quiet days, the magnetic field in the anti-solar direction is less than the field in the subsolar direction by about 35 γ. Thus the reduction of field on the nightside is the predominant factor in the daily variation of H at low latitudes.

So, if ΔH_A is mainly due to magnetospheric current systems, then let us see how it is related to various interplanetary parameters. Data in Table 1 show the correlations between the geomagnetic parameters (ΔH_A and ΣK_P) with the observed interplanetary parameters. Here B is the total interplanetary magnetic field strength; σB_x, σB_y and σB_z, the standard deviations of the field components along x, y and z directions; and V_s, the observed solar wind velocity. It can be seen that, ΔH_A is well related to the kinetic energy density of the interplanetary plasma, and the variance of the component of the interplanetary magnetic field perpendicular to the plane of the ecliptic.

The effects of the currents in the magnetosphere and the ionosphere, and their progressive contributions to the unperturbed geomagnetic field at a low latitude station, such as Alibag, can be conceptually and diagrammatically depicted as in Fig. 16. It has been suggested by us that ΔH, the daily variation of H, is caused by (1) the dynamo current, mainly in the ionospheric E-region, (2) the surface currents at the magnetopause, and

TABLE 1 — CORRELATIONS BETWEEN INTERPLANETARY PARAMETERS AND GEOMAGNETIC FIELD PARAMETERS DURING IMP-1 PERIOD (FOR 27-DAY AVERAGE PATTERN)

	ΔH_A	ΣK_P
B	0·60±0·13	0·42±0·16
σB_x	0·56±0·13	0·67±0·11
σB_y	0·57±0·13	0·69±0·10
σB_z	0·77±0·08	0·74±0·09
V_s	0·29±0·18	0·79±0·07
KE density	0·73±0·09	0·56±0·14

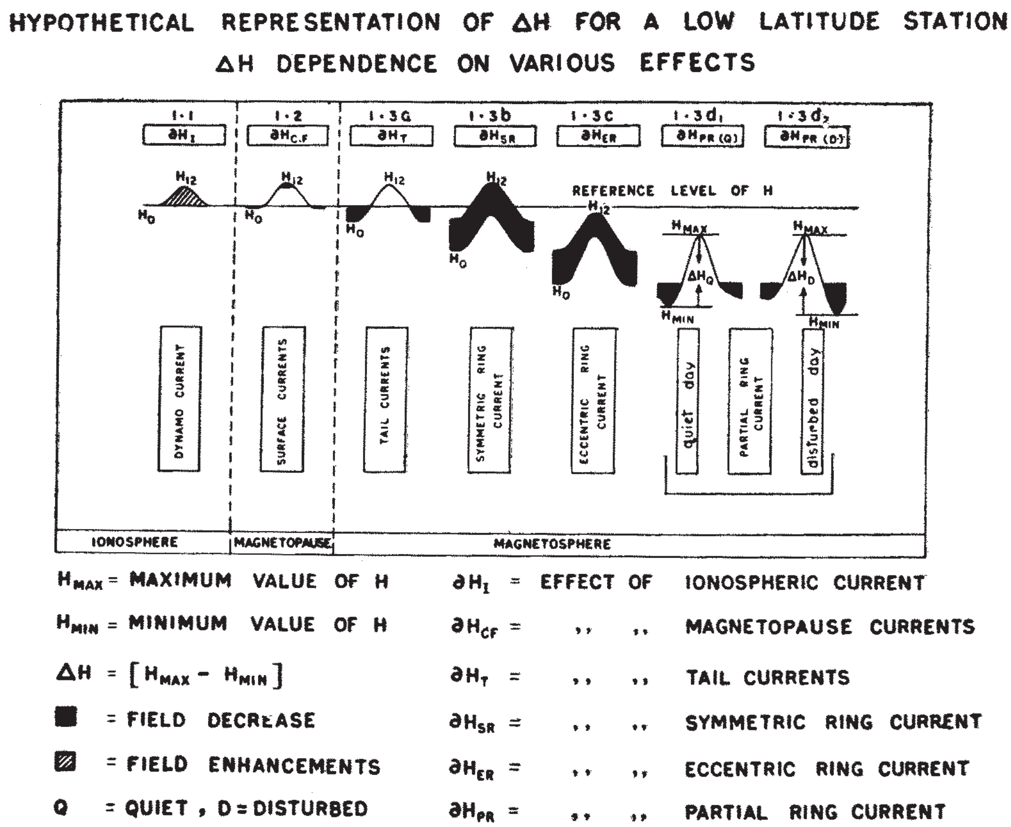

Fig. 16 — Dependence of ΔH at a low latitude station on various effects in the ionosphere, magnetopause and magnetosphere (ref. 7)

(3) the tail currents, the eccentric ring current, and the partial ring current in the magnetosphere.

In conclusion, I would say that, if only we have to listen to the music in the noise, our work becomes very rewarding indeed.

Summary

Fluctuations of the geomagnetic field intensity of the order of 5-10 γ exist all the time. It has been established that these fluctuations are not caused by instrumentation, but are signatures of very important phenomena occurring at various levels not only in the atmosphere, ionosphere and magnetosphere, but also in the interplanetary space connected with the solar activity. The research work done in this field by the author and his collaborators over the last 25 years to understand the significance of these geomagnetic fluctuations is described.

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DR. VIKRAM A SARABHAI, SCIENTIST - EDUCATIONIST

By

Prof. K.R. Ramanathan
Physical Research Laboratory
Ahmedabad - 9

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1. The country and the world have suffered a grievous loss by the sudden death at Kovalam near Trivandrum in the early morning hours of 30 December 1971 of Professor Vikram A. Sarabhai, Director, Physical Research Laboratory, Ahmedabad, Chairman, Atomic Energy Commission and Indian Space Research Organization and Secretary, Department of Atomic Energy, Government of India.

Dr. Vikram A. Sarabhai was born in 1919 and had his school and undergraduate education in Ahmedabad. His father, the late Shri Ambalal Sarabhai was an outstanding industrialist and his mother Sreemathi Saraladevi has been an equally outstanding social worker and organizer with Gandhian ideals. Dr. Vikram married the famous dancer and creative artist, Sreemathi Mrinalini Sarabhai in 1942. They have a son Kartikeya and a daughter Mallika.

2. From his early years, Vikram showed keen interest in science and scientific devices. For his collegiate education, he was sent to St. John's College, Cambridge in 1937. He took his B.A. degree with Physics and Mathematics in 1940 and

began to work on problems of Nuclear Physics, but the World War started and he came back to India and joined the Indian Institute of Science to continue his postgraduate studies under Sir C.V. Raman. He chose Cosmic Rays as the subject for his post-graduate research.

He personally built up the necessary equipment for his experimental work and made measurements and studies at Bangalore, Poona and Apharwat in Kashmir Himalayas. In 1945, at the end of the World War he returned to Cambridge and took the Ph.D. degree of the Cambridge University with a thesis on "Cosmic Ray Investigations in tropical latitudes". He was awarded the degree in 1947.

3. Dr. Sarabhai's aptitudes and talents and the intellectual and cultural atmospheres of Cambridge, Bangalore and Ahmedabad produced in him a keen desire to create institutions in which new science and advancing technology could be nurtured and developed and used for improving the living conditions of large populations. This began to simmer in his mind even when he was doing his post-graduate work in Bangalore. In 1942-43, he was planning to start a Physical Research Laboratory at Ahmedabad. In 1945, the Sarabhai family established the "Karmakshetra Educational Foundation (KEF)" for the purposes, among others, of

starting, carrying on, and helping to carry on advanced scientific research, and educational activities of all types.

Shortly after Dr. Sarabhai's return to India in 1947, he set about the work of starting the PRL. He enlisted the cooperation of Shri Kasturbhai Lalbhai, Shri G.V. Mavlankar and other members of the Ahmedabad Education Society and of Dr. Shanti Swarup Bhatnagar, and in November 1947, an agreement was reached between the AES and KEF to start a Physical Research Laboratory at Ahmedabad for the study of Atmospheric Physics and Cosmic Rays. I had agreed to join Dr. Vikram immediately after my retirement from the India Met. Department in February 1948. The Laboratory started with a couple of Research Assistants, a small office, a small workshop and a few Research Scholars. We were able to get support for our work from the CSIR and the Ministry of Education and from the Department of Atomic Energy. We were temporarily housed in a few rooms in the M.G. Science Institute of the Ahmedabad Education Society.

The over-all programme of the laboratory as chalked out by us in 1948 was to make an integrated study of the different radiations which reach the earth from the sun, stars and space and their geophysical consequences. The necessity was felt to provide for studies in theoretical Physics, radio physics and electronics and also for a separate properly planned research laboratory. With the sympathetic assistance of the Ministry of Natural Resources and Scientific Research and the Atomic Energy Commission, and land and funds found by AES and KEF it was possible to go ahead with the construction of the laboratory, and the foundation stone of the new laboratory building was laid by Sir C.V. Raman in February 1952. The Laboratory was opened by Shri Jawaharlal Nehru in April 1954.

Am important additional aim of the Laboratory has been to serve as a post-graduate study centre for physics in Western India and to train research students in experimental and theoretical physics. The Laboratory does not take any fees from research scholars and most of them receive scholarships or fellowships.

4. Dr. Sarabhai's range of interests has always been wide and he had an integrating mind with an eye towards the future. Between 1947 and 1955, besides the Physical Research Laboratory, Dr. Sarabhai was mainly responsible for the creation of two other Institutions in Ahmedabad which have proved to be of all-India importance. These are the ATIRA, the Ahmedabad Textile Industry's Research Association, an

organisation also started in 1947 with support from the Industry and the Council of Scientific and Industrial Research, and the Indian Institute of Management which was started in 1955. Of both these Institutions, he was the first Hon. Director who nurtured them in their early formative years until competent full-time Directors could be appointed.

5. A new responsibility came to Dr. Sarabhai when, in 1961, he succeeded the late Sir K.S. Krishnan as a member of the Atomic Energy Commission. By that time, the use of earth satellites for exploring particles and fields in the earth's exosphere, magnetosphere, and in interplanetary space had become well established. With his active interest in Cosmic Rays and the Upper Atmosphere, and with the awareness that India was an important area in which space exploration by rockets and satellites would be of great long-term value to science, and in which bright young Indian scientists with fresh minds could develop new techniques and evolve new ideas, Dr. Sarabhai and Dr. Bhabha decided that this was a field to whose cultivation the Department of Atomic Energy should give full support. The expansion of the PRL, the organization of INCOSPAR (Indian National Committee for Space Research), the establishment of the Rocket Launching Station at Thumba very close to

the magnetic equator, followed by its recognition by UN as and International Equatorial Rocket Launching Station, and the growth of the Space Science and Technology Centre at Thumba were the outcome of the creative efforts of Dr. Sarabhai fully supported by Dr. Bhabha, Pandit Jawaharlal Nehru and Sreemathi Indira Gandhi.

Dr. Sarabhai visualised from the very beginning the potential value of space science and space technology for national development and for promotion of International peace.

6. In 1966, after the tragic death of Dr. Homi Bhabha, Dr. Sarabhai was asked to take up the Chairmanship of the Atomic Energy Commission and his work increased manyfold. He threw himself whole-heartedly into the work with tireless energy and brought the activities of the Department of Atomic Energy and Space Research Organisation (ISRO) into even closer contact. This has resulted in the development of SSTC (Space Science and Technology Centre) at Thumba, of the Rocket and potential satellite launching Range at Sriharikota on the Pulicat Lake north of Madras, of the Experimental Satellite Communication Station at Ahmedabad and the construction of the Overseas Satellite

Communication Centre at Arvi in Maharashtra.

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DR. VIKRAM A SARABHAI, SCIENTIST - EDUCATIONIST

By

Prof. K.R. Ramanathan
Physical Research Laboratory
Ahmedabad - 9

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1. The country and the world have suffered a grievous loss by the sudden death at Kovalam near Trivandrum in the early morning hours of 30 December 1971 of Professor Vikram A. Sarabhai, Director, Physical Research Laboratory, Ahmedabad, Chairman, Atomic Energy Commission and Indian Space Research Organization and Secretary, Department of Atomic Energy, Government of India.

Dr. Vikram A. Sarabhai was born in 1919 and had his school and undergraduate education in Ahmedabad. His father, the late Shri Ambalal Sarabhai was an outstanding industrialist and his mother Sreemathi Saraladevi has been an equally outstanding social worker and organizer with Gandhian ideals. Dr. Vikram married the famous dancer and creative artist, Sreemathi Mrinalini Sarabhai in 1942. They have a son Kartikeya and a daughter Mallika.

2. From his early years, Vikram showed keen interest in science and scientific devices. For his collegiate education, he was sent to St. John's College, Cambridge in 1937. He took his B.A. degree with Physics and Mathematics in 1940 and

began to work on problems of Nuclear Physics, but the World War started and he came back to India and joined the Indian Institute of Science to continue his postgraduate studies under Sir C.V. Raman. He chose Cosmic Rays as the subject for his post-graduate research.

He personally built up the necessary equipment for his experimental work and made measurements and studies at Bangalore, Poona and Apharwat in Kashmir Himalayas. In 1945, at the end of the World War he returned to Cambridge and took the Ph.D. degree of the Cambridge University with a thesis on "Cosmic Ray Investigations in tropical latitudes". He was awarded the degree in 1947.

3. Dr. Sarabhai's aptitudes and talents and the intellectual and cultural atmospheres of Cambridge, Bangalore and Ahmedabad produced in him a keen desire to create institutions in which new science and advancing technology could be nurtured and developed and used for improving the living conditions of large populations. This began to simmer in his mind even when he was doing his post-graduate work in Bangalore. In 1942-43, he was planning to start a Physical Research Laboratory at Ahmedabad. In 1945, the Sarabhai family established the "Karmakshetra Educational Foundation (KEF)" for the purposes, among others, of

starting, carrying on, and helping to carry on advanced scientific research, and educational activities of all types.

Shortly after Dr. Sarabhai's return to India in 1947, he set about the work of starting the PRL. He enlisted the cooperation of Shri Kasturbhai Lalbhai, Shri G.V. Mavlankar and other members of the Ahmedabad Education Society and of Dr. Shanti Swarup Bhatnagar, and in November 1947, an agreement was reached between the AES and KEF to start a Physical Research Laboratory at Ahmedabad for the study of Atmospheric Physics and Cosmic Rays. I had agreed to join Dr. Vikram immediately after my retirement from the India Met. Department in February 1948. The Laboratory started with a couple of Research Assistants, a small office, a small workshop and a few Research Scholars. We were able to get support for our work from the CSIR and the Ministry of Education and from the Department of Atomic Energy. We were temporarily housed in a few rooms in the M.G. Science Institute of the Ahmedabad Education Society.

The over-all programme of the laboratory as chalked out by us in 1948 was to make an integrated study of the different radiations which reach the earth from the sun, stars and space and their geophysical consequences. The necessity was felt to provide for studies in theoretical Physics, radio physics and electronics and also for a separate properly planned research laboratory. With the sympathetic assistance of the Ministry of Natural Resources and Scientific Research and the Atomic Energy Commission, and land and funds found by AES and KEF it was possible to go ahead with the construction of the laboratory, and the foundation stone of the new laboratory building was laid by Sir C.V. Raman in February 1952. The Laboratory was opened by Shri Jawaharlal Nehru in April 1954.

Am important additional aim of the Laboratory has been to serve as a post-graduate study centre for physics in Western India and to train research students in experimental and theoretical physics. The Laboratory does not take any fees from research scholars and most of them receive scholarships or fellowships.

4. Dr. Sarabhai's range of interests has always been wide and he had an integrating mind with an eye towards the future. Between 1947 and 1955, besides the Physical Research Laboratory, Dr. Sarabhai was mainly responsible for the creation of two other Institutions in Ahmedabad which have proved to be of all-India importance. These are the ATIRA, the Ahmedabad Textile Industry's Research Association, an

organisatiom also started in 1947 with support from the Industry and the Council of Scientific and Industrial Research, and the Indian Institute of Management which was started in 1955. Of both these Institutions, he was the first Hon. Director who nurtured them in their early formative years until competent full-time Directors could be appointed.

5. A new responsibility came to Dr. Sarabhai when, in 1961, he succeeded the late Sir K.S. Krishnan as a member of the Atomic Energy Commission. By that time, the use of earth satellites for exploring particles and fields in the earth's exosphere, magnetosphere, and in interplanetary space had become well established. With his active interest in Cosmic Rays and the Upper Atmosphere, and with the awareness that India was an important area in which space exploration by rockets and satellites would be of great long-term value to science, and in which bright young Indian scientists with fresh minds could develop new techniques and evolve new ideas, Dr. Sarabhai and Dr. Bhabha decided that this was a field to whose cultivation the Department of Atomic Energy should give full support. The expansion of the PRL, the organization of INCOSPAR (Indian National Committee for Space Research), the establishment of the Rocket Launching Station at Thumba very close to

the magnetic equator, followed by its recognition by UN as and International Equatorial Rocket Launching Station, and the growth of the Space Science and Technology Centre at Thumba were the outcome of the creative efforts of Dr. Sarabhai fully supported by Dr. Bhabha, Pandit Jawaharlal Nehru and Sreemathi Indira Gandhi.

Dr. Sarabhai visualised from the very beginning the potential value of space science and space technology for national development and for promotion of International peace.

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GOVERNMENT OF INDIA
ATOMIC ENERGY COMMISSION

NUCLEAR POWER IN AGRICULTURAL DEVELC

by

Vikram Sarabhai
Chairman, Atomic Energy Commission

and

K. T. Thomas
Desalination and Effluent Engineering Division

BHABHA ATOMIC RESEARCH CENTRE
BOMBAY, INDIA
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NUCLEAR POWER IN AGRICULTURAL DEVELOPMENT*

by

Vikram Sarabhai and K. T. Thomas

Energy is an essential ingredient for increasing productivity in agriculture as in industry. The green revolution in India, to sustain, needs energy in bulk at economic prices. With the advent of large power reactors and consequent reduction in costs, nuclear energy appears to promise this.

The major inputs to agriculture which have a bearing on power consumption are water and fertiliser. How nuclear energy can be a catalyst to provide these inputs has been discussed before in the context of nuclear powered agro-industrial complexes.

The Agro-Industrial Complex has been described earlier on a number of occasions. Detailed investigations of nuclear powered agro-industrial complexes have been carried out for two locations in India. The studies are described in a separate paper. Both complexes generate low-cost nuclear energy in areas where energy from coal-based plants would be more expensive. The energy is used for producing fertilisers and supplying water for irrigation, in such a manner that the required high load factor for the economic operation of a large nuclear power unit is provided. Inexpensive energy in both places makes possible the

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* Text of a speech delivered on 30-11-1971 by Dr. Sarabhai at the Seminar on "Use of Isotopes and Radiation in Agriculture and Animal Husbandary Research" held at the Indian Agricultural Research Institute, New Delhi.

production of phosphorus using technology which substitute imported sulphur. The energy is used in an arid location near the sea for producing desalted water and in the Gangetic Plain for lift irrigation.

In the Gangetic Plain, the return on investment for the industrial portion of the project including the power plant is expected to be 18%. For the agricultural portion, if efficient agricultural practices are followed, we can derive a return of 99% with bullock farming and about 119% with mechanised farming. Additonal food production of 7.8 million tonnes of cereals and 1.66 million tonnes of pulses will result. This can meet the food requirement of about 30 million people. The programme would create all the year round direct employment on farms for about 1.4 million persons, and increase the gross national product by about 1,300 million dollars. Based even on conservative estimates of improvement in agricultural practices and yields, the additional food grain production will be 4.0 million tonnes and the return on agricultural portion will still be more than 50 per cent.

It has been pointed out in studies conducted elsewhere in the world how nuclear energy can be used to recover millions of cubic metres of fresh water from the sea and for use in irrigation. In so far as India is concerned – this may be true in the case of some other countries also – energy can be used to tap water from another source also. Geohydrologists believe that the vast Indo-Gangetic Plain which is perhaps the most extensive single piece of fertile land in the world has itself underneath what is virtually an underground fresh water lake waiting to be pumped up.

Whereas energy, whatever its source, had always a crucial bearing on industry, there is a special relationship between nuclear energy and the fertiliser industry. Low cost energy available in bulk has in itself elements which can revolutionise the whole pattern of fertiliser production.

Now if we take for instance, the production of ammonia, which is the form in which nitrogen is applied to the soil, the hydrocarbons are the base feed for its production today. The pre-eminent position of natural gas and naphtha in this field is due to the low cost of production in clean and efficient plants. But if you consider the water electrolysis plant if at all it is only a shade better as far as efficiency and cleanliness are concerned. What prevents electrolysis from competing is only its cost. It is here that nuclear energy provides the answer. The link between nuclear energy and the largest single plant nutrient in use in India should be clear from this.

Phosphorus as a plant nutrient is next in importance only to nitrogen. In fact, ultimately it is expected that phosphorus consumption in agriculture will equal nitrogen. Almost all the phosphorus for agriculture comes via the sulphuric acid process. The use of electrothermal phosphorus for this purpose is negligible. Again it is the cost and availability of energy that mainly stands in the way. One can envisage the increasing adoption of the electric furnace if the nuclear reactor can provide the answer.

Though it is certain that nuclear energy can be the basic foundation on which the superstructure of abundance in agriculture can be built, there is a great deal of ground work to be done before this link can be formalised.

If we take the case of desalination the development that is required before it can establish itself in agriculture, is two-fold. First the cost of desalination itself has to be reduced considerably before it can be applied for irrigation. In conjunction with reduction in cost of desalted water there is the question of plant utilisation factor and thrift in the use of water. The first one calls for year round operation of the plant which means year round agriculture. Year round agriculture in other words means multiple cropping, and more the number of crops, more the production, and more the profits. The number of crops, among other things, is inversely proportional to the durations of crops. Multiple cropping adopting high yield short duration crops is imperative if economy using desalted water is to be achieved.

Cost analysis under Indian conditions for the dual purpose plants based on MSF (Multistage Flesh Distillation) and LTVE-MSF (Multistage Flash Distillation in combination with Long Tube Vertical Evaporators) desalination processes has been carried out. Our studies show that in large scale application (1000 - 1200 MWe power and water 100 to 500 MIGD) nuclear desalination would cost in the range of Rs. 2/- to Rs. 3/- per 1000 gallons of fresh water produced. Cost analysis of the two desalination processes indicates that investment requirements as well as production costs are lower in the case of LTVE-MSF process.

The cost estimates were based on advanced technology using double fluted tubes and on the assumption that it would be possible to operate at a concentration factor of 2.5 and a top brine temperature of $200^{o}F$.

In order to assess the validity of the various assumptions and to collect necessary design data and acquire operating experience for large scale seawater distillation plants, a research and development programme has been undertaken.

These studies will have the ultimate objective of developing indigenous materials and technical know-how to the extent of designing and commissioning desalting plants and they include the following:

i) Experimental Studies

These studies are concerned with alkaline and sulphate scale prevention, corrosion behaviour and sutability of various materials of construction such as copper, cupro-nickel, aluminium, titanium etc., selection of suitable construction and coating materials for evaporator shells and deaeration for the removal of dissolved oxygen, carbondioxide etc.

Regarding the chemical treatment studies for scale suppression, stress is being laid on HCl treatment for alkaline scale prevention. The major advantage of this method is, in so far as India is concerned, HCl is a byproduct with limited use from the caustic chlorine plant. Moreover, use of HCl would avoid import of sulphur necessary if H_2SO_4 is used.

ii) Pilot Plant Studies

a) MSF distillation

In this area the objective is limited to the setting up of multi-stage flash evaporator unit with about 5 stages. Setting up of this facility would help in obtaining operating experience in addition to design data for MSF feed preheater, for the LTVE-MSF combination distillation plants.

b) Long Tube Vertical Evaporation

A five-effect multi-tube pilot plant of capacity nearly 20,000 gallons/day is under construction at present. The principal aim of this set up is to study the performance of tubes with enhanced surfaces. In addition to this, studies would be carried out to find suitable brine-distribution-devices for thin film flow inside the tubes. Effect of non-condensables would be studied in detail, to assess the performance of heat transfer surfaces in case concrete shells are used for the evaporators where there are possibilities of inleakage of air inside the shells.

iii) Prototype Plants

The data obtained from the pilot plant studies on MSF and LTVE processes would be used for design and operation of a 1 million imperial gallons per day desalination plant based on LTVE-MSF combined desalination process. This size plant can provide sufficient information on large scale use of tubes with enhanced surface and selection of various equipment like pumps ejectors entrainment separators etc. for large size plants and more importantly on the problems of process dynamics of such plants.

In order to reduce the investment costs for the desalination plant, it would be necessary to obtain maximum number of components from local suppliers. Most of the construction materials such as copper, cupro-nickel, stainless steel etc. will have to be imported which would mean considerable expenditure of foreign exchange. Stress is being given on the development of such alloys which can be produced from materials available within the country.

Development work for the production of tubes with enhanced heat transfer surfaces is under way. Double fluted tubes required for the use in the five-effect LTVE pilot plant are being fabricated at Trombay and can be manufactured on a commercial scale at the Nuclear Fuel Complex at Hyderabad.

While evaluating the economics of high cost desalinated water for agriculture in arid/semi-arid regions as is the case in Kutch-Saurashtra one of the regions which was selected for study under the Nuclear-Powered Agro-Industrial Complex – a number of assumptions were made regarding the water requirements of various crops, intensity of cropping and yields of different crops. The land proposed to be covered under the Kutch-Saurashtra project is not under cultivation at present. It has to be evaluated in more detail whether the land can be economically brough under cultivation using desalinated water before any large scale agricultural activities are started in the area.

In order to check the validity of the various assumptions concerning agriculture a suitably sized pilot farm is proposed to be set up in the project area. The size of the farm has been fixed at 50 acres. About 25 acres of the farm can be irrigated from local underground water sources. Rest of the water will be made by desalinated or demineralised seawater. Sprinkler irrigation will be provided to study the economics of water management.

Two possible sites for the farm one in Jamnagar District and another in Kutch District of Gujarat are under consideration. The crops to be tried would include mainly crops which are of high cash value and are in great demand.

The data thus obtained would be evaluated to see whether desalinated water expected to be produced from future dual purpose (power and water) nuclear plants will have an economic impact on agriculture.

The main objectives of starting the experimental farm are to evaluate the

(1) suitability and economics of methods of field irrigation for crops proposed in the Agro-Industrial Complex,

(2) profitability of different cropping pattern, suggested earlier and experimentation with new ones,

(3) determination of water requirements of crops, so as to be useful in planning irrigation in proposed Agro-Industrial Complex,

(4) methods of cultivation of crops and determination of extent of mechanisation in relation to size of farm holding to be recommended for the proposed Agro-Industrial Complex.

As mentioned earlier, the underground water resources of the Gangetic Plain are abundant but at present they are not being exploited either economically or in a planned manner, essentially because the nature and precise quantity of the resources have not been properly established. The investigation that need to be carried out are as below:-

(1) Determination of aquifer conditions, e.g. thickness, depth, interconnections and water content in the aquifer. Existing strata charts and spring level observations could be used for this purpose.

(2) Study of seasonal changes affecting the movement of ground water. Determination of the age of ground water.

(3) Study of the sources of recharging the aquifers (i) due to rain, (ii) charge and discharge through streams, canals and rivers; and (iii) possible future change from projects in IV and V Plans.

The major sources which contribute to the availability of ground water in the Gangetic Plain are direct rain water, percolating sub-surface flow from hill catchments and seepage from canals. Tritium being an ideal radioactive tracer involving the least health hazard is proposed to be used to estimate the individual recharges quantitatively. So far three series of tritium injections have been carried out in this area in the last two years with periodical soil sampling and analysis. Detailed analysis and further injections are to continue for the next three or four years. It is hoped this will help greatly in the scientific exploitation of the underground water resources.

It has been realised that nitrogenous fertiliser production using water electrolysis cells to be economical has to be based on advanced electrolytic cells which use catalysed porous electrodes. These types of cells are still under development and are expected to operate at current densities as high as 800 - 1600 Amps/sq. ft. and at pressure of 300 to 400 psi. Development of such cells are expected to reduce considerably the capital investment as well as cost of production of hydrogen in large plants.

One disadvantage of electrolysis is that if urea is to be the end-product, then, unlike the fossil fuel based processes, no by-product carbon-dioxide being available, the need for manufacture of the gas will increase the cost of production. This can be obviated if, instead of urea, ammonium nitrate or anhydrous ammonia is the end-product. As far as India is concerned this would call for promotional activities to develop safe handling practices for ammonium nitrate and transportation and application techniques in the case of anhydrous ammonia.

Precise advnatages of the electric furnance for phosphatic fertiliser production are that

(1) Whereas the wet process requires phosphate rock which should have 30% or more P_2O_5 content, in the furnace process, low grade rock phosphate having P_2O_5 as low as 20% can be used.

(2) Furnace process eliminates the use of sulphur which has to be imported for the wet process. This results in considerable saving in foreign exchange.

(3) Phosphorus production can be carried out within economic distance of rock-phosphate source with conversion of phosphorus into fertilizer forms being done at centres close to the consuming areas. Plant nutrient content of elemental

phosphorus is about eight times that of phosphate rock and, therefore, if transportation costs are also taken into consideration, the economics of phosphatic fertilizer manucacture via elemental phosphorus would improve considerably. The electric furnace also yields carbon monoxide as a byproduct which it may be possible to use for production of urea. Steam oxidation of phosphorus can also be considered as a source of hydrogen for ammonia production.

iv) Research and Development Programme

In order to verify the assumption made with respect to the performance of the advanced cells, development work has been started at the Bhabha Atomic Research Centre. Stress is being given on the indigenous manufacture of these cells. A small unit is expected to be ready shortly.

A phosphorus furnace of 600 KVA rating is being designed for carrying out the development work in the field of elemental phosphorus production particularly with the Indian rock phosphate of Rajasthan. Detailed parametric studies will be carried out to collect the necessary information for design and operation of large elemental phosphorus furnaces.

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THREE DIMENSIONAL DYNAMO THEORY IN THE MAGNETOSPHERE

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THREE DIMENSIONAL DYNAMO THEORY IN THE MAGNETOSPHERE

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Abstract. We have solved in this paper the three dimensional dynamo equation consistent with the conditions in the magnetosphere. The conductivity we have adopted here is that for a fully ionised but highly rarefied gas in a magnetic field. The velocity field is based on the measurements of the convection patterns made by different satellites. The solution obtained of the dynamo equation is presented here in the most general form so that it can be used when the various parameters are known to a higher degree of accuracy in future. We have then made a model calculation based on the particular solution of the inhomogeneous differential equation and have computed the components of the current as well as the isointensity curves in the midday-midnight meridional plane. as well as on the dawn-dusk meridional plane. These theoretical results have then been matched with observations.

1. Introduction

A harmonic analysis of the magnetic records show a very dominant daily variation of the geomagnetic field components with respect to solar local time. From the global study of the daily variation, Chapman (1919) estimated the electric current system which could be responsible for this daily variation. He also observed from his harmonic analysis that the seat of this equivalent current system is located external to the Earth. From the magnetic observations from a network of stations distributed over the globe, one can draw this equivalent current system in the ionosphere that could produce the observed magnetic variations, if such magnetic variations are caused only due to ionospheric E region current (Chapman and Bartels, 1940; Sugiura and Heppner, 1965; Matsushita and Campbell, 1967).

Rocket-borne magnetometers have observed the magnetic field discontinuity at E-region heights in the equatorial electrojet region (Sastry, 1968, 1970). But at low and middle latitudes the results are not consistent. The explanation given for this is that the high values of the dip, I, at these regions make ΔH small, and hence below the detection level (Sugiura and Heppner, 1965).

Magnetometers on board ATS-1 satellite have measured with high accuracy the true diurnal variation of the geomagnetic field at the equator at an altitude of 6.6 Earth radii. The amplitude of the diurnal variation of H for quiet days is nearly 35

* The passing away on December 30, 1971 of Professor Sarabhai prevented his seeing this final write up.

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to 45 γ (Cummings *et al.*, 1971; Coleman, 1970). This spacecraft orbits with the same velocity with which the geomagnetic field is corotating and so asymmetries in the internal field are not important and radial motion of the spacecraft through spatially varying field is not a complicating factor. Sugiura *et al.* (1969) using data from OGO satellites 1, 2 and 3 have computed contours of ΔB, the constant deviation of the measured field magnitude from the reference field. It can be seen that even during geomagnetically quiet periods, at an altitude of 6.6 Earth radii in the equatorial plane, there is a field depression of about 30 γ during night side compared to day side.

Until recently the daily variation of the geomagnetic field was believed to be primarily related to current systems in the ionospheric *E*-region, particularly in the absence of geomagnetic disturbances (Chakrabarty and Pratap, 1954). However, in terms of the dynamo theory a number of anomalies were seen to occur and much evidence has been accumulating recently to indicate that the classical representation of dynamo currents on a thin spherical shell is inadequate to explain the observed variations, even during geomagnetically quiet days (Price, 1969; Maeda, 1968).

With a growing understanding of the solar wind interaction with the magnetosphere it became clear that a small contribution to ΔH even on quiet days could arise from currents at the magnetopause (Beard and Jenkins, 1962; Mead, 1964; Olson, 1969; Matsushita, 1969; 1971; Sastry, 1972). This as well as the dynamo effect should produce an increase of H near noon, compared to night for low altitudes. On the other hand evidence has been presented by Sarabhai and Nair (1969a, b) which indicates that the dominant effect at low latitude stations outside the influence of the equatorial electrojet has the character of a decrease of the field during night time. Since the *E*-region current system is very weak during night time, an ionospheric contribution to ΔH in the form of reduction of the field during night time is not significant and one must look to current systems in the magnetosphere to understand the observations. Nair *et al.* (1970) have reported that while at Trivandrum (at the dip equator) the ionospheric contribution to the daily variation of the horizontal force is similar in magnitude to the magnetospheric contribution on a normal day, at Alibag the ionospheric contribution is about a third of the daily variation of the horizontal force. Sarabhai and Nair (1969c, 1971), Nair and Sarabhai (1970) have summarised the situation as follows: the daily variation of the horizontal component of the geomagnetic field at a low latitude station outside the influence of the equatorial electrojet is caused by (1) the dynamo current, mainly at the ionospheric *E*-region (2) the surface currents at the magnetopause and (3) the tail currents, the eccentric ring current and the partial ring current in the magnetosphere. Moreover the various processes are all operative on each day, though their relative importance varies depending on solar, terrestrial and interplanetary conditions in the neighbourhood of the Earth. They have also suggested that the time dependent azimuthal electric fields in the magnetosphere along with the azimuthal asymmetry of the outer magnetosphere play an important part in enhancing the daily range of H, through lowering of H during night time.

Recently Olson (1970) has reported that the calculations done with models of the magnetopause, asymmetric ring and neutral sheet current systems show that they all produce variations in the Earth's surface magnetic field similar to the observed *Sq*. pattern and that, after giving allowance for the induced Earth currents, the combined effects of these three non-ionospheric current systems could account for more than 10 γ to the *Sq*-variations. He has concluded that 'because of the large observed fluctuations in the solar wind parameters (which determine the strength of these currents), it is suggested that magnetospheric currents may make a significant contribution on the day-to-day variability in *Sq*.'

Based on the analysis of ground based geomagnetic data Kane (1970) has recently pointed out the possibility of a magnetospheric contribution to the daily variation of the geomagnetic field. Kane (1971a) has also stated that the day-to-day variability in H and the apparent changes in the focus position may be due to contributions from magnetospheric currents. Kane (1971b) has reported that even after giving due allowance of $\frac{1}{3}$rd contribution due to induced currents, a non-ionospheric (magnetospheric?) contribution of about 15 gammas in winter months and about 40 gammas in other seasons is indicated in geomagnetic daily variation. Kane (1971c) has pointed out that during quiet days, the magnitude of the total interplanetary magnetic field is partly responsible for the day-to-day variability of the *Sq*. current system, B_z component affecting the strength and B_x component the position of the *Sq* focus.

2. Conductivity in the Upper Atmosphere

Electrical conductivity in the dynamo theory plays a very crucial role which is seldom appreciated. In this discussion we shall, by upper atmosphere, consider the region from *D*-layer up to the magnetosphere. The *D* and *E* regions are mostly collision dominated, in which electron and ion collisions with neutrals are more dominant, thereby the gas can be considered as weakly ionised. Thus at 90 km, the neutral density is 6×10^{13} particles cc^{-1}, while the electron density is 2.3×10^{4} particles cc^{-1}. In the magnetosphere however, the neutral particles are absent, and we have only ions and electrons. Thus in this region we have a fully ionised but a very highly rarefied gas in the Knudsen range. There does not exist at present a kinetic theory which could give results in both the domains by different limiting processes, since the kinetic equations in these different regions are formulated by expansions based on different time scales. Thus while in the collision dominated domains, the transport coefficients such as viscosity, electrical and thermal conductivities are essentially derived from the Boltzmann's kinetic equations (Cowling, 1933; Chapman and Cowling, 1960), the conductivity in regions such as magnetosphere are derived from entirely different physical arguments (Spitzer 1952, 1962), wherein they have taken an infinite number of infinitesimal collisions, such that the particle's trajectory is turned through 90° there by it loses its memory of its initial state. Thus the physics in one domain can not be obtained by limiting process in the physics in the other region. This very important point is often not realised when extrapolations of conductivity expressions are made by taking the collision frequency to the zero limit, and thereby arguing that *the parallel conductivity is infinite in the higher layers of ionosphere and magnetosphere.*

A. ISOTROPIC AND ANISOTROPIC CONDUCTIVITY IN THE IONOSPHERE

Schuster (1908), Chapman (1919) and Chakrabarty and Pratap (1954) as well as Pratap (1954a, b, 1955 and 1957) have considered the dynamo theory on a thin ionospheric sheet, and have taken the conductivity to be isotropic in the north-south and east-west directions but dependent on space and time through the zenith distance of the Sun. Baker and Martyn (1953), Baker (1953), Sugiura and Porus (1969) and Untied (1967) have considered the conductivity to be anisotropic depending on the longitudinal (Pederson) and Hall conductivities but independent of space and time. One of the most natural questions would thus be: under what condition can the isotropic conductivity be valid. This question can be answered by considering the three conductivities (following the notations of Baker and Martyn, 1953)
(Longitudinal)

$$\sigma_0 = N_e^2\left(\frac{1}{m_e\nu_e} + \frac{1}{m_i\nu_i}\right) \tag{2.1}$$

(Pederson)

$$\sigma_1 = N_e^2\left(\frac{\nu_e}{m_e(\nu_e^2+\omega_e^2)} + \frac{\nu_i}{m_i\,({}_i+\omega_i^2)}\right) \tag{2.2}$$

(Hall)

$$\sigma_2 = N_e^2\left(\frac{\omega_e}{m_e(\nu_e^2+\omega_e^2)} - \frac{\omega_i}{m_i\,({}_i+\omega_i^2)}\right). \tag{2.3}$$

If we take the domain as collision dominated such that $\omega_e/\nu_e(=x_e)$, $\omega_i/\nu_i(=x_i)$ are less than unity, we then get the above by expanding binomially as

$$\sigma_0 = N_e^2\left(\frac{1}{m_e\nu_e} + \frac{1}{m_i\nu_i}\right) \tag{2.4}$$

$$\sigma_1 = \sigma_0 - N_e^2\left(\frac{x_e^2}{m_e\nu_e} + \frac{x_i^2}{m_i\nu_i}\right) \tag{2.5}$$

$$\sigma_2 = N_e^2\left(\frac{x_e}{m_e\nu_e(1+x_e^2)} - \frac{x_i}{m_i\nu_i(1+x_i^2)}\right). \tag{2.6}$$

Thus in a region where $x_{e,i} \ll 1$, $\sigma_1 \approx \sigma_0$ and $\sigma_2 \approx 0$, the conductivity could be isotropic. These conditions are valid in the lower regions of the ionosphere namely *D*-layer. However, as we go up, the neutral density decreases and the electron-ion density increases and thus the conductivity also become space-time dependent. The exact dependence with height however is not known to any degree of accuracy. It is to circumvent these difficulties that one always takes an *integrated* conductivity in the usual two dimension dynamo theory.

B. CONDUCTIVITIES IN THE MAGNETOSPHERE

In the magnetosphere the medium is completely ionized and the electron ion collisions are more dominant. The plasma is highly rarefied and hence the interactions between the electrically charged particles are of long range. This is precisely the situation envisaged by Spitzer (1952) when he derived the conductivity using a relaxation time defined by the time of flight taken by the particles to turn its trajectory through 90° from a given initial direction. He has also shown that the resistivity for a highly rarefied plasma along and perpendicular to the magnetic field are in the ratio 2:1 and that Hall resistivity is negligible. Hence we are justified in taking an isotropic conductivity which however will be functions of space and time. From the above it is quite obvious that one cannot reproduce the Spitzer conductivity from (2.4)–(2.6) by taking $\nu_{e,i} \to 0$. This is also clear when one realises that in (2.4)–(2.6) the dominant collisional processes are between charged particles and neutrals while in the magnetosphere the electron-ion collisions are the only ones existing. Secondly the physical considerations in a dense, weakly ionized collision dominated domain are very different from that of a highly rarefied (of Knudson range) fully ionized plasma with long range interactions and in which collective processes are more dominant.

We propose to take a conductivity of the form

$$\sigma = \sum_{n,m} \sigma_n^m(r)\, Y_n^m(\theta, \phi), \tag{2.7}$$

where $Y_n^m(\theta, \phi)$ are tessoral harmonics and σ_n^m are functions of r. In the conductivity expression given by Spitzer, the space time dependence is through the electron/ion density distributions. We made a harmonic analysis of the density profile reported by De Forest and McIlwain (1971) from the analysis of the data given by ATS-5 on the equatorial plane and we obtained the dependence of the number density on the equatorial plane as

$$n = n(r, \theta)\,(1.2 - 0.8 \cos\phi). \tag{2.8}$$

Equation (2.8) can then be written as

$$n(r, \theta, \varphi) = n_0(r)\,[1.2 + \alpha P_1 - 0.8 P_1^1 \cos\phi], \tag{2.9}$$

where α is a constant. With the present knowledge of the number density variation, there is no way of determining α. We therefore chose a value such that n is not negative definite at all and the minimum value should be $\geqslant 0$. Thus we arrive at $\alpha = 0.2$. We can thus write (2.7) as

$$\sigma = kn(r)\,[\tilde{\sigma}_0 + \tilde{\sigma}_1 P_1 + \tilde{\sigma}_2 P_1^1 \cos\phi] \tag{2.10}$$

comparing coefficients of (2.10) with (2.9) we get $\tilde{\sigma}_0 = 1.2\sigma_0$ $\tilde{\sigma}_1 = 0.2\sigma_0$ and $\tilde{\sigma}_2 = -0.8\sigma_0$. The radial dependence of $n(r)$ has been taken as $n_0 r^{-7}$ following Higuchi and Jacobs (1970). Thus the final conductivity expression for the present analysis has been taken as

$$\sigma = \sigma_0 r^{-7}[1.2 + 0.2P_1 - 0.8P_1^1 \cos\phi]. \tag{2.11}$$

We shall conclude this section by stressing the importance of the spatial dependence of the conductivity. Space-time dependence of the conductivity was incorporated by the earlier authors through the zenith angle dependence. This dependence was however ignored by Baker and Martyn (1953) and instead introduced the constant anisotropic conductivity. One can very easily see that if we set $a_1 = a_2 = 0$ in Equation (1) of Chakrabarty and Pratap (1954) and take $a_0 = \sigma_1 + \sigma_2^2/\sigma_1$, we reproduce the dynamo equation of Baker and Martyn (1953) from the Equation (7) of *loc. cit.* Furthermore, if we take the above limits in the solution for Chapman's equation given in Table I of *loc. cit*, we obtain the only nonzero coefficient as $p_3^2 = \frac{2}{15}(\sigma_1 + \sigma_2^2/\sigma_1)$ and hence the current function as defined in Equation (11) reduces to

$$R = \tfrac{2}{15} k_\sigma^\tau ck\,(\sigma_1 + \sigma_2^2/\sigma_1)\, P_3^2 \sin(2t - \alpha_2) \tag{2.12}$$

which is exactly the solution given by Baker (Equation (30) of Baker, 1953). Thus we want to emphasize this fact that the dynamo equation derived by Baker and Martyn (1953) is a very special and trivial case of that of Chapman (1919). Furthermore if we calculate the magnetic field variations due to a current defined by the current function (2.12) (or Equation (30) of Baker, 1953), we shall be getting only a semi diurnal magnetic field variation and *not* a diurnal magnetic field variation as is observed. It is very clear from the series of papers (Chakrabarty and Pratap, 1954; Pratap 1954a, b; 1955, 1957) that by assuming a semi diurnal atmospheric oscillation in the dynamo theory, a dominant diurnal current function such as P_2^1 and thereby a diurnal magnetic field variation, has been obtained by the phenomenon of beats between the time dependent conductivity as well as the velocity potential. Hence it is of paramount importance, that the conductivity expression should be space-time dependent, to have any meaningful dynamo theory. From this point of view, the results of Martyn and Baker as well as the various authors who have computed models based on these results have failed to deliver a satisfactory theory for the *Sq* variations as well as the anomalous increase in the *Sq* at the equatorial belt.

3. Velocity Field

In the earlier attempts of the dynamo theory, the velocity field has been assumed to be derived from a potential function which is independent of the height but having a semi-diurnal character – and thus derived from the sectorial harmonic Y_2^2. We obtained the phase of this mode as 275° by assuming that the magnetic field variation is completely derived from the dynamo in the *E*-region (Pratap, 1954b). The diurnal mode was found to be very small from the measurements of the pressure oscillations on the surface of the Earth and by constructing a dynamo theory for this velocity potential, we have shown that the magnetic field variation due to this mode is also very small (Pratap, 1954a) since its aplitude is negligible. Recently Lindzen (1967) has shown that this mode is very important in the higher layers of the ionosphere. Could this mode be important in the magnetosphere too?

There has been recently a large amount of measurements of the convection in the magnetosphere and various models have been proposed by different authors (Brice, 1967; Chen, 1970). These measurements have been interpreted as drifts and the equivalent electric fields that would produce the correct velocity profiles are given in the above references. The velocity field in the equatorial plane has therefore been given as due to three sources namely an $\mathbf{E}\times\mathbf{B}$ drift, a gradient drift and that due to corotation. Thus one can write the equivalent electric field as $\mathbf{E}_{eq}=-\nabla\Phi$, with (Chen, 1970)

$$\Phi = -\frac{\Omega M_{\mathrm{E}}}{c}\frac{\sin^2\theta}{R} - E_0 R\sin\phi + \frac{\bar{\mu}M_{\mathrm{E}}}{q}\frac{1}{R^3}, \tag{3.1}$$

where now Ω is the angular frequency of the Earth's rotation M_{E} is the geomagnetic dipole moment of the Earth, E_0 is the magnitude of the convection of the electric field, and ϕ is the azimuthal angle measured counter clockwise from the subsolar point (or local time reckoned from midday), $\bar{\mu}$ and q are the magnetic moment and charge respectively. As can be seen this expression consists of three parts: the first represents the corotation (Taylor and Hones, 1965), the second represents the convection electric field and the third a gradient drift. Excepting the first term the others are defined in the equatorial plane. We shall rewrite this as a function in three dimensional space as

$$\Phi = -\frac{\Omega M_{\mathrm{E}}}{c}\frac{\sin^2\theta}{R} - E_0 R P_1^1\sin\phi - \frac{2\bar{\mu}M_{\mathrm{E}}}{qR^3}P_2, \tag{3.2}$$

where in general we should have written $\sum_n P_n^1$ instead of P_1^1 as the coefficient of $\sin\phi$. However since the term is only a linear function in R, we choose the first sectorial harmonic. This in general justifies the P_1^1 mode in the magnetosphere as well as a continuation of this mode from the ionosphere heights. Following Chen (1970) we can write (3.2) in dimensionless parameters as

$$\Phi = -\frac{2}{3}\frac{1}{r}P_0 - \left(\frac{\mu}{r^3} - \frac{2}{3}\frac{1}{r}\right)P_2 - rP_1^1\sin\phi. \tag{3.3}$$

With this potential the bulk velocity is given as

$$V_{\mathrm{D}} = c\frac{\mathbf{B}\times\nabla\phi}{|B|^2}. \tag{3.4}$$

$|B|^2$ appearing in the denominator has been taken averaged over the unit sphere and hence only a function of r. We shall make use of this velocity field in our following analysis. It may be stressed here that (3.4) is only a way of representing the actually observed bulk motion in terms of an equivalent electric field generated by a potential Φ and thereby the velocity field as a drift velocity.

4. Three Dimensional Dynamo Theory

In recent years several attempts have been made to formulate the problem of three dimensional dynamo (Cocks and Price, 1969; Mishin *et al.*, 1971; Matveeu, 1971; Mishin, 1971; Popov, 1971) but have met with limited success. While Cocks and Price have formulated the problem in a slab geometry in the ionospheric shell, they have tried to introduce a finite thickness d of the shell and also have claimed that even if J_r is small $\partial J_r/\partial r$ need not be small. However they have made an assumption that $J_r/J_\theta^2+J_\phi^2)^{1/2}\approx\varepsilon$ a very small quantity and it is not quite obvious how they have reconciled these two assumptions. The work of Mishin and his coworkers were the first to realize the importance of Σ_3 being a function of space and time in the analysis and also they have shown that the integrated Pederson (Σ_1) and Hall (Σ_2) conductivities are comparable with that of the parallel conductivity (Σ_0). These results make the assumptions of Baker and Martyn (1953) in obtaining the dynamo equation unrealistic.

We propose to consider the equation for the current

$$\mathbf{J}=\sigma\left[\nabla\Omega+\frac{1}{c}\mathbf{V}\times\mathbf{B}\right], \tag{4.1}$$

where we shall take σ as given by (2.11). It may be pointed out here that one can assume an anisotropic conductivity here instead of a scalar one and carry out the entire analysis developed in this section. While it does increase the algebra, there is absolutely no analytical difficulty. We shall be considering σ as a function of r, θ and ϕ and hence shall not be taking integrated conductivity as is necessitated by two dimensional models. Our method is essentially as follows: In the Equation (4.1) in determining $\mathbf{J}$, it is enough if we determine Ω the electric potential, since we know $\mathbf{V}$ from (3.4), σ from (2.11) and $\mathbf{B}$ is the dipole field. Having determined $\mathbf{J}$, we shall then determine the induced magnetic field from

$$\mathbf{J}=\nabla\times[\nabla\times(\mathbf{r}u)+\nabla\times\nabla\times(\mathbf{r}v)], \tag{4.2}$$

where u and v are functions of space and time. The expression in the square bracket is the induced field which is constituted by a toroidal and poloidal components. In this paper, we shall be only determining the current $\mathbf{J}$ from (4.1) and the induced magnetic field will be discussed in a later communication. Taking the divergence of (4.1) and setting it to zero, we shall obtain after substituting for $\mathbf{V}$ from (3.4) as

$$\sigma\nabla^2\Omega+\nabla\sigma\cdot\nabla\Omega=-\sigma\nabla^2\Phi-\nabla\sigma\cdot\nabla\Phi+\mathbf{B}\cdot\nabla\left(\frac{\sigma\mathbf{B}\cdot\nabla\Phi}{|B|^2}\right). \tag{4.3}$$

Equation (4.3) is an inhomogeneous linear partial differential equation and this equation can be rewritten as

$$\sigma\nabla^2\tilde{\Omega}+\nabla\sigma\cdot\nabla\tilde{\Omega}=\mathbf{B}\cdot\nabla\left(\frac{\sigma\mathbf{B}\cdot\nabla\Phi}{|B|^2}\right) \tag{4.4}$$

where now

$$\tilde{\Omega} = \Omega + \Phi \tag{4.5}$$

we can now expand

$$\tilde{\Omega} = \sum_{nm} \left[C_n^m(r) \cos m\varphi + S_n^m(r) \sin m\varphi \right] P_n^m, \tag{4.6}$$

where C_n^m and S_n^m are functions of r only.

Substituting (4.6) in (4.4) and using the full expression for σ and using the usual recurrence relations of Legendre harmonics (Appendix 1), we get the coefficient of $Y_{nc}^m (= P_n^m \cos m\phi)$ of L.H.S. as

$$\begin{aligned} &\sigma_0 U_n^m C_n^m + \frac{n-m}{2n-1} \sigma_1 V_n^m C_{n-1}^m + \frac{n+m+1}{2n+3} \sigma_1 W_n^m C_{n+1}^m + \\ &+ \frac{\sigma_2}{2(2n-1)} V_n^m C_{n-1}^{m-1} - \frac{\sigma_2}{2(2n+3)} W_n^m C_{n+1}^{m-1} + \\ &+ \frac{(n+m+1)(n+m+2)}{2(2n+3)} \sigma_2 W_n^m C_{n+1}^{m+1} - \\ &- \frac{(n-m)(n-m-1)}{2(2n-1)} \sigma_2 V_n^m C_{n-1}^{m+1} \end{aligned} \tag{4.7}$$

and a similar term in S_n^m also, where U_n^m, V_n^m and W_n^m are operators defined as

$$U_n^m = \frac{1}{r^2} \frac{\mathrm{d}}{\mathrm{d}r} r^2 \frac{\mathrm{d}}{\mathrm{d}r} + \frac{\mathrm{d}}{\mathrm{d}r} (\log \sigma) \frac{\mathrm{d}}{\mathrm{d}r} - \frac{n(n+1)}{r^2} \tag{4.8a}$$

$$V_n^m = \frac{1}{r^2} \frac{\mathrm{d}}{\mathrm{d}r} r^2 \frac{\mathrm{d}}{\mathrm{d}r} + \frac{\mathrm{d}}{\mathrm{d}r} (\log \sigma) \frac{\mathrm{d}}{\mathrm{d}r} - \frac{(n^2-1)}{r^2} \tag{4.8b}$$

$$W_n^m = \frac{1}{r^2} \frac{\mathrm{d}}{\mathrm{d}r} r^2 \frac{\mathrm{d}}{\mathrm{d}r} + \frac{\mathrm{d}}{\mathrm{d}r} (\log \sigma) \frac{\mathrm{d}}{\mathrm{d}r} - \frac{n(n+2)}{r^2}. \tag{4.8c}$$

In writing these operators, we have assumed that $\sigma_0(r)$, $\sigma_1(r)$ and $\sigma_2(r)$ are given by $\sigma_0 r^\sigma$, $\sigma_1 r^\sigma$, and $\sigma_2 r^\sigma$, where the coefficients of r^σ are now constants and independent of r. This is in view of (2.11) based on observations. If we take $\sigma_0 = 1.2\sigma_0$, $\sigma_1 = 0.2\sigma_0$, $\sigma_2 = -0.8\sigma_0$ we shall be reproducing (2.11). In the actual numerical computations, we have used the above values together with (the index) $\sigma = -7$. We are however using this representation to keep up with the generality, since one could plug in values when they are known more accurately. The right hand side of the equations is given in the Appendix 2. We shall now use the orthogonality property of the Legendre Harmonics and obtain each equation for the corresponding harmonic. One can see that the highest harmonic on the R.H.S. is $P_4^2 \sin 2\phi$, and hence (4.7) becomes.

$$\sigma_0 U_4^2 C_4^2 + \tfrac{2}{7}\sigma_1 V_4^2 C_3^2 + \tfrac{7}{11}\sigma_1 W_4^2 C_5^2 + \frac{\sigma_2}{14} V_4^2 C_3^1 -$$

$$- \frac{\sigma_2}{22} W_4^2 C_5^1 + \tfrac{28}{11}\sigma_2 W_4^2 C_5^3 - \tfrac{1}{7}\sigma_2 V_4^2 C_3^3 = 0 \tag{4.9a}$$

and

$$\sigma_0 U_4^2 S_4^2 + \tfrac{2}{7}\sigma_1 V_4^2 S_3^2 + \tfrac{7}{11}\sigma_1 W_4^2 S_5^2 + \frac{\sigma_2}{14} V_4^2 S_3^1 - \frac{\sigma_2}{22} W_4^2 S_5^1 +$$

$$+ \tfrac{25}{11}\sigma_2 W_4^2 S_5^3 - \tfrac{1}{7}\sigma_2 V_4^2 S_3^3 = - \sigma_2 \frac{(2\sigma + 9)}{35}\frac{1}{r}. \tag{4.9b}$$

In solving these equations, we shall assume $C_5^2 = C_4^2 = C_3^2 = C_2^2 = 0$; $C_5^3 = C_4^3 = C_3^3 = 0$ and $C_5^1 = C_4^1 = 0$. This has been necessitated for the following reasons: for the higher harmonics the R.H.S. is zero and hence we get equations to be homogeneous and that these infinite set of equations are not closed. Since the three operators defined in (4.8) are distinct, the only plausible solutions for these functions are the ones given above. Also they form a hierarchy. With this assumption Equations (4.9a, b) becomes

$$V_4^2 C_3^1 = 0 \tag{4.10a}$$

and

$$V_4^2 S_3^1 = - \frac{2(2\sigma + 9)}{5}\frac{1}{r}. \tag{4.10b}$$

One can easily write the solutions of these differential equations as

$$C_3^1 = p_3^1 r^{\alpha_3} + q_3^1 r^{\beta_3} \tag{4.11a}$$

and

$$S_3^1 = \frac{2(2\sigma + 9)}{5(13 - \sigma)} r + a_3^1 r^{\alpha_3} + b_3^1 r^{\beta_3}, \tag{4.11b}$$

where

$$\begin{matrix}\alpha_3\\ \beta_3\end{matrix} = - \frac{(1 + \sigma)}{2} \pm \frac{[(1 + \sigma)^2 + 60]^{1/2}}{2} \tag{4.12}$$

and a_3^1, b_3^1, p_3^1 and q_3^1 are constants. Next we compare the coefficients of Y_{3s}^2, Y_{3c}^2 and we obtain in view of the above assumptions as

$$V_3^2 S_2^1 = 0 \quad \text{and} \quad V_3^2 C_2^1 = 0 \tag{4.13}$$

and since these equations are homogeneous, the solutions can be written as

$$S_2^1 = a_2^1 r^{\alpha_2} + b_2^1 r^{\beta_2}$$
$$C_2^1 = p_2^1 r^{\alpha_2} + q_2^1 r^{\beta_2}, \tag{4.14}$$

where

$$\frac{\alpha_2}{\beta_2} = -\frac{(1+\sigma)}{2} \pm \frac{[(1+\sigma)^2 + 32]^{1/2}}{2} \tag{4.15}$$

and a_2^1, b_2^1, p_2^1 and q_2^1 are all constants. Again if we compare the coefficients of Y_{2s}^2 and Y_{2c}^2 the equation becomes

$$V_2^2 S_1^1 = \tfrac{3}{7} W_2^2 S_3^1 + \frac{\sigma - 13}{7} \frac{1}{r} \tag{4.16}$$

and

$$V_2^2 C_1^1 = \tfrac{3}{7} W_2^2 C_3^1 . \tag{4.17}$$

This is the special feature of this method. The Equations (4.16) and (4.17) now depend on S_3^1 and C_3^1 which have been obtained in (4.11a) and 4.11b). The essential difference between the two and three dimensional models is that in the former case, these equations were algebraic in nature while in the present case, they are differential equations. Remembering that W_2^2 is also an operator, one has to substitute the solutions given by (4.11a, b) in (4.16) and (4.17) and have to operate with W_2^2. Having done these, the solution of (4.16) and (4.17) are

$$S_1^1 = \tfrac{1}{4} S_3^1 - \frac{5}{2(\sigma - 1)} r + a_1^1 r^{\alpha_1} + b_1^1 r^{\beta_1} \tag{4.18}$$

$$C_1^1 = \tfrac{1}{4} C_3^1 + p_1^1 r^{\alpha_1} + q_1^1 r^{\beta_1} , \tag{4.19}$$

where

$$\frac{\alpha_1}{\beta_1} = -\frac{(1+\sigma)}{2} \pm \frac{[(1+\sigma)^2 + 12]^{1/2}}{2} \tag{4.20}$$

and a_1^1, b_1^1, p_1^1, and q_1^1 are all constants. Thus at every equation we have to find out the particular solution as well as the complimentary functions. These final solutions are given as:

$$\begin{aligned}
S_3^1 &= \frac{2(2\sigma + 9)}{5(13 - \sigma)} r && + a_3^1 r^{\alpha_3} + b_3^1 r^{\beta_3} \\
C_3^1 &= && p_3^1 r^{\alpha_3} + q_3^1 r^{\beta_3} \\
S_2^1 &= && a_2^1 r^{\alpha_2} + b_2^1 r^{\beta_2} \\
C_2^1 &= && p_2^1 r^{\alpha_2} + q_2^1 r^{\beta_2} \\
S_1^1 &= -\frac{5}{2(\sigma - 1)} r + \tfrac{1}{4} S_3^1 && + a_1^1 r^{\alpha_1} + b_1^1 r^{\beta_1} \\
C_1^1 &= \tfrac{1}{4} C_3^1 && + p_1^1 r^{\alpha_1} + q_1^1 r^{\beta_1} \\
S_4^0 &= && a_4^0 r^{\alpha_4} + b_4^0 r^{\beta_4} \\
C_4^0 &= -\frac{64(\sigma + 1)}{35(\sigma + 6)} \frac{\mu}{r^3} && + p_4^0 r^{\alpha_4} + q_4^0 r^{\beta_4}
\end{aligned}$$

$$S_3^0 = a_3^0 r^{\alpha_3} + b_3^0 r^{\beta_3}$$

$$C_3^0 = p_3^0 r^{\alpha_3} + q_3^0 r^{\beta_3}$$

$$S_2^0 = -\frac{8(3\sigma+10)}{7(\sigma-6)}\frac{\sigma_0}{\sigma_2} r - \frac{30}{7}\frac{\sigma_0}{\sigma_2} S_3^1 + \tfrac{5}{16} S_4^0 + a_2^0 r^{\alpha_2} + b_2^0 r^{\beta_2}$$

$$C_2^0 = -\frac{4}{3}\frac{1}{r} - \frac{2\mu(3\sigma-8)}{3\sigma+2}\frac{1}{r^3} - \frac{30}{7}\frac{\sigma_0}{\sigma_2} C_3^1 + \tfrac{5}{16} C_4^0 + p_2^0 r^{\alpha_2} + q_2^0 r^{\beta_2}$$

$$S_1^0 = -\frac{2\sigma+3}{\sigma-1}\frac{\sigma_1}{\sigma_2} r - \frac{12}{5}\frac{\sigma_0}{\sigma_2} S_2^1 - \frac{5}{2}\frac{\sigma_1}{\sigma_2} S_3^1 + \tfrac{1}{4} S_3^0 + a_1^0 r^{\alpha_1} + b_1^0 r^{\beta_1}$$

$$C_1^0 = -\frac{12}{5}\frac{\sigma_0}{\sigma_2} C_2^1 - \frac{5}{2}\frac{\sigma_1}{\sigma_2} C_3^1 + \tfrac{1}{4} C_3^0 + p_1^0 r^{\alpha_1} + q_1^0 r^{\beta_1}$$

$$S_0^0 = -\frac{(7\sigma+4)}{15(\sigma+2)}\frac{\sigma_0}{\sigma_2} r - \frac{2}{3}\frac{\sigma_0}{\sigma_2} S_1^1 - \frac{5}{12}\frac{\sigma_0}{\sigma_2} S_3^1 + \tfrac{1}{8} S_2^0 - $$
$$- \frac{3}{4}\frac{\sigma_1}{\sigma_2} S_2^1 + \tfrac{1}{64} S_4^0 + a_0^0 + b_0^0 r^{-(1+\sigma)}$$

$$C_0^0 = \frac{3}{2}\frac{1}{r} - \frac{5\mu}{4}\frac{1}{r^3} - \frac{2}{3}\frac{\sigma_0}{\sigma_2} C_1^1 - \frac{3}{4}\frac{\sigma_1}{\sigma_2} C_2^1 - \frac{5}{12}\frac{\sigma_0}{\sigma_1} C_3^1 + \tfrac{1}{8} C_2^0 +$$
$$+ \tfrac{1}{64} C_4^0 + p_0^0 + q_0^0 r^{-(1+\sigma)}$$

$$S_4^{-1} = a_4^{-1} r^{\alpha_4} + b_4^{-1} r^{\beta_4}$$

$$C_4^{-1} = \frac{64}{7}\frac{\sigma_1}{\sigma_2}\left(\frac{\sigma+1}{\sigma+6}\right)\frac{\mu}{r^3} + p_4^{-1} r^{\alpha_4} + q_4^{-1} r^{\beta_4}$$

$$S_3^{-1} = -\frac{24}{5}\left(\frac{2\sigma+9}{\sigma-13}\right) r - \frac{56}{9}\frac{\sigma_0}{\sigma_2} S_4^0 + a_3^{-1} r^{\alpha_3} + b_3^{-1} r^{\beta_3}$$

$$C_3^{-1} = \frac{32}{45}\frac{\sigma_0}{\sigma_2}\mu\frac{2\sigma+11}{\sigma+3}\frac{1}{r^3} - \frac{56}{9}\frac{\sigma_0}{\sigma_2} C_4^0 + p_3^{-1} r^{\alpha_3} + q_3^{-1} r^{\beta_3}$$

$$S_2^{-1} = \frac{48}{7}\frac{\sigma_0\sigma_1}{\sigma_2^2}\left(\frac{3\sigma+10}{\sigma-6}\right) r - \frac{30}{7}\frac{\sigma_0}{\sigma_2} S_3^0 + \frac{180}{7}\frac{\sigma_0\sigma_1}{\sigma_2^2} S_3^1 - \frac{35}{8}\frac{\sigma_1}{\sigma_2} S_4^0 +$$
$$+ \tfrac{5}{16} S_4^{-1} + a_2^{-1} r^{\alpha_2} + b_2^{-1} r^{\beta_2}$$

$$C_2^{-1} = 4\frac{\sigma_1}{\sigma_2}\frac{1}{r} + 6\frac{\sigma_1}{\sigma_2}\left(\frac{3\sigma-4}{3\sigma+2}\right)\frac{\mu}{r^3} - \frac{30}{7}\frac{\sigma_0}{\sigma_2} C_3^0 + \frac{180}{7}\frac{\sigma_0\sigma_1}{\sigma_2^2} C_3^1 -$$
$$- \frac{35}{8}\frac{\sigma_1}{\sigma_2} C_4^0 + \tfrac{5}{16} C_4^{-1} + p_2^{-1} r^{\alpha_2} + q_2^{-1} r^{\beta_2}$$

$$S_1^{-1} = \left[-\frac{2(2\sigma-15)}{5(\sigma-1)}\frac{\sigma_0^2}{\sigma_2^2} + \frac{4(2\sigma+3)}{\sigma-1}\frac{\sigma_0^2+\sigma_1^2}{\sigma_2^2} - \frac{5}{\sigma-1}\right] r - \frac{12}{5}\frac{\sigma_0}{\sigma_2} S_2^0 +$$
$$+ \left[\frac{9\sigma_0^2 + 10\sigma_1^2}{\sigma_2^2} - \frac{5}{2}\right] S_3^1 + \frac{48}{5}\frac{\sigma_0\sigma_1}{\sigma_2^2} S_2^1 - \frac{4}{3}\frac{\sigma_0}{\sigma_2} S_4^0 - \frac{5}{2}\frac{\sigma_1}{\sigma_2} S_3^0 +$$
$$+ \tfrac{1}{4} S_3^{-1} + a_1^{-1} r^{\alpha_1} + b_1^{-1} r^{\beta_1}$$

$$C_1^{-1} = \frac{4}{5}\frac{\sigma_0}{\sigma_2}\left(\frac{\sigma+18}{\sigma+3}\right)\frac{1}{r} - \frac{2}{105}\frac{\sigma_0}{\sigma_2}\left(\frac{73\sigma+52}{1-\sigma}\right)\frac{\mu}{r^3} - \frac{12}{5}\frac{\sigma_0}{\sigma_2}C_2^0 +$$
$$+\left[\frac{9\sigma_0^2+10\sigma_1^2}{\sigma_2^2} - \frac{5}{2}\right]C_3^1 + \frac{48}{5}\frac{\sigma_0\sigma_1}{\sigma_2^2}C_2^1 - \frac{4}{3}\frac{\sigma_0}{\sigma_2}C_4^0 -$$
$$-\frac{5}{2}\frac{\sigma_1}{\sigma_2}C_3^0 + \tfrac{1}{4}C_3^{-1} + p_1^{-1}r^{\alpha_1} + q_1^{-1}r^{\beta_1}. \tag{4.21}$$

In the above, we have

$$\begin{matrix}\alpha_i\\ \beta_i\end{matrix} = -\frac{(1+\sigma)}{2} \pm \frac{[(1+\sigma)^2+g_i]^{1/2}}{2} \tag{4.22}$$

with $g_4=96$, $g_3=60$, $g_2=32$, $g_1=12$.

In evaluating the current densities, S_n^{-m} or C_n^{-m} are coefficients of Y_{ns}^{-m} or Y_{nc}^{-m} and we have made use of the relation

$$P_n^{-m} = (-1)^n \frac{\Gamma(n-m+1}{\Gamma(n+m+1)}. \tag{4.23}$$

5. Boundary Conditions

The various coefficients appearing in the solutions C_j^i and S_j^i have to be determined by fitting at a specified boundary. This however is very difficult to do with the present state of our knowledge. If we know the exact current profiles at the ionospheric layer, one could fit up the boundary conditions at that sheet. However, this is not known to any degree of accuracy. Furthermore, while the anisotropic conductivity is very dominant in the ionospheric layers, matching the boundary at the ionosphere would be questionable, since, as has already been mentioned, it is difficult if not impossible to have a conductivity tensor as a function of **r** which exhibits direct, Pederson and Hall conductivities at the ionospheric layers and reduces to direct and cross conductivities in the magnetosphere; in other words to have a conductivity expression which can give values in the collision dominated regions as well as regions in which collisions are absent is well neigh impossible.

A second aspect to be considered is that the magnetosphere is the region with an inner boundary at the ionosphere and outer boundary formed by the magnetopause. The information on both these boundaries is inadequate while some reliable data exist at an intermediate region spanned by the ATS satellites. One can fit these functions with the measurements from these satellites and following Bullard (1949) assert that only these harmonics are relevant in this annular space. Any contribution due to other harmonics that comes from the ionospheric dynamo should therefore vanish in this space. We have not tried to make such a fit in this paper, but we hope to do it on a later occasion. Here we have set all the complimentary functions to zero by choosing a_j^i, b_j^i, p_j^i and q_j^i to be zero. This choice is indeed arbitrary and hence the computations we have carried out only have the status of a model. This however has a motivation. In the usual two dimensional dynamo theory the entire solution is given by the particular integral rather than the complimentary functions. We did some calculations by choosing these coefficients arbitrarily but we find that the contours become highly electric field dominated. One can get a realistic picture only by choosing these coefficient in a more realistic way.

6. Discussion

The current density **J**, as has been pointed out earlier, can be considered completely determined, once we know Ω. In the previous section, we have determined $\tilde{\Omega}$ and from this, we have, using Equations (4.5) and (3.3) determined Ω and thus the current density **J** using the relation (4.1). In computing **J**, we have to assign values for a_j^i, b_j^i, p_j^i and q_j^i. An inspection of the solution given in the Table shows that the above coefficients occur in the complimentary function of the solution of the differential Equation (4.4), i.e., these constitute the solution of the homogeneous part of the above differential equation. The remaining part of the solution which are explicit functions of σ, σ_0, σ_1, σ_2 and μ are the particular integrals of the Equation (4.1). We shall, in this discussion, include only the particular integral and exclude the complimentary function. This is achieved by setting $a_j^i = b_j^i = p_j^i = q_j^i = 0$. The motivation for this particular choice is two fold. In the earlier treatment of the dynamo theory (two dimensional), the solutions that have been taken are only the particular integral and hence any comparison with them would be justified only if we take the particular integral in this case as well. Secondly the velocity field **V** enters into this analysis only through the particular integral, while the homogeneous part of the solution does not have any contribution from the dynamo term either through the velocity field or the dipole field **B**.

In the present coordinate system, we have reckoned the local time from mid-day meridian. Figure 1 gives the meridional plane in which we have plotted the isointensity curves of $(J_r^2 + J_\theta^2)^{1/2}$ for $\phi = 0$ for geomagnetically quiet period. The point $\theta = 90°$ on the left half of the polar plot is the sub-solar point and $\theta = 90°$ on the right half is the antipodal point (midnight). The contours can be understood as lines of intersection of the meridional plane and the surfaces of constant $(J_r^2 + J_\theta^2)^{1/2}$. One can see clearly that the lines are much closer to the Earth on the daylit hemisphere than on the night hemisphere. Hence the induced magnetic field on the daylit hemisphere would be more than that on the night side. This has the same topology as one would get when the solar wind coming from the Sun gives a compression on the daylit hemisphere and the rarefaction or a 'wake' on the night side.

In Figure 2 we have again drawn the isometrics of $(J_r^2 + J_\theta^2)^{1/2}$ in the dawn-dusk meridional plane for geomagnetically quiet period. Here the Sun-Earth line is normal to the plane of the diagram and that the Sun is above the plane of the paper. Here again we observe that the lines are nearer to the Earth on the dusk half than on the dawn half. Consequently the magnetic field on the dusk hemisphere would be more than that on the dawn side for quiet period. This is consistent with the observations of

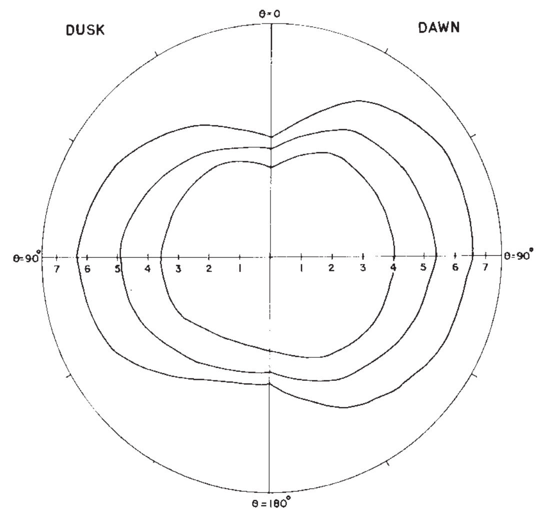

Fig. 1. The midday-midnight meridional plane in which the isointensity $(J_\theta^2 + J_r^2)^{1/2}$ curves are drawn. $\theta = 90°$ on the left is the sub solar point.

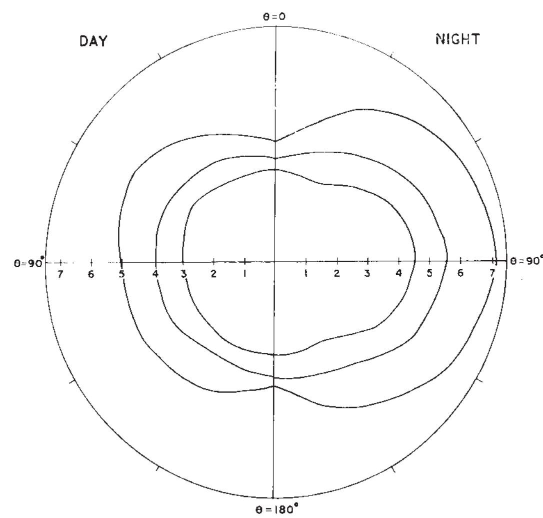

Fig. 2. The dusk-dawn meridional plane in which the iso-intensity $(J_\theta^2 + J_r^2)^{1/2}$ curves are drawn. The asymmetry is seen in the intensity lines.

Sarabhai and Nair (1969a, 1971), wherein they have shown that there is a shift in the time of minimum of H, from dawn hours during quiet days to dusk hours during disturbed days, for low latitudes.

In Figure 3a, b we have plotted J_2 and J_3 as a function of θ and ϕ at $3R_e$. The following features are worth observing:

(i) On the mid-day meridian ($\phi = 0$), while J_2 is insignificant, J_3 is non-zero. On the

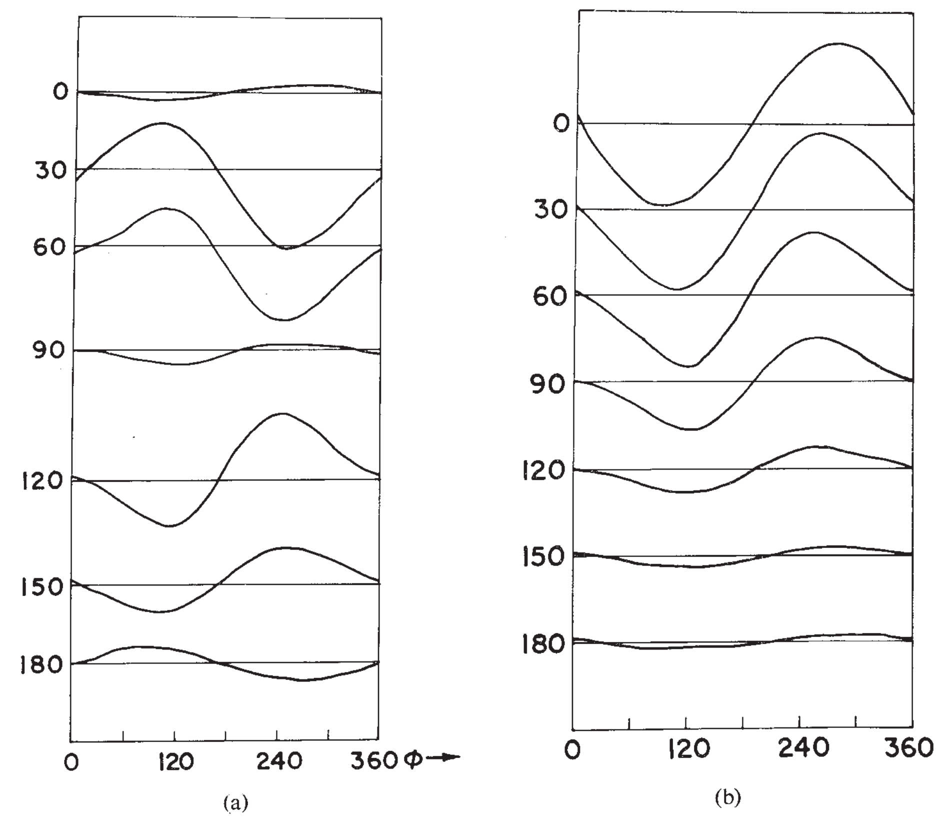

Fig. 3a. J_θ intensity is plotted for each latitude (on the y-axis) as a function of longitude or local time at $3R_e$.

Fig. 3b. J_φ intensity is plotted for each latitude (y-axis) as a function of longitude (x-axis) or local time at $3R_e$.

other hand at the midnight meridian ($\phi = 180°$), J_2 is again significantly small while we do have a very prominent J_3. This shows that the ϕ component of the current plays a very significant role on the night side of the magnetosphere.

(ii) While at both the poles $|J_2|$ is small as a function of latitudes, J_2 shows an inversion about the magnetic equator. J_3 however does not show this inversion, but the amplitude slowly decreases as we come down from north pole to south pole. One could understand this as due to the behaviour of the conductivity expression which is no longer symmetric with the Sun-Earth line as one would take in the case of solar zenith dependent conductivity. In the northern hemisphere ($\theta < 90°$), the first two terms of (2.11) are positive, while for $90° < \theta < 180°$, the second and third terms are both negative for the mid-day meridian. Hence on the mid-day meridian the number density is more in the northern hemisphere than in the southern one. However, on the mid-night meridian, while the middle term behaves in the same manner, the last term be-

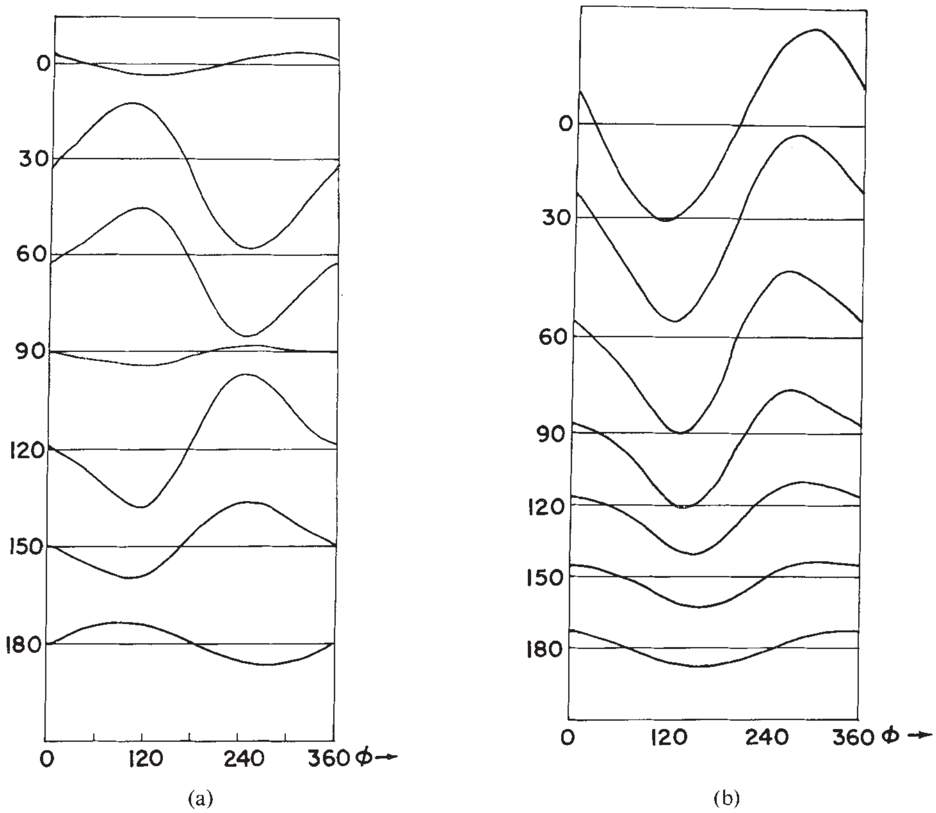

Fig. 4a. J_θ intensity is plotted for each latitude (y-axis) as a function of local time (x-axis) at $6.6R_e$.
Fig. 4b. J_φ intensity is plotted for each latitude (y-axis) as a function of local time (x-axis) at $6.6R_e$.

comes positive definite. In these plots one should remember that the scales for J_2 and J_3 are different, and that J_3 is invariably much higher than J_2.

In Figure 4a, b we have plotted these variations $(\theta-\phi)$ at 6.6 R_e which is spanned by ATS-satellites. The amplitudes of the two components are smaller than at $3R_e$. One may note that while Φ has a linearly increasing Y_{1s}^1 mode, the general amplitude is basically decided by the number density function entering through the conductivity, as well as the weakening of the dipole field as r increases. It is very difficult to visualize the contribution of the two causes separately. None the less one can assert that the velocity mode Y_{1s}^1 appearing through the potential Φ does become independent of the radius because of the gradient operation and hence the controlling factor is indeed σ. Hence any functional form of σ independent of r θ and ϕ will not be realistic and that it will not contribute towards the spatial and temporal behaviour of the current system. Again ATS-1 observations (Coleman, 1970; Cummings *et al.*, 1971) clearly indicate that at about $6.6R_e$ the amplitude of the daily variation of H predominates over the amplitude of the daily variations of V and D, indicating that the currents at these latitudes are mainly azimuthal in the equatorial plane. These observations substantiate our result amply. The amplitudes of these variations are again smaller than that at $3R_e$.

The current systems evaluated here again shows another feature. These currents do not change direction as we go outwards, i.e., there are no surfaces on which the current density is zero. This explains the feature that the magnetic field observed by ATS at 6.6 agrees in phase as well as amplitude with that observed at Honolulu. If there were surfaces in which the currents flew in opposite directions then the magnetic fields would have cancelled each other. We however observe in this analysis that while the intensity does fall off as a function of radius, the general directions of the current field components remain the same as we go outwards, and thus the induced magnetic field would also remain the same.

7. Conclusions

The main conclusions are the following:

(1) For any realistic model of the dynamo theory, we have to consider a conductivity which is a space time dependent function and not a constant.

(2) In developing a dynamo theory in the magnetosphere, the appropriate conductivity would be one for a highly rarefied completely ionized plasma and not the direct, Pederson, and Hall conductivities developed for a medium dominated by neutrals and a dense gas.

(3) The three dimensional dynamo current systems evaluated here do not show a periodicity or quasiperiodicity as a function of r. The currents maintain the same direction and hence the induced magnetic field varation measured either within the domain (at ATS position) or at the bottom of the system (at ground level) will have the same features.

(4) We have observed that the different harmonics have phases which depend upon the radial distance. Thus for example S_1^1 and C_1^1 have coefficients which are different and this shows itself in the phase.

This analysis however has not been carried to the extent as to give the ratio of the contributions from the magnetosphere to that from the ionosphere. This has not been achieved because the initial conditions that we have chosen here are only arbitrary and hence the results computed here correspond to an idealized case. A more realistic case would be to fit the boundary conditions at some preassigned level such as the ATS height, and this requires a much more accurate interpretation of the ATS data. The capability which now exists, of simultaneously measuring the daily variation of H at ground stations in low latitudes away from the effect of the equatorial electrojet and at synchronous altitude with geostationary satellites, would make it possible in the years to come to estimate with refinement the relative contributions of the different mechanisms under varying conditions.

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Appendix-1

The recurrence relations for the Legendre functions which have been used in this analysis are given here for the sake of completeness.

$$(2n+1)\cos\theta P_n^m = (n-m+1)P_{n+1}^m + (n+m)P_{n-1}^m$$

$$\begin{aligned}(2n+1)\sin\theta P_n^m &= P_{n+1}^{m+1} - P_{n-1}^{m+1}\\ &= (n+m)(n+m-1)P_{n-1}^{m-1} - \\ &\quad - (n-m+1)(n-m+2)P_{n+1}^{m-1}\end{aligned}$$

$$2\frac{\mathrm{d}P_n^m}{\mathrm{d}\theta} = (n+m)(n-m+1)P_n^{m-1} - P_n^{m+1}$$

$$(2n+1)\sin\theta\frac{\mathrm{d}P_n^m}{\mathrm{d}\theta} = n(n-m+1)P_{n+1}^m - (n+1)(n+m)P_{n-1}^m$$

$$\begin{aligned}\frac{2mP_n^m}{\sin\theta} &= (n+m)(n+m-1)P_{n-1}^{m-1} + P_{n-1}^{m+1}\\ &= (n-m+1)(n-m+2)P_{n+1}^{m-1} + P_{n+1}^{m+1}\end{aligned}$$

$$2m\cos\theta P_n^m = \sin\theta P_n^{m+1} + (n+m)(n-m+1)\sin\theta P_n^{m-1}$$

$$\begin{aligned}(2n+1)\left(\cos\theta\frac{\mathrm{d}P_n^m}{\mathrm{d}\theta} + \frac{mP_n^m}{\sin\theta}\right) &= (n+1)(n+m)(n+m-1)P_{n-1}^{m-1} + \\ &\quad + n(n-m+1)(n-m+2)P_{n+1}^{m-1}\end{aligned}$$

$$(2n+1)\left(\cos\theta\frac{\mathrm{d}P_n^m}{\mathrm{d}\theta} - \frac{mP_n^m}{\sin\theta}\right) = -\left[nP_{n+1}^{m+1} + (n+1)P_{n-1}^{m+1}\right]$$

$$2m\cot\theta P_n^m = P_n^{m+1} + (n+m)(n-m+1)P_n^{m-1}$$

$$\frac{\mathrm{d}P_n^m}{\mathrm{d}\theta} - m\cot\theta P_n^m = -P_n^{m+1}$$

$$\frac{\mathrm{d}P_n^m}{\mathrm{d}\theta} + m\cot\theta P_n^m = (n+m)(n-m+1)P_n^{m-1}.$$

Appendix-2

The terms on the right hand side of Equations (3.4) are given in this appendix. In the analysis we have compared the coefficients of similar harmonics.

$$P_4^2\sin 2\phi\left[-\sigma_2\frac{(2\sigma+9)}{35}\frac{1}{r}\right]$$

$$P_3^2\sin 2\phi\left[\sigma_2\frac{(\sigma-13)}{42}\frac{1}{r}\right]$$

$$P_5^1 \cos\phi \left[\sigma_2 \frac{32(\sigma+1)}{105} \frac{\mu}{r^5} \right]$$

$$P_4^1 \sin\varphi \left[-\sigma_1 \frac{6(2\sigma+9)}{35} \frac{1}{r} \right]$$

$$P_3^1 \sin\varphi \left[-\sigma_0 \frac{4(\sigma+4)}{5} \frac{1}{r} \right]$$

$$P_3^1 \cos\varphi \left[\sigma_2 \left\{ \frac{2(\sigma+8)}{15} \frac{1}{r^3} + \frac{\mu(7\sigma-26)}{15} \frac{1}{r^5} \right\} \right]$$

$$P_2^1 \sin\varphi \left[-\sigma_1 \frac{(11\sigma+46)}{21} \frac{1}{r} \right]$$

$$P_1^1 \sin\varphi \left[-\sigma_0 \frac{(\sigma+9)}{5} \frac{1}{r} \right]$$

$$P_1^1 \cos\varphi \left[\sigma_2 \left\{ -\frac{2(2\sigma+1)}{5} \frac{1}{r^3} + \frac{\mu(57\sigma-11)}{35} \frac{1}{r^5} \right\} \right]$$

$$P_5 \left[\sigma_1 \frac{32\mu(\sigma+1)}{21} \frac{1}{r^5} \right]$$

$$P_4 \left[\sigma_0 \frac{48(2\sigma+1)}{35} \frac{\mu}{r^5} \right]$$

$$P_3 \left[\sigma_1 \left\{ \frac{2(\sigma+8)}{5} \frac{1}{r^3} + \frac{(53\sigma-82)}{15} \frac{\mu}{r^5} \right\} \right]$$

$$P_2 \left[\sigma_0 \left\{ \frac{2(\sigma+6)}{3} \frac{1}{r^3} + \frac{\mu(27\sigma-60)}{7} \frac{1}{r^5} \right\} \right]$$

$$P_1 \left[\sigma_1 \left\{ \frac{6(23\sigma-47)}{35} \frac{\mu}{r^5} + \frac{2(2-\sigma)}{5} \frac{1}{r^3} \right\} \right]$$

$$P_0 \left[\sigma_0 \left\{ -\frac{2\sigma}{3} \frac{1}{r^3} + \frac{12(\sigma-2)}{5} \frac{\mu}{r^5} \right\} \right]$$

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ORGANIZATION FOR DEVELOPMENTAL TASKS: ATOMIC ENERGY COMMISSION OF INDIA

Kamla Chowdhry and Vikram Sarabhai

IT is a common observation that understanding of the human factors of growth of institutions has lagged far behind advances in science and technology. Certainly some of the most perplexing and urgent problems of our time are not technological but human, organizational, social and political. One way to advance our understanding of the growth of institutions is through a wider sharing of knowledge gained from meaningful experience.

This article is presented in this spirit of sharing the meaning of a comprehensive experience. At one level it is the story of atomic energy in India, at another level the story of Bhabha, the great innovator and organizer, and yet at another level, of the growth of institutions and the introduction of change based on advanced technologies.

One often talks of the imprint of the personality of a man on the organization he has created. Surely, what is referred to is the manner in which his assumptions concerning the task and the motivations of people are translated into a management system. Decentralization, delegation, reporting and control, evaluation and motivation are aspects of the management system closely related to the objective of an organization. They also bear the imprint of assumptions which are made concerning the task. At one end of the spectrum are certain administrative services, acting on past precedents and traditions providing security and continuity, impersonalized to the extent that if one person is substituted by another, every one knows how the successor will behave and operate under a given set of circumstances. At the other end, there are organizations based on research and development, involving individuals who act on insights and hunches, non-conformists questioning assumptions, innovating and learning. The two extremes require organizations and working cultures which are rather different. Yet many tasks encountered in the contemporary world call for organizations wherein creative thinking and innovation are essential ingredients of survival as well as growth. The diversity of tasks that require to be performed within the governmental framework require individuals who are not only sensitive to the needs of the two cultures but can also provide a dynamic relationship to the conflicting systems. In this context, the study of atomic energy in India is of relevance, for a culture appropriate to research and developmental tasks was established within the framework of government.

This article examines the assumptions which influenced Bhabha's strategy when he created the Atomic Energy Commission, the Department of Atomic Energy and the Atomic Energy Establishment at Trombay. It follows how strategy was translated into organizational structures and administrative practices. Moreover, it discusses the implications of his assumptions and strategy indicating their relevance to other organizations and tasks.

APPROACH TO DEVELOPMENT OF SCIENCE[1]

The initial conditions for developing institutions based on modern science and technology are somewhat different in India (and many other developing countries) as compared to the more developed countries. Even though there is a substantial base of those who have a University degree, there is a shortage of competent scientists, technologists, and administrators. Bhabha emphasized that in India, the first step in building institutions was the training and development of people. In the Tata Institute of Fundamental Research, the first Institute Bhabha started in 1944, he brought together a group of young scientists who were given all the facilities and freedom to develop research and to develop "second generation" scientists. From the beginning he was careful not to take scientists away from universities, for he believed this would weaken the universities and consequently any programme of development of scientists in India. He worked towards strengthening the relationship between the Tata Institute of Fundamental Research and universities.

On the other hand, many national laboratories were at that time filling their senior posts with mature scientists from universities.

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[1] This section is largely based on Bhabha's paper "Science and the Problems of Development", Bombay, Hind Kitab Press, 1966.

Bhabha said, "the attempt to fill senior posts by mature scientists from outside must inevitably lead to their being taken away from the only institutions which have scientists in some measure, however inadequate in an underdeveloped country, namely, the universities". He added that this step by the national laboratories had resulted in a weakening of universities by taking away their (universities) most valuable asset.

In starting a new institution Bhabha considered it important to build the organization around people rather than draw an organization chart first and then fill in the vacancies. In discussing the Tata Institute of Fundamental Research he said, "No organizational chart of the future development of the Institute was submitted either when it was founded or later, and the philosophy has always been to support ability whenever it is found in the fields of work covered by the Institute. Indeed, the philosophy underlying the founding of the Institute was the same as that underlying the Max Planck Institutes in Germany, namely, "The Kaiser Wilhelm Society shall not first build an institute for research and then seek out the suitable man but shall first pick up an outstanding man, and then build in institute for him'."

Two examples are given of building projects and development around people. To quote Bhabha:

(1) "As early as June 1944, Sir A. V. Hill had written to me suggesting that biophysics was a neglected subject in India and that it should be taken under the wing of the Institute. While I agreed with his suggestion, I did not think that it would be wise to embark on this line till someone was found, mature enough to be able to work on his own and build up a group. When, however, in 1962 my attention was drawn by the late Dr. Leo Szilard to a very promising Indian molecular biologist, it was decided to start work in microbiology, which has since then been growing very satisfactory.

(2) "Four Indian radioastronomers had jointly written identical letters to the Chairman of the University Grants Commission, the Director General of the Council of Scientific and Industrial Research, and to me as the Chairman of the Atomic Energy Commission offering to return to India as a group and establish radioastronomy here, if facilities and support could be given to them. Having ascertained that the members of the group had considerable original work to their credit and were of sufficient maturity to be able to work on their own in India, it was decided to take up radioastronomy at the Institute."

With such an approach only the broad lines of work were laid down and the greatest possible freedom was given to the staff to develop new ideas and fruitful lines of work. Institutions grew on the ability of various groups to expand fruitfully.

Equally important was Bhabha's approach to administration of scientific research and development. He said that it is a fallacy to believe that "we are reasonably advanced in administration but backward in science and technology". He was aware that different tasks and institutions required different types of administrative practices, and that the transfer of government administrative practices, either to industrial enterprises or research and development produced inefficiencies and lack of morale.

Thus he said, "The type of administration required for the growth of science and technology is quite different from the type of administration required for the operation of industrial enterprises, and both of these are again quite different from the type of administration required for such matters as the preservation of law and order, administration of justice, finance, and so on. It is my personal view, which is shared by many eminent foreign scientists, that the general absence of the proper administrative set-up for science is a bigger obstacle to the rapid growth of science and technology than the paucity of scientists and technologists, because a majority of the scientists and technologists we have are made less effective through the lack of the right type of administrative support. The administration of scientific research and development is an even more subtle matter than the administration of industrial enterprises, and I am convinced that it cannot be done on the basis of borrowed knowledge."

Bhabha introduced administrative practices in the Tata Institute of Fundamental Research and later in the Department of Atomic Energy, which were alien to established university and government procedures. Scientists and engineers were paid according to their merit and maturity, rather than in terms of organizational position and status. Promotion did not imply handing over charge of one task and going over to another. Positions were created whenever competent people were available for identified tasks. As with personnel functions, Bhabha established for procurement as well as for civil construction procedures in which major decisions were taken by the scientists concerned.

Another factor that was important in Bhabha's approach was to provide to scientists and technologists opportunities of building their own know-how, of minimizing dependence on foreign know-how, and of gaining experience even at the risk of failures. Thus, he said, "the emphasis has been throughout on developing know-how indigenously and on growing people able to tackle the tasks which lie ahead. The generation of self-confidence and the ability to engineer and execute industrial projects without foreign technical assistance have been major objectives." The Apsara reactor with its control system, which was decided to be built in 1955 "was entirely designed and built by our own scientists and engineers in just over a year". Regarding the control system for the reactor he said, "the important fact remains that the original control system even if more cumbersome and less elegant gave trouble free service for four years, and the confidence gained in doing it oneself fully justified the course that had been followed". Similarly in discussing the fuel fabrication plant built by the scientists and engineers at Trombay, he said, "producing fuel elements (from nuclear grade uranium metal) at a time when there were only about half a dozen countries in the world producing their own fuel elements added further to the self-confidence of our staff to undertake difficult tasks". To quote further his approach on foreign assistance:

> "The recent stoppage of foreign aid has shown our tremendous foreign dependence on a vast variety of materials and equipment, many of which could and should have been produced in the country long before this. We have found that a very large number of them can be produced as a result of the know-how which already exists in scientific organizations here, and steps are being taken to produce these in the country without foreign assistance. The results will show themselves within the next few years, and I have no doubt that the confidence which Indian technologists will gain thereby will spread to Indian industrialists and administrators, many of whom not having any basis of technical judgments of their own, are inclined to play safe by relying on foreign consultancy. Many examples can be given of foreign collaboration resulting in badly engineered plants or technical mistakes, and when such technical mistakes are corrected the foreign consultant benefits from the experience. Whereas, if an Indian scientific or engineering organization had been employed, the experience gained even from initial failures would have been a gain to the country. The Soviet Union did not hesitate to follow this path. One should also remember that in buying foreign know-how one is paying for an element which covers the cost of research and development done by the foreign consultant, and it is clear that a more permanent benefit would result to the country if this money were made available for supporting research and development in India."

The importance of Bhabha's approach as applied to industrial development is even more significant.

> "The steel industry has existed in India since the First World War, and one of the two steel plants was among the largest in the British Commonwealth in the early twenties. Yet, when these steel plants had to be expanded, it was necessary to draw upon foreign consultants and engineering firms to plan and carry out the expansion. When the Government decided to establish a steel plant in the public sector at Rourkela, a German consortium had to be asked to undertake the job. For the next steel plant with Russian technical collaboration. The third public sector steel plant at Durgapur had similarly to be set up with the help of a British consortium, and essentially the same method is being followed with regard to the fourth public sector steel plant at Bokaro. Thus, the construction and operation of a number of steel plants has not automatically generated the ability to design and build new steel plants. Unless powerful scientific and engineering groups are established during the construction and operation of existing steel plants as a matter of deliberate policy, the dependence on foreign technical assistance will continue and the steel industry will not reach a stage of technical self-reliance. A similar situation exists in almost every other industry."

A number of factors have been mentioned in this article which were emphasized by Bhabha. No single factor was decisive by itself. It was the combination and the inter-relatedness of these factors applied consistently that generated the forces of growth in the institutions with which Bhabha was connected.

GROWTH AND ACTIVITIES OF THE ATOMIC ENERGY COMMISSION OF INDIA

Atomic Energy Commission

Under the terms of the Atomic Energy Act, 1948, an Atomic Energy Commission was set up in August 1948. The Commission which was a policy-making body was assigned the tasks of "surveying the country for atomic minerals, to work and develop such minerals on an industrial scale, to do research in the scientific and technical problems connected with the release of atomic energy for peaceful purposes, to train and develop the necessary scientific and technical personnel for this work and foster fundamental research in nuclear sciences in its own laboratories and in the universities and research institutions in India". The decisions of the Commission were to be implemented through the Ministry of Natural Resources and Scientific Research.

Dr. Bhabha was appointed the first Chairman of the Commission. Other members were Dr. Bhatnagar, Director General of the Council for Scientific and Industrial Research, and Dr. Krishnan, Director, National Physical Research Laboratory—all eminent scientists and deeply committed to the growth of science and technology in India.

The Commission decided that its first task was to develop scientific personnel that would be needed in future for its activities. It also decided to use existing institutions to do its preliminary scientific work instead of planning at the outset a number of new laboratories. Foremost amongst the institutions used was the Tata Institute of Fundamental Research of which Bhabha was the Director. The early history of atomic energy in India is so closely interwoven with that of the Tata Institute of Fundamental Research, where the early work of atomic energy and of training scientists was done that it has rightly been called "the cradle of India's atomic energy programme". The Tata Institute of Fundamental Research undertook research and later certain administrative responsibilities for the Commission, such as selection of scientists, purchase of equipment and stores, etc.

By 1965 it was felt that research and development in the peaceful uses of atomic energy had made such important strides that a greatly expanded programme would be required. The expanded programme would include producing all the basic materials required for the utilization of atomic energy and the building of atomic power stations for producing electric power. The Government realized that in order to plan and implement the envisaged programme it would have to modify the Constitution of the Commission so as to give it full financial and executive powers. The notification of the Government concerning the organization of the Atomic Energy Commission stated: "These developments call for an organization with full authority to plan and implement the various measures on sound technical and economic principles and free from all non-essential restrictions or needlessly inelastic rules. The special requirements of atomic energy, the newness of the field, the strategic nature of its activities and its international and political significance have to be borne in mind in devising such an organisation."[2]

In 1958, the constitution of the Atomic Energy was amended to provide it with greater powers. The amended constitution stated:

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[2] **Department of Atomic Energy Resolution No. 13/7/58-Adm. dated March 1, 1958**

"(*a*) The Commission shall consist of full-time and part-time members and the total number of members shall not be less than three and not more than seven; (*b*) The Secretary to the Government of India in the Department of Atomic Energy shall be the *ex-officio* Chairman of the Commission; (*c*) Another full-time member of the Commission shall be the Member for Finance and Administration, who shall also, be *ex-officio* Secretary to the Government of India in the Department of Atomic Energy in financial matters; and (*d*) The Director of the Atomic Energy Establishment, Trombay, shall be the third *ex-officio* full-time member in charge of research and development."

Regarding the Member for Finance and Administration it stated: "The Member for Finance and Administration shall exercise the powers of the Government of India in all financial matters concerning the Department of Atomic Energy. No proposal with financial implications shall be sanctioned without his prior concurrence."

A full-time member for Finance and Administration was included because the idea was that this member would be the chief official in the Department for finance and administration. However, it was soon realized that with the given set-up and nomenclature there was confusion as to the responsibility and accountability of the Chairman-cum-Secretary and the Member for Finance and Administration.

In 1962, the constitution of the Atomic Energy Commission was again amended largely to clarify the role of the Member for Finance in relation to the accountability of the Chairman-cum-Secretary of the Department. The revision provided: "(*a*) Instead of having a full-time Member for Finance and Administration, one of the members of the Commission was to be the Member for Finance and he was to exercise the powers of the Government of India in financial matters concerning the DAE except insofar as much powers had been or are in future conferred on or delegated to the Department. (*b*) The Chairman could also authorize any member of the Commission to exercise such of his powers and responsibilities as he may decide." Thus, it was amply clarified that the Secretary was responsible for the total administration of the department and that the Finance Member was to advise only on matters not delegated to the Department. It was also considered unnecessary to have a full-time Member for Finance.

The size of the first Commission was three members. With the first amendment, the Member for Finance was added, and later Shri J. R. D. Tata and Dr. Vikram Sarabhai were added. At no time the

Commission consisted of more than five members. In early 1966, the Commission was: Dr. H. J. Bhabha (Chairman), Shri S. Jagannathan (Member for Finance), Shri J. R. D. Tata, Shri Dharam Vira (Cabinet Secretary), and Dr. Vikram A. Sarabhai.

Bhabha being also Director of the Atomic Energy Establishment, Trombay, there was no separate member for Research and Development.

Some important landmarks in the development of Atomic Energy in India are given in Appendix I (p.20).

In reviewing the developments of atomic energy in India, three phases can be identified. The first phase from 1944 to 1954 was the training of scientists, and the starting of scientific groups under the leadership of competent scientist who could, with appropriate facilities and "autonomy of work", develop an excellent work. In this phase, the Tata Institute of Fundamental Research played a significant role.

The second phase could be broadly identified from 1954 to 1962. It marked the growth of the Atomic Energy Establishment at Trombay with emphasis on problems of technology. Three research reactors were built, and simultaneously, the prospecting of atomic minerals was pursued energetically through the Atomic Minerals Division. In this phase, research and development were important leading to pilot plants processing uranium ore, fabricating fuel elements, manufacturing electronic instruments, developing nuclear engineering for reactors, building a plutonium extraction plant, and establishing other facilities at Trombay.

The third phase which commenced around 1962 involved a logical continuation of the earlier development. This phase was the utilization of knowledge and skills acquired. Emphasis was placed on the contribution of the Department of Atomic Energy to economic development through atomic power projects and public sector industries based on the technology developed at Trombay. Trombay was considered a nursery where new developments would be continually nurtured and other sites in the country were identified where know-how and processes could be commercially established.

In the following sections, the role and management system of the Department of Atomic Energy with special reference to the Atomic Energy Establishment at Trombay are outlined.

Department of Atomic Energy

By 1964, the activities of the Commission had so expanded that the Government decided to set up a separate Department of Atomic Energy. The Minister in charge of the Department was the Prime Minister, at that time Shri Jawaharlal Nehru. For administrative convenience and close contacts with the main scientific activities which were in Bombay, the Department's headquarters were located in Bombay instead of Delhi. The Secretary of the Department was also the *ex-officio* Chairman of the Commission.

The research units, projects and other enterprises for which the Department of Atomic Energy was responsible in 1966 are: (1) Atomic Energy Establishment, Trombay; (2) Tarapore Atomic Power Project; (3) Rajasthan Atomic Power Project; (4) Madras Atomic Power Project; (5) Jaduguda Mines Project; (6) Thumba Equatorial Rocket Launching Station; (7) Space Science and Technology Centre; (8) Experimental Satellite Communication Earth Station; (9) Atomic Minerals Division; and (10) Trombay Township Project.

There are a number of institutions which are administratively attached to the Department of Atomic Energy for purposes of receiving grants-in-aid from the Central Government. The institutions falling under this category are: (1) Tata Institute of Fundamental Research; (2) Tata Memorial Hospital, (3) Indian Cancer Research Centre, (4) Physical Research Laboratory, and (5) Saha Institute of Nuclear Physics.

The Indian Rare Earths Limited, a Government Company, is under the administrative control of the Department. Proposals are also afoot to have the following industrial operations converted into public sector undertakings: (1) Electronics Production Unit at Hyderabad, and (2) Jaduguda Uranium Mines & Mill.

The Department has always been of the view that the constituent units of the Department should have wide powers for their day-to-day working. The Heads of these units have, therefore, been declared as Heads of Departments for administrative purposes and in the case of large projects, such as the Atomic Power Stations, apart from the powers delegated to Project Administrators as Head of the Department, fairly wide powers have been given to the Project Boards to enable them to give decisions on all administrative, financial and technical matters arising in connection with the execution of the projects. Only in a few restricted fields, the Boards are required to come up to the Department of Atomic Energy for sanctions.

In order to understand the role of the Department in relation to the units, the process of decision-making, service and control functions, selection and evaluation procedures, are discussed with reference to the Atomic Energy Establishment, Trombay.

Atomic Energy Establishment, Trombay (Bhabha Atomic Research Centre)

In 1954, the Commission decided to set up a separate institution for research and development—the Atomic Energy Establishment Trombay (AEET). To the existing groups for Chemistry and Metallurgy which were operating till then under the Department, were added the scientific groups for theoretical physics, nuclear physics and electronics, which were working on behalf of the Commission at the Tata Institute of Fundamental Research. Along with the scientists were transferred a few administrators to man the newly established Atomic Energy Establishment, Trombay. The number of officers involved in the transfer were about 54. These formed a numerically significant group in the Establishment and hence were able to carry successfully with them a culture appropriate to research and development.

In contrast, the established pattern of setting up new research laboratories was at that time significantly different. Although many of them were created under autonomous organizations, they were started in many cases by a "Planning Officer" seconded by Government. The result was a transfer of culture, but in this case of government administrative practices of recruitment, budgetary controls, purchase of equipment, etc., that were in fact inappropriate to the functioning of a scientific institution. The autonomy that was given to these research institutes was lost to a large extent by the omnibus adoption of Government rules and regulations.

By 1966, the Atomic Energy Establishment, Trombay was the largest scientific centre in the country. It employed a total of about 8,500 persons, of whom approximately 2,000 were professional scientists and engineers, and another 3,000 were technical staff, many of whom are science graduates. The annual budget of the Establishment is about Rs. 11 crores.

For the first few years the main task at Trombay was to provide much of the scientific knowledge and understanding needed to design and construct reactors. The work soon expanded into many fields—atomic fuel, heavy water, radioisotopes, electronic instrumentation and equipment, uranium plant, agriculture, health physics, medical, etc.

The organization structure of the Atomic Energy Establishment, Trombay is given in Appendix II (p. 21) The work is divided into five main research groups and an administration group, all reporting to the Director. The research groups and administrative functions are:

Research Groups	*Administration Groups*
1. Physics	Personnel
2. Metallurgy	Accounts
3. Electronics	Purchase and Stores
4. Engineering	Scientific Information (including Library)
5. Biology	

Within the broad policy formulated by the Atomic Energy Commission, the Director, Atomic Energy Establishment Trombay, is assisted in his scientific and administrative decision-making by the Trombay Council and the Trombay Scientific Committee. The Trombay Scientific Committee consists of the Directors of five major research groups and 25 heads of Divisions. The Committee discusses proposals of research projects from each division, equipment and personnel required in relation to each project, and other related matters. The Committee meets once a fortnight.

The Trombay Council consists of the five Directors of Research Groups and the Administrative Controller. The Director, Atomic Energy Establishment Trombay, is the Chairman of the Council. The Council discusses not only action to be taken arising from current problems, but also forward planning based partly on information from the Chairman and partly on information from the Trombay Scientific Committee. The Council meets once a week.

Within the approved budget and subject to specific approval of capital items in the ways outlined, Trombay has considerable autonomy to manage its own financial affairs. By agreement of the Commission, the Director delegates financial powers up to approved limits to Directors of Research Groups and Divisional heads. Within the overall budget there are divisional budgets.

The Director of the Trombay Establishment is an *ex-officio* Member of the Atomic Energy Commission for Research and Development and has been delegated wide powers. Some idea of the delegated powers of the Director can be seen from the following: (*i*) Reappropriation of funds under the Revenue Grant, (*ii*) Creation of temporary posts up to a salary of Rs. 2,000/- p.m., (*iii*) Granting higher starting pay and grant of advance increments, (*iv*) Sanction contingent expenditure after consultation with the internal finance adviser regarding availability of funds, and (*v*) Write off losses up to Rs. 25,000 in respect of stores. The Director can delegate his powers to any authority subordinate to him.

The problem of consultation, communication and control between the Atomic Energy Commission and the Atomic Energy Establishment Trombay was relatively simple since Bhabha was the Chairman of the Commission, Secretary of the Department, and Director of Atomic Energy Establishment. Projects which were approved at the Trombay Scientific Committee and the Trombay Council were assured simultaneously the sanction of the Department and the Commission because of Bhabha's common role. In such a situation, the role of administration in the Secretariat became one of service rather than of control. The Department assisted in getting the necessary equipment, stores, foreign exchange, etc., for carrying out projects.

Great care was given to the selection, training, development and appraisal of staff. In general, the policy was to recruit young science graduates, train and develop them within the Establishment. In order to meet the growing requirements for suitable scientific personnel a Training Institute was started in 1957. Selections are made on the basis of recommendations of duly constituted selection committees with elaborate selection procedures. Experts from universities and industry are invited to serve on these selection committees. Applications from science and engineering graduates with first and second class degrees are invited. Each selected candidate is given a stipend of Rs. 300/- per month. The faculty of the Training School is partly from the Atomic Energy Establishment Trombay and partly from the Tata Institute of Fundamental Research. In 1965, about 3,400 applications with first and second class degrees were received. Out of these 251 were selected on the basis of an interview—130 actually joined the school, and 125 completed the course and were appointed at Atomic Energy Establishment Trombay and in other units of the Department. About these young trainees, Bhabha said, "at the end of two to three years they become very useful scientists. The best among them are likely to become future leaders. We have found this method of recruitment very satisfactory, and although it has placed a heavy load on our senior staff by making the spectrum of our scientific staff much heavier at the junior levels than as it should be, it has provided a powerful source of able young scientists on the basis of which the programme can be expanded continuously in future."[3]

The evaluation procedures at the Atomic Energy Establishment Trombay are the same as those evolved by Bhabha at Tata Institute of Fundamental Research. In evaluating a research worker's performance the first step is for the research worker to write his own report about his past performance in relation to the tasks set, mentioning any special accomplishments or problems. This report is then processed independently by two other assessors. The total report is then forwarded to the Director with recommendations for increments or promotions. Promotions from one grade to another are made not on the basis of vacancies, but on the development and worth of the individual research worker.

Bhabha was the Director of the Atomic Energy Establishment Trombay as well as of the Tata Institute of Fundamental Research. Practices and procedures "innovated" at the Tata Institute of Fundamental Research were used at the Atomic Energy Establishment Trombay, so that tested administrative practices appropriate to research and developmental tasks were introduced within a government organization.

SOME IMPLICATIONS

The question arose "Why did it happen? Are the experiences drawn from the growth of atomic energy in India translatable to other institutions and fields?" In the account we have presented, we cannot help noting a remarkable coming together of people and events: Independent India led by Jawaharlal Nehru who believed in transforming the nation through the application of science; Bhabha, a sophisticated engineer-cum-theoretical physicist who enjoyed the confidence of Nehru and possessed a wide international reputation and contacts; the exploding of the atom bomb over Hiroshima and Nagasaki which led to an unprecedented nuclear arms race under conditions of great secrecy; a horrified world eager to promote the peaceful uses of the atom and thereby coping with the guilt arising from ruthless military preparations; the release of scientific and technological know-how on an unprecedented scale following the first Atoms for Peace Conference in 1954, making available to countries, such as India, basic data which in other areas of economic significance could be purchased only at great cost. But if the ecology

[3] S. N. Gupta (Ed.), *Ten Years of Atomic Energy in India, 1954-64*, Bombay, Times of India Press.

and the factors for growth were ripe to make possible what has been described in this article, there is nevertheless a lesson in the story, which has significance in a much wider context. The following is a summary of what are believed to be factors contributing to the success of atomic energy in India and it is hoped that some useful guidelines will emerge, on the one hand, for policy makers concerned with developing institutions and organizations and, on the other hand, for organizational structures and administrative practices relevant wherever developmental tasks are to be undertaken:

(1) The concern, care and nurture of people who have knowledge and skills conveyed to them a sense of trust and the significance of their role in building society. Bhabha received all these from Shri J. R. D. Tata and Prime Minister Nehru, and in turn, gave it to the young scientists and engineers who came to work with him.

When Bhabha returned to India during World War II the Dorab Tata Trust created a Chair for him at the Institute of Science, Bangalore, so that he would have the freedom and facilities to do research. Later in 1944, when Bhabha wrote to Shri J. R. D. Tata suggesting an Institute for fundamental research in physics and mathematics, the Tatas accepted the proposal and the financial responsibility for such an idea. It is significant to note that the Tatas supported the idea at a time when nuclear physics had not become the "bandwagon" of science and more than a year before the explosion of the first atom bomb in Hiroshima. Also as Bhabha pointed out at a time "before it had been made public that atomic piles had been successfully operated and long before there was any talk of atomic power stations".

Bhabha also received support and understanding to an unusual degree from Prime Minister Nehru. Both men saw the essential role of science in transforming not only the economy of the country but transforming man. Nehru believed that if India was to be transformed from an industrially underdeveloped to a developed country, it was essential to establish science as a live and vital force in society. Nehru was the President of the Council for Scientific and Industrial Research, and later when the Department of Atomic Energy was established, he became the Minister in charge of the Department.

As mentioned earlier, Bhabha's approach to building institutions was to build the organization around men. No organization chart stood in the way of recognizing and rewarding talent. The Apsara reactor was built almost entirely by Indian scientists and engineers. He conveyed confidence in the ability of men and the men usually rose to the occasion. Bhabha "protected" his scientists from bureaucratic procedures and organized administration largely as a service rather than a control function.

(2) The combination of policy-making, executive and scientific roles provided the Chief Executive, power, freedom and authority which were important. Bhabha was the Chairman of the Atomic Energy Commission, the Secretary of the Department of Atomic Energy, the Director of Atomic Energy Establishment Trombay, and Director of the Tata Institute of Fundamental Research. The combination of these four roles provided the Chief Executive with sufficient freedom and flexibility in decision making and commitment of resources. It also meant that the Chief Executive had powers and responsibilities which permitted full accountability.

The combination of these roles also meant that Bhabha was able to keep his "grass-roots" in scientific research. It was this facility of working as a policy maker, organizer and administrator on the one hand, and participating in the scientific work at the "coalface" level on the other hand that provided him the on-going understanding to motivate and manage his research workers. In research laboratories, and in other developmental tasks it seems important that the Chief Executive, besides policy-making and administration, maintain direct contact with his professional role. The creation of administrative practices appropriate to a given technology or set of tasks comes with familiarity and knowledge-of-acquaintance of the technology or tasks concerned.

(3) The early beginnings of any institution are crucial, and the "culture" (or lack of it) brought by the first entrants play a significant role in establishing norms, procedures and practices in the organization. The numbers should be large enough to achieve a critical size to permit positive interactions.

The establishment of research groups and the development of second generation scientists in the Tata Institute of Fundamental Research and in the Chemistry and Metallurgy Groups of the Commission preceded the setting up of the Atomic Energy Establishment at Trombay by about ten years. This transfer of a large group rather than a few individuals was significant in terms of the "culture" and success at the Atomic Energy Establishment, Trombay. In this connection, it is often necessary to spin off new institutions from existing ones transferring not only expertise but a social culture appropriate to the task.

An inappropriate social culture can also be transferred by appointing persons from a different working "culture". In this connection, the appointment in a key position or in large numbers at lower positions, of competent Government officials whose experience is primarily derived from routine administration, in research organizations or in industrial enterprises is very questionable. Even though many of these organizations are established as autonomous in the legal sense, administrative practices are introduced which negates the formal autonomy granted. The existing government procedures of selection, promotion, evaluation, budgetary controls, buying of supplies and equipment are highly inappropriate to the effective functioning of scientific laboratories and industries involving complex technologies. In other words, conditions have to be created through the selection of appropriate men and through association with a mother organization to ensure that the formal and administrative cultures support each other for the fulfilment of the task.

(4) In professional groups, scientists, engineers and others, it is important to recognize that motivation and control is largely inherent and contained in professional commitments. In organizations using large professional groups, the role of administration has largely become one of service and not of control. This requires a basic change in attitudes rather than a change in procedures and practices.

In the Atomic Energy Establishment, Trombay and other units administratively connected with the Department of Atomic Energy, the organization structure and procedures were those of decentralization. There was a minimum organization structure and formal control. Even though there was a hierarchical structure, because of the nature of work it was not used as a means of communication and decision-making.

Within the broad policy set, research groups discussed and defined their objectives and targets. When research projects were approved, associated with it was approval for budgets, equipment and manpower. Budgetary and other controls were self-contained in the formulation of projects. This again re-emphasized the role of administration as facilitation of work rather than outside control. The need to control is almost an inevitable psychological product of the structured field of which bureaucratic organizations are an example. With the devaluation of hierarchical authority and positional status in scientific work, mechanisms of administrative control were also devaluated. Control was exercised through discussion and judgment of peers.

(5) The body to which the Chief Executive refers for policy and strategic decisions must be compact in size and consist of members chosen for their expertise and roles, rather than from a representational angle.

The number and membership of the Atomic Energy Commission were important factors in setting the "tone" and "quality" of meetings and the policy decisions taken there. As mentioned earlier, the members of the first Commission were Dr. Bhabha, Chairman, Dr Shanti-swarup Bhatnagar and Dr. Krishnan, Director of the National Physical Laboratory. When the Department of Atomic Energy was established, a member for Finance and Shri J. R. D. Tata were added as members. Subsequently, Dr. Vikram Sarabhai was invited to be a Commission member. The Commission consisted of 5 to 6 members (The Board of the C.S.I.R. at present consists of 34 members), all significantly able to contribute to policy making regarding nuclear energy and its development in India.

(6) There is a need for a constant interplay between the basic sciences, technology and industrial practice of economic progress is to result from the activity undertaken. The wearing of several hats by the same person, as in the case of Bhabha and the mobility of personnel from one type of activity to another have undoubtedly provided the impetus for growth in the projects of the Department of Atomic Energy. We may contrast this with the practice prevalent in higher educational institutions for basic sciences and technology and national laboratories where the work of applying the results of research to practical ends has to be done through other units, not organically related to the laboratories or the men that work in them.

(7) The conditions under which scientists and professional workers are motivated are somewhat different from those who work in bureaucratic or industrial enterprises. Money, hierarchical status and power are important needs for most, but to scientists and professional groups the need for autonomy of working conditions and self-development are also important factors.

Bhabha's philosophy was to identify the right persons, and then give them all the autonomy and support they wanted within the broad objectives. As mentioned earlier, these were also Bhabha's needs which were supported by Nehru and Tata.

There were a number of research institutions administratively connected with the Department of Atomic Energy—the Tata Institute of Fundamental Research, the Saha Institute of Nuclear Research, the Physical Research Laboratory at Ahmedabad, and other educational institutions. This loose federation of institutions provided a unique opportunity to the scientists of sharing experiences and information. Bhabha also encouraged and sponsored his scientists to attend international meetings. The opportunity of meeting scientists who came from abroad, of sharing facilities, of attending meetings and symposia provided by intellectual environment, which would have been difficult to provide by any single institution. The relative autonomy, the mobility and interaction of scientists and engineers nationally and internationally were important factors in the motivation and morale of these people.

CONCLUSION

In this story of the phenomenal growth of atomic energy in India, it has been attempted to identify some factors which facilitated growth. By implication it is also possible to discern factors which are unhelpful and inhibit development. The various factors indicated earlier are interrelated and mutually dependent. A change in one influences the total scheme of things, for in organizational structures and culture, the whole is more than the sum of its parts. Structures, procedures and techniques are important but these must be sustained by a cluster of attitudes conveying care, trust and nurture on the part of responsible persons. There is need to understand that there is a shift from simple to complex technologies, from stability to innovation, from experience-based knowledge and skills to highly conceptual knowledge. The understanding of this change means the recognition of socio-technical systems rather than a mechanistic organization structure, the recognition that highly trained and professional groups have different needs and motivations, the realization that hierarchical structures and systems need to be minimized and that the concept of control is inherent and contained in professional commitments rather than exercised from outside.

APPENDIX I

Some Important Landmarks in the Development of Atomic Energy in India

1945	April	Tata Institute of Fundamental Research
1948	April	Atomic Energy Act of 1948 received assent of Governor General
	August	Atomic Energy Commission set up
1950	August	Indian Rare Earths registered as a limited company

1954	January	AEC decides to set up Atomic Energy Establishment, Trombay
	August	Department of Atomic Energy created
1955	March	AEC decides to build Apsara reactor
	August	First U.N International Conference on the Peaceful Uses of Atomic Energy opens in Geneva under the presidentship of Dr. Bhabha
1956	February	Work on CIR reactor with Canadian assistance Radiochemistry Laboratory set up
	May	Decision to set up Uranium Metal Plant and Fuel Element Fabrication Facility
	October	Travancore Minerals Ltd. registered as a limited company
1957	August	Training School started
1958	March	Constitution of AEC revised
	June	AEC reconstituted
	July	Decision to build Plutonium Plant
	August	Planning Commission approves the building of India's first atomic power station at Tarapur
1960	February	AEC decides to build Uranium Ore Mill at Jaduguda
	May	Erection of Zerlina reactor begins
	September	Heavy Water Reconcentration Plant commissioned
1962	February	Administrative responsibility for Indian Cancer Research Centre and Tata Memorial Hospital both at Bombay transferred to the Department to facilitate rapid development and expansion of medical facilities and research in cancer and other diseases with the help of isotopes, etc. Indian National Committee for Space Research constituted.
	March	Constitution of AEC further amended
	August	Decision to build second atomic power station at Rana Pratap Sagar, Rajasthan
	September	Atomic Energy Act, 1962 comes in force
	December	Kalpakkam selected as site for third atomic power plant
1964	January	Six more rockets launched from Thumba
	July	Three meteorological rockets launched from Thumba
	November	Three Nike-Apache rockets launched from Thumba in the international synoptic launching series.

ORGANISATION FOR DEVELOPMENTAL TASKS: ATOMIC ENERGY COMMISSION OF INDIA

by

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C O N T E N T S

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ORGANISATION FOR DEVELOPMENTAL TASKS:
ATOMIC ENERGY COMMISSION OF INDIA

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Introduction

It is a common observation that understanding of the human factors of growth of institutions has lagged far behind advances in science and technology. Certainly some of the most perplexing and urgent problems of our time are not technological, but human, organisational, social and political. One way to advance our understanding of the growth of institutions is through a wider sharing of knowledge gained from meaningful experience.

It is in this spirit of sharing the meaning of a comprehensive experience that we present this paper. At one level it is the story of Atomic Energy in India, at another level the story of Bhabha, the great innovator and organiser, and yet at another level, of the growth of institutions and the introduction of change based on advanced technologies.

We often talk of the imprint of the personality of a man on the organisation he has created. Surely, what we are referring to is the manner in which his assumptions concerning the task and the motivations of people are translated into a management system. Decentralisation, delegation, reporting and control, evaluation and motivation are aspects of the management system closely related to the objective of an organisation. They also bear the imprint of assumptions which are made concerning the task. At one end of the spectrum are certain administrative services, acting on past precedents and traditions providing security and continuity, impersonalised to the extent that if one person is substituted by another, every one knows how the successor will behave and operate under a given set of circumstances. At the other end, there are organisations based on research and development, involving individuals who act on insights and hunches, non-conformists questioning assumptions, innovating and learning. The two extremes require organisations and working cultures which are rather different. Yet many tasks encountered in the contemporary world call for organisations wherein creative thinking and innovation are essential ingredients of survival as well as growth. The diversity of tasks that require to be performed within the governmental frame work require individuals who are not only sensitive to the needs of the two cultures but can provide a dynamic relationship to the conflicting systems. In this context, the study of atomic energy in India is of relevance, for a culture appropriate to research and developmental tasks was established within the framework of government.

In this paper we shall examine the assumptions which influenced Bhabha's strategy when he created the Atomic Energy Commission, the

Department of Atomic Energy and the Atomic Energy Establishment at Trombay. We shall follow how strategy was translated into organisational structures and administrative practices. Moreover, we shall discuss the implications of his assumptions and strategy indicating their relevance to other organisations and tasks.

Approach to Development of Science*

The initial conditions for developing institutions based on modern science and technology are somewhat different in India (and many other developing countries) as compared to the more developed countries. Even though there is a substantial base of those who have a University degree, there is a shortage of competent scientists, technologists, and administrators. Bhabha emphasised that in India, the first step in building institutions was the training and development of people. In the Tata Institute of Fundamental Research, the first Institute Bhabha started in 1944, he brought together a group of young scientists who were given all the facilities and freedom to develop research and to develop 'second generation' scientists. From the beginning he was careful not to take scientists away from Universities, for he believed this would weaken the Universities and consequently any programme of development of scientists in India. He worked towards strengthening the relationship between the Tata Institute of Fundamental Research and the Universities.

On the other hand, many national laboratories were at that time filling their senior posts with mature scientists from Universities. Bhabha said "the attempt to fill senior posts by mature scientists from outside must inevitably lead to their being taken away from the only institutions which have scientists in some measure, however inadequate in an underveloped country, namely, the Universities". He added that this step by the national laboratories had resulted in a weakening of Universities by taking away their (Universities) most valuable asset.

In starting a new institution Bhabha considered it important to build the organisation around people rather than draw an organisation chart first and then fill in the vacancies. In discussing the Tata Institute of Fundamental Research he said:

> "No organisational chart of the future development of the Institute was submitted either when it was founded or later, and the philosophy has always been to support ability whenever it is found in the fields of work covered by the Institute. Indeed, the philosophy underlying the

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* This section is largely based on Bhabha's paper 'Science and the Problems of Development' - January 1966.

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> founding of the Institute was the same as that underlying the Max Planck Institutes in Germany, namely 'The Kaiser Wilhelm Society shall not first build an institute for research and then seek out the suitable man but shall first pick up an outstanding man, and then build an institute for him' ".

Two examples are given of building projects and development around people. To quote Bhabha:

> "As early as June 1944, Sir A.V. Hill had written to me suggesting that biophysics was a neglected subject in India and that it should be taken under the wing of the Institute. While I agreed with his suggestion, I did not think that it would be wise to embark on this line till someone was found, mature enough to be able to work on his own and build up a group. When however in 1962 my attention was drawn by the late Dr. Leo Szilard to a very promising Indian molecular biologist, it was decided to start work in microbiology, which has since then been growing very satisfactory".

> "Four Indian radioastronomers had jointly written identical letters to the Chairman of the University Grants Commission, the Director General of the Council of Scientific and Industrial Research, and to me as the Chairman of the Atomic Energy Commission offering to return to India as a group and establish radioastronomy here, if facilities and support could be given to them. Having ascertained that the members of the group had considerable original work to their credit and were of sufficient maturity to be able to work on their own in India, it was decided to take up radioastronomy at the Institute".

With such an approach only the broad lines of work were laid down and the greatest possible freedom was given to the staff to develop new ideas and fruitful lines of work. Institutions grew on the ability of various groups to expand fruitfully.

Equally important was Bhabha's approach to administration of scientific research and development. He said that it is a fallacy to believe that "we are reasonably advanced in administration but backward in science and technology". He was aware that different tasks and institutions required different types of administrative practices, and that the transfer of government administrâtive practices, either to industrial enterprises or research and development produced inefficiencies and lack of morale.

Thus he said:

> "The type of administration required for the growth of science and technology is quite different from the type of administration required for the operation of industrial enterprises, and both of these are again quite different from the type of administration required for such matters as the preservation of law and order, administration of justice, finance, and so on. It is my personal view, which is shared by many eminent foreign scientists, that the general absence of the proper administrative set-up for science is a bigger obstacle to the rapid growth of science and technology than the paucity of scientists and technologists, because a majority of the scientists and technologists we have are made less effective through the lack of the right type of administrative support. The administration of scientific research and development is an even more subtle matter than the administration of industrial enterprises, and I am convinced that it cannot be done on the basis of borrowed knowledge".

Bhabha introduced administrative practices in the Tata Institute of Fundamental Research and later in the Department of Atomic Energy, which were alien to established University and Government procedures. Scientists and engineers were paid according to their merit and maturity, rather than in terms of organisational position and status. Promotion did not imply handing over charge of one task and going over to another. Positions were created whenever competent people were available for identified tasks. As with personnel functions, Bhabha established for procurement as well as for civil construction procedures in which major decisions were taken by the scientists concerned.

Another factor that was important in Bhabha's approach was to provide to scientists and technologists opportunities of building their own know-how, of minimising dependence on foreign know-how, and of gaining experience even at the risk of failures. Thus, he said, "the emphasis has been throughout on developing know-how indigenously and on growing people able to tackle the tasks which lie ahead. The generation of self-confidence and the ability to engineer and execute industrial projects without foreign technical assistance have been major objectives." The Apsara reactor with its control system, which was decided to be built in 1955 "was entirely designed and built by our own scientists and engineers in just over a year." Regarding the control system for the reactor he said, "the important fact remains that the original control system even if more cumbersome and less elegant gave trouble free service for four years, and the confidence gained in doing it oneself fully justified the course that had been followed." Similarly in discussing the fuel fabrication plant built by the scientists and engineers at Trombay, he said, "producing fuel elements (from nuclear grade uranium metal) at a time when there were only about half a dozen countries in the world producing their own fuel elements added further to the self-confidence of our staff to undertake difficult tasks." To quote further his approach on foreign assistance:

> "The recent stoppage of foreign aid has shown our tremendous foreign dependence on a vast variety of materials and equipment, many of which could and should have been produced in the country long before this. We have found that a very large number of them can be produced as a result of the know-how which already exists in scientific organisations here, and steps are being taken to produce these in the country without foreign assistance. The results will show themselves within the next few years, and I have no doubt that the confidence which Indian technologists will gain thereby will spread to Indian industrialists and administrators, many of whom not having any basis for technical judgments of their own, are inclined to play safe by relying on foreign consultancy. Many examples can be given of foreign colloboration resulting in badly engineered plants or technical mistakes, and when such technical mistakes are corrected the foreign consultant benefits from the experience. Whereas, if an Indian scientific or engineering organisation had been employed, the experience gained even from initial failures would have been a gain to the country. The Soviet Union did not hesitate to follow this path. One should also remember that in buying foreign know-how one is paying for an element which covers the cost of research and development done by the foreign consultant, and it is clear that a more permanent benefit would result to the country if this money were made available for supporting research and development in India."

The importance of Bhabha's approach as applied to industrial development is even more significant.

> "The steel industry has existed in India since the First World War, and one of the two steel plants was among the largest in the British Commonwealth in the early twenties. Yet, when these steel plants had to be expanded, it was

necessary to draw upon foreign consultants and engineering firms to plan and carry out the expansion. When the Government decided to establish a steel plant in the public sector at Rourkela, a German consortium had to be asked to undertake the job. For the next steel plant with Russian technical collaboration. The third public sector steel plant at Durgapur had similarly to be set up with the help of a British consortium, and essentially the same method is being followed with regard to the fourth public sector steel plant at Bokaro. Thus, the construction and operation of a number of steel plants has not automatically generated the ability to design and build new steel plants. Unless powerful scientific and engineering groups are established during the construction and operation of existing steel plants as a matter of deliberate policy, the dependence on foreign technical assistance will continue and the steel industry will not reach a stage of technical self-reliance. A similar situation exists in almost every other industry."

We have mentioned a number of factors which were emphasised by Bhabha. No single factor was decisive by itself. It was the combination and the inter-relatedness of these factors applied consistently that generated the forces of growth in the institutions with which Bhabha was connected.

Growth and Activities of the Atomic Energy Commission of India

Atomic Energy Commission

Under the terms of the Atomic Energy Act, 1948, an Atomic Energy Commission was set up in August 1948. The Commission which was a policy making body was assigned the tasks of "surveying the country for atomic minerals, to work and develop such minerals on an industrial scale, to do research in the scientific and technical problems connected with the release of atomic energy for peaceful purposes, to train and develop the necessary scientific and technical personnel for this work and foster fundamental research in nuclear sciences in its own laboratories and in the universities and research institutions in India." The decisions of the Commission were to be implemented through the Ministry of Natural Resources and Scientific Research.

Dr. Bhabha was appointed the first Chairman of the Commission. Other members were Dr. Bhatnagar, Director General of the Council for Scientific and Industrial Research, and Dr. Krishnan, Director, National Physical Research Laboratory - all eminent scientists and deeply committed to the growth of science and technology in India.

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The Commission decided that its first task was to develop scientific personnel that would be needed in future for its activities. It also decided to use existing institutions to do its preliminary scientific work instead of planning at the outset a number of new laboratories. Foremost amongst the institutions used was the Tata Institute of Fundamental Research of which Bhabha was the Director. The early history of atomic energy in India is so closely interwoven with that of the Tata Institute of Fundamental Research, where the early work of atomic energy and of training scientists was done that it has rightly been called "the cradle of India's atomic energy programme". The Tata Institute of Fundamental Research undertook research and later certain administrative responsibilities for the Commission, such as selection of scientists, purchase of equipment and stores, etc.

By 1955 it was felt that research and development in the peaceful uses of atomic energy had made such important strides that a greatly expanded programme would be required. The expanded programme would include producing all the basic materials required for the utilisation of atomic energy and the building of atomic power stations for producing electric power. The Government realised that in order to plan and implement the envisaged programme it would have to modify the Constitution of the Commission so as to give it full financial and executive powers. The notification of the Government concerning the organisation of the Atomic Energy Commission stated:

> "These developments call for an organisation with full authority to plan and implement the various measures on sound technical and economic principles and free from all non-essential restrictions or needlessly inelastic rules. The special requirements of atomic energy, the newness of the field, the strategic nature of its activities and its international and political significance have to be borne in mind in devising such an organisation". 1

In 1958, the Constitution of the Atomic Energy was amended to provide it with greater powers. The amended constitution stated:

> "a. The Commission shall consist of full-time and part-time members and the total number of members shall not be less than three and not more than seven.

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1 Department of Atomic Energy Resolution No.13/7/58-Adm. dated March 1,1958

b. The Secretary to the Government of India in the Department of Atomic Energy shall be the ex-officio Chairman of the Commission.

c. Another full-time member of the Commission shall be the Member for Finance and Administration, who shall also be ex-officio Secretary to the Government of India in the Department of Atomic Energy in financial matters.

d. The Director of the Atomic Energy Establishment, Trombay, shall be the third ex-officio full-time member in charge of research and development".

Regarding the Member for Finance and Administration it stated:

> "The Member for Finance and Administration shall exercise the powers of the Governme nt of India in all financial matters concerning the Department of Atomic Energy. No proposal with financial implications shall be sanctioned without his prior concurrence".

A full-time member for Finance and Administration was included because the idea was that this member would be the chief official in the Department for finance and administration. However, it was soon realised that with the given set-up and nomenclature there was confusion as to the responsibility and accountability of the Chairman-cum-Secretary and the Member for Finance and Administration.

In 1962, the Constitution of the Atomic Energy Commission was again amended largely to clarify the role of the Member for Finance in relation to the accountability of the Chairman-cum-Secretary of the Department. The revision provided as under:

"(a) Instead of having a full time Member for Finance and Administration, one of the members of the Commission was to be the Member for Finance and he was to exercise the powers of the Government of India in financial matters concerning the DAE except in so far as such powers had been or are in future conferred on or delegated to the Department.

(b) The Chairman could also authorise any member of the Commission to exercise such of his powers and responsibilities as he may decide."

Thus, it was amply clarified that the Secretary was responsible for the total administration of the department and that the Finance Member was to advise only on matters not delegated to the Department. It was also considered unnecessary to have a full time Member for Finance.

The size of the first Commission was three members. With the first amendment, the Member for Finance was added, and later Mr. J.R.D. Tata and Dr. Vikram Sarabhai were added. At no time the Commission consisted of more than five members. In early 1966, the Commission was as under:

Dr. H.J. Bhabha	-	Chairman
Mr. S. Jagannathan	-	Member for Finance
Mr. J.R.D. Tata		
Mr. Dharma Vira	-	Cabinet Secretary
Dr. Vikram A. Sarabhai		

Bhabha being also Director of the Atomic Energy Establishment Trombay, there was no separate member for Research and Development.

Some important landmarks in the development of Atomic Energy in India are given in Appendix I.

In reviewing the developments of atomic energy in India, three phases can be identified. The first phase from 1944 to 1954 was the training of scientists, and the starting of scientific groups under the leadership of competent scientists who could, with appropriate facilities and 'autonomy of work', develop an excellent work. In this phase the Tata Institute of Fundamental Research played a significant role.

The second phase could be broadly identified from 1954 to 1962. It marked the growth of the Atomic Energy Establishment at Trombay with emphasis on problems of technology. Three research reactors were built, and simultaneously, the prospecting of atomic minerals was pursued energetically through the Atomic Minerals Division. In this phase, research and development were important leading to pilot plants processing uranium ore, fabricating fuel elements, manufacturing electronic instruments, developing nuclear engineering for reactors, building a plutonium extraction plant, and establishing other facilities at Trombay.

The third phase which commenced around 1962 involved a logical continuation of the earlier development. This phase was the utilisation of knowledge and skills acquired. Emphasis was placed on the contribution of the Department of Atomic Energy to economic development through atomic power projects and public sector industries based on the technology developed at Trombay. Trombay was considered a nursery where new developments would be continually nurtured and other sites in the country

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were identified where know-how and processes could be commercially established.

In the following sections, the role and management system of the Department of Atomic Energy with special reference to the Atomic Energy Establishment at Trombay are outlined.

Department of Atomic Energy

By 1954 the activities of the Commission had so expanded that the Government decided to set up a separate Department of Atomic Energy. The Minister in charge of the Department was the Prime Minister, at that time Shri Jawaharlal Nehru. For administrative convenience and close contacts with the main scientific activities which were in Bombay, the Department's headquarters were located in Bombay instead of Delhi. The Secretary of the Department was also the ex-officio Chairman of the Commission.

The research units, projects and other enterprises for which the Department of Atomic Energy was responsible in 1966 are given below:

1. Atomic Energy Establishment, Trombay
2. Tarapore Atomic Power Project
3. Rajasthan Atomic Power Project
4. Madras Atomic Power Project
5. Jaduguda Mines Project
6. Thumba Equatorial Rocket Launching Station
7. Space Science and Technology Centre
8. Experimental Satellite Communication Earth Station
9. Atomic Minerals Division
10. Trombay Township Project

There are a number of institutions which are administratively attached to the Department of Atomic Energy for purposes of receiving grants-in-aid from the Central Government. The institutions falling under this category are as follows:

1. Tata Institute of Fundamental Research
2. Tata Memorial Hospital
3. Indian Cancer Research Centre
4. Physical Research Laboratory
5. Saha Institute of Nuclear Physics.

The Indian Rare Earths Limited, a Government Company, is under the administrative control of the Department. Proposals are also afoot to have the following industrial operations converted into public sector undertakings:

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1. Electronics Production Unit at Hyderabad
2. Jaduguda Uranium Mines & Mill

The Department has always been of the view that the constituent units of the Department should have wide powers for their day-to-day working. The Heads of these units have, therefore, been declared as Heads of Departments for administrative purposes and in the case of large projects such as the Atomic Power Stations apart from the powers delegated to Project Administrators as Head of the Department, fairly wide powers have been given to the Project Boards to enable them to give decisions on all administrative, financial and technical matters arising in connection with the execution of the projects. Only in a few restricted fields, the Boards are required to come up to the Department of Atomic Energy for sanctions.

In order to understand the role of the Department in relation to the units, the process of decision-making, service and control functions, selection and evaluation procedures, are discussed with reference to the Atomic Energy Establishment, Trombay.

Atomic Energy Establishment, Trombay(Bhabha Atomic Research Centre)

In 1954, the Commission decided to set up a separate institution for research and development - the Atomic Energy Establishment Trombay(AEET). To the existing groups for Chemistry and Metallurgy which were operating till then under the Department, were added the scientific groups for theoretical physics, nuclear physics and electronics, which were working on behalf of the Commission at the Tata Institute of Fundamental Research. Along with the scientists were transferred a few administrators to man the newly established Atomic Energy Establishment, Trombay. The number of officers involved in the transfer were about 54. These formed a numerically significant group in the Establishment and hence were able to carry successfully with them a culture appropriate to research and development.

In contrast, the established pattern of setting up new research laboratories was at that time significantly different. Although many of them were created under autonomous organisations, they were started in many cases by a 'Planning Officer' seconded by Government. The result was a transfer of culture, but in this case of government administrative practices of recruitment, budgetary controls, purchase of equipment, etc., that were in fact inappropriate to the functioning of a scientific institution. The autonomy that was given to these research institutes was lost to a large extent by the omnibus adoption of Government rules and regulations.

By 1966, the Atomic Energy Establishment, Trombay was the largest scientific centre in the country. It employed a total of about 8500 persons, of whom approximately 2000 were professional scientists and engineers, and another 3000 were technical staff, many of whom are science graduates. The annual budget of the Establishment is about Rs. 11 crores.

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For the first few years the main task at Trombay was to provide much of the scientific knowledge and understanding needed to design and construct reactors. The work soon expanded into many fields - atomic fuel, heavy water, radioisotopes, electronic instrumentation and equipment, uranium plant, agriculture, health physics, medical, etc.

The organisation structure of the Atomic Energy Establishment, Trombay is given in Chart 1. The work is divided into five main research groups and an administration group, all reporting to the Director. The research groups and administrative functions are:

Research Groups	Administration Group
1. Physics	Personnel
2. Metallurgy	Accounts
3. Electronics	Purchase and Stores
4. Engineering	Scientific Information (including Library)
5. Biology	

Within the broad policy formulated by the Atomic Energy Commission, the Director, Atomic Energy Establishment Trombay, is assisted in his scientific and administrative decision-making by the Trombay Council and the Trombay Scientific Committee. The Trombay Scientific Committee consists of the Directors of five major research groups and 25 heads of Divisions. The Committee discusses proposals of research projects from each division, equipment and personnel required in relation to each project, and other related matters. The Committee meets once a fortnight.

The Trombay Council consists of the five Directors of Research Groups and the Administrative Controller. The Director, Atomic Energy Establishment Trombay, is the Chairman of the Council. The Council discusses not only action to be taken arising from current problems, but also forward planning based partly on information from the Chairman and partly on information from the Trombay Scientific Committee. The Council meets once a week.

Within the approved budget and subject to specific approval of capital items in the ways outlined, Trombay has considerable autonomy to manage its own financial affairs. By agreement of the Commission, the Director delegates financial powers upto approved limits to Directors of Research Groups and Divisional heads. Within the overall budget there are divisional budgets.

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The Director of the Trombay Establishment is an ex-officio Member of the Atomic Energy Commission for Research and Development and has been delegated wide powers. Some idea of the delegated powers of the Director can be seen from the following:

- Reappropriation of funds under the Revenue Grant
- Creation of temporary posts upto a salary of Rs 2000/- p.m.
- Granting higher starting pay and grant of advance increments
- Sanction contingent expenditure after consultation with the internal finance adviser regarding availability of funds
- Write off losses up to Rs 25,000 in respect of stores

The Director can delegate his powers to any authority subordinate to him.

The problem of consultation, communication and control between the Atomic Energy Commission and the Atomic Energy Establishment Trombay was relatively simple since Bhabha was the Chairman of the Commission, Secretary of the Department, and Director of Atomic Energy Establishment. Projects which were approved at the Trombay Scientific Committee and the Trombay Council were assured simultaneously the sanction of the Department and the Commission because of Bhabha's common role. In such a situation, the role of administration in the Secretariat became one of service rather than of control. The Department assisted in getting the necessary equipment, stores, foreign exchange, etc. for carrying out projects.

Great care was given to the selection, training, development and appraisal of staff. In general, the policy was to recruit young science graduates, train and develop them within the Establishment. In order to meet the growing requirements for suitable scientific personnel a Training Institute was started in 1957. Selections are made on the basis of recommendations of duly constituted selection committees with elaborate selection procedures. Experts from universities and industry are invited to serve on these selection committees. Applications from science and engineering graduates with first and second class degrees are invited. Each selected candidate is given a stipend of Rs 300/- per month. The faculty of the Training School is partly from the Atomic Energy Establishment Trombay and partly from the Tata Institute of Fundamental Research. In 1965 about 3400 applications with first and second class

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degrees were received. Out of these 251 were selected on the basis of an interview. 130 actually joined the school, and 125 completed the course and were appointed at Atomic Energy Establishment Trombay and in other units of the Department. About these young trainees, Bhabha said, "at the end of two to three years they become very useful scientists. The best among them are likely to become future leaders. We have found this method of recruitment very satisfactory, and although it has placed a heavy load on our senior staff by making the spectrum of our scientific staff much heavier at the junior levels than as it should be, it has provided a powerful source of able young scientists on the basis of which the programme can be expanded continously in future".[1]

The evaluation procedures at the Atomic Energy Establishment Trombay are the same as those evolved by Bhabha at Tata Institute of Fundamental Research. In evaluating a research worker's performance the first step is for the research worker to write his own report about his past performance in relation to the tasks set, mentioning any special accomplishments or problems. This report is then processed independently by two other assessors. The total report is then forwarded to the Director with recommendations for increments or promotions. Promotions from one grade to another are made not on the basis of vacancies, but on the development and worth of the individual research worker.

Bhabha was the Director of the Atomic Energy Establishment Trombay as well as of the Tata Institute of Fundamental Research. Practices and procedures 'innovated' at the Tata Institute of Fundamental Research were used at the Atomic Energy Establishment Trombay, so that tested administrative practices appropriate to research and developmental tasks were introduced within a government organisation.

Some Implications

We asked the question, "Why did it happen? Are the experiences drawn from the growth of atomic energy in India translatable to other institutions and fields?" In the account we have presented, we cannot help noting a remarkable coming together of people and events: Independent India led by Jawaharlal Nehru, who believed in transforming the nation through the application of science; Bhabha, a sophisticated engineer-cum-theoretical physicist, who enjoyed the confidence of Nehru and possessed a wide international reputation and contacts; the exploding of the atom bomb over Hiroshima and Nagasaki, which led to an unprecedented nuclear arms race under conditions of great secrecy; a horrified world eager to promote the peaceful uses of the atom and thereby coping with the guilt arising from ruthless military preparations; the release of scientific and technological know-how on an unprecedented scale following the first Atoms for Peace Conference in 1954, making available to countries such as India basic data which in other areas of economic significance could be purchased only at great cost. But if the ecology and the factors for growth were ripe to make possible

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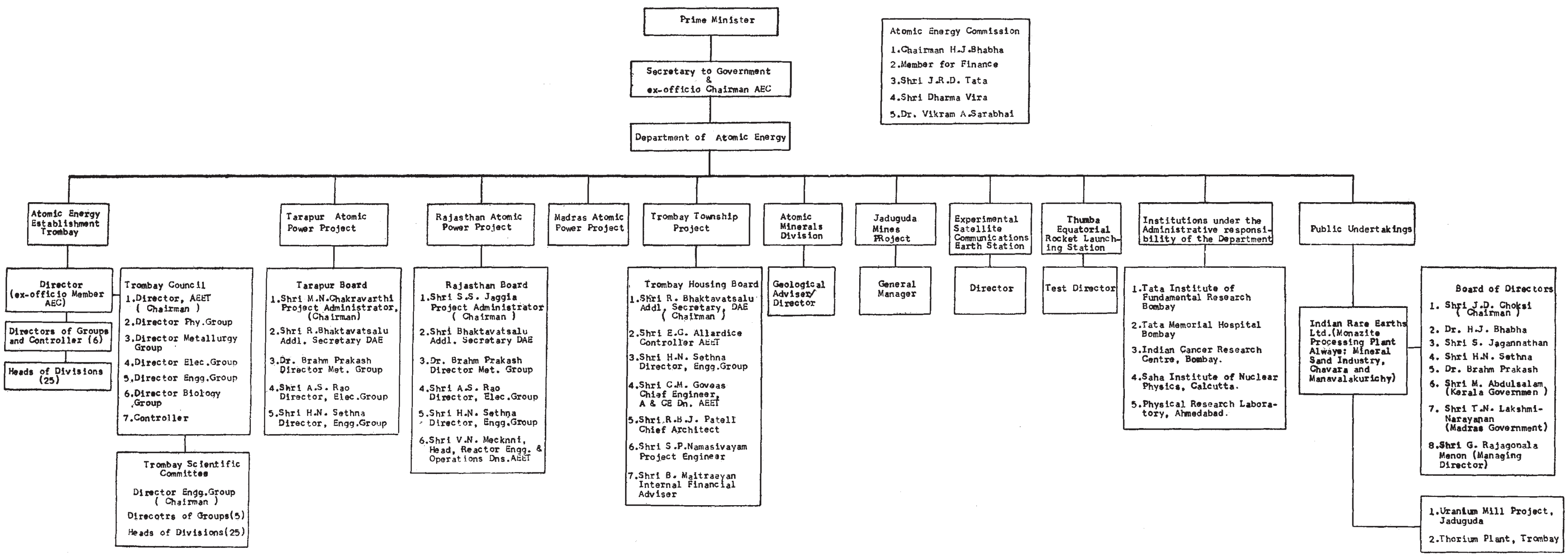
1 'Ten Years of Atomic Energy in India, 1954-64'

APPENDIX II

ORGANIZATION AND STRUCTURE OF ATOMIC ENERGY COMMISSION, TROMBAY

As on January 1, 1966



(Reprinted from the Indian Journal of Public Administration Vol. XIV No. 1, pp. 1-22)

what we have described in this paper, there is nevertheless a lesson in the story, which has significance in a much wider context. We shall summarise below what we believe to be factors contributing to the success of atomic energy in India and hope some useful guidelines will emerge, on the one hand, for policy makers concerned with developing institutions and organisations and, on the other hand, for organisational structures and administrative practices relevant wherever developmental tasks are to be undertaken.

1. The concern, care and nurturance of people who have knowledge and skills conveyed to them a sense of trust and the significance of their role in building society. Bhabha received all these from Mr J.R.D. Tata and Prime Minister Nehru, and in turn, gave it to the young scientists and engineers who came to work with him.

When Bhabha returned to India during World War II the Dorab Tata Trust created a Chair for him at the Institute of Science, Bangalore, so that he would have the freedom and facilities to do research. Later in 1944, when Bhabha wrote to Mr J.R.D. Tata suggesting an Institute for fundamental research in physics and mathematics, the Tatas accepted the proposal and the financial responsibility for such an idea. It is significant to note that the Tatas supported the idea at a time when nuclear physics had not become the 'bandwagon' of science and more than a year before the explosion of the first atom bomb in Hiroshima. Also as Bhabha pointed out at a time "before it had been made public that atomic piles had been successfully operated and long before there was any talk of atomic power stations".

Bhabha also received support and understanding to an unusual degree from Prime Minister Nehru. Both men saw the essential role of science in transforming not only the economy of the country but in transforming man. Nehru believed that if India was to be transformed from an industrially under-developed to a developed country, it was essential to establish science as a live and vital force in society. Nehru was the President of the Council for Scientific and Industrial Research, and later when the Department of Atomic Energy was established, he became the Minister in charge of the Department.

As mentioned earlier, Bhabha's approach to building institutions was to build the organisation around men. No organisation chart stood in the way of recognising and rewarding talent. The Apsara reactor was built almost entirely by Indian scientists and engineers. He conveyed confidence in the ability of men and the men usually rose to the occasion. Bhabha 'protected' his scientists from bureaucratic procedures and organised administration largely as a service rather than a control function.

2. The combination of policy making, executive and scientific roles provided the Chief Executive, power, freedom and authority which were important. Bhabha was the Chairman of the Atomic Energy Commission,

the Secretary of the Department of Atomic Energy, the Director of Atomic Energy Establishment, Trombay, and Director of the Tata Institute of Fundamental Research. The combination of these four roles provided the Chief Executive with sufficient freedom and flexibility in decision making and commitment of resources. It also meant that the Chief Executive had powers and responsibilities which permitted full accountability.

The combination of these roles also meant that Bhabha was able to keep his 'grass-roots' in scientific research. It was this facility of working as a policy maker, organiser and administrator on the one hand, and participating in the scientific work at the 'coalface' level on the other hand that provided him the on-going understanding to motivate and manage his research workers. In research laboratories, and in other developmental tasks it seems important that the Chief Executive, besides policy-making and administration, maintain direct contact with his professional role. The creation of administrative practices appropriate to a given technology or set of tasks comes with familiarity and knowledge-of-acquaintance of the technology or tasks concerned.

3. The early beginnings of any institution are crucial, and the 'culture' (or lack of it) brought by the first entrants play a significant role in establishing norms, procedures and practices in the organisation. The numbers should be large enough to achieve a critical size to permit positive interactions.

The establishment of research groups and the development of second generation scientists in the Tata Institute of Fundamental Research and in the Chemistry and Metallurgy Groups of the Commission preceded the setting up of the Atomic Energy Establishment at Trombay by about ten years. This transfer of a large group rather than a few individuals was significant in terms of the 'culture' and success at the Atomic Energy Establishment, Trombay. In this connection, it is often necessary to spin off new institutions from existing ones transferring not only expertise but a social culture appropriate to the task.

An inappropriate social culture can also be transferred by appointing persons from a different working 'culture'. In this connection, the appointment in a key position or in large numbers at lower positions, of competent Government officials whose experience is primarily derived from routine administration, in research organisations or in industrial enterprises is very questionable. Even though many of these organisations are established as autonomous in the legal sense, administrative practices are introduced which negates the formal autonomy granted. The existing government procedures of selection, promotion, evaluation, budgetary controls, buying of supplies and equipment are highly inappropriate to the effective functioning of scientific laboratories and industries involving complex technologies.

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In other words, conditions have to be created through the selection of appropriate men and through association with a mother organisation to ensure that the formal and administrative cultures support each other for the fulfilment of the task.

4. In professional groups, scientists, engineers and others, it is important to recognise that motivation and control is largely inherent and contained in professional commitments. In organisations using large professional groups, the role of administration has largely become one of service and not of control. This requires a basic change in attitudes rather than a change in procedures and practices.

In the Atomic Energy Establishment, Trombay and other units administratively connected with the Department of Atomic Energy, the organisation structure and procedures were those of decentralisation. There was a minimum organisation structure and formal control. Even though there was a hierarchical structure, because of the nature of work it was not used as a means of communication and decision-making.

Within the broad policy set, research groups discussed and defined their objectives and targets. When research projects were approved, associated with it was approval for budgets, equipment and manpower. Budgetary and other controls were self-contained in the formulation of projects. This again re-emphasised the role of administration as facilitation of work rather than outside control. The need to control is almost an inevitable psychological product of the structured field of which bureaucratic organisations are an example. With the devaluation of hierarchical authority and positional status in scientific work, mechanisms of administrative control were also devaluated. Control was exercised through discussion and judgment of peers.

5. The body to which the Chief Executive refers for policy and strategic decisions must be compact in size and consist of members chosen for their expertise and roles, rather than from a representational angle.

The number and membership of the Atomic Energy Commission were important factors in setting the 'tone' and 'quality' of meetings and the policy decisions taken there. As mentioned earlier, the members of the first Commission were Dr. Bhabha, Chairman, Dr Shantiswarup Bhatnagar and Dr Krishnan, Director of the National Physical Laboratory. When the Department of Atomic Energy was established, a member for Finance and Mr J.R.D. Tata were added as members. Subsequently, Dr. Vikram Sarabhai was invited to be a Commission member. The Commission consisted of 5 to 6 members (The Board of the C.S.I.R. at present consists of 34 members), all significantly able to contribute to policy making regarding nuclear energy and its development in India.

6. There is a need for a constant interplay between the basic sciences, technology and industrial practice if economic progress is to result from the activity undertaken. The wearing of several hats by the same person, as in the case of Bhabha and the mobility of personnel from one type of activity to another have undoubtedly provided the impetus for growth in the projects of the Department of Atomic Energy. We may contrast this with the practice prevalent in higher educational institutions for basic sciences and technology and national laboratories where the work of applying the results of research to practical ends has to be done through other units, not organically related to the laboratories or the men that work in them.

7. The conditions under which scientists and professional workers are motivated are somewhat different from those who work in bureaucratic or industrial enterprises. Money, hierarchical status and power are important needs for most, but to scientists and professional groups the need for autonomy of working conditions and self-development are also important factors.

Bhabha's philosophy was to identify the right persons, and then give them all the autonomy and support they wanted within the broad objectives. As mentioned earlier, these were also Bhabha's needs which were supported by Nehru and Tata.

There were a number of research institutions administratively connected with the Department of Atomic Energy - the Tata Institute of Fundamental Research, the Saha Institute of Nuclear Research, the Physical Research Laboratory at Ahmedabad, and other educational institutions. This loose federation of institutions provided a unique opportunity to the scientists of sharing experiences and information. Bhabha also encouraged and sponsored his scientists to attend international meetings. The opportunity of meeting scientists who came from abroad, of sharing facilities, of attending meetings and symposia provided an intellectual environment, which would have been difficult to provide by any single institution. The relative autonomy, the mobility and interaction of scientists and engineers nationally and internationally were important factors in the motivation and morale of these people.

Conclusions

In this story of the phenomenal growth of Atomic Energy in India, we have attempted to identify some factors which in our opinion facilitated growth. By implication it is also possible to discern factors which are unhelpful and inhibit development. The various factors indicated earlier are interrelated and mutually dependent. A change in one influences the total scheme of things, for in organisational structures and culture, the whole is more than the sum of its parts. Structures, procedures and techniques are important but these must be sustained by a cluster of attitudes conveying care, trust and nurturance on the part of responsible persons. There is need to understand that there is a shift from

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simple to complex technologies, from stability to innovation, from experience based knowledge and skills to highly conceptual knowledge. The understanding of this change means the recognition of socio-technical systems rather than a mechanistic organisation structure, the recognition that highly trained and professional groups have different needs and motivations, the realisation that hierarchical structures and systems need to be minimised and that the concept of control is inherent and contained in professional commitments rather than exercised from outside.

Kamla Chowdhry
Vikram A. Sarabhai

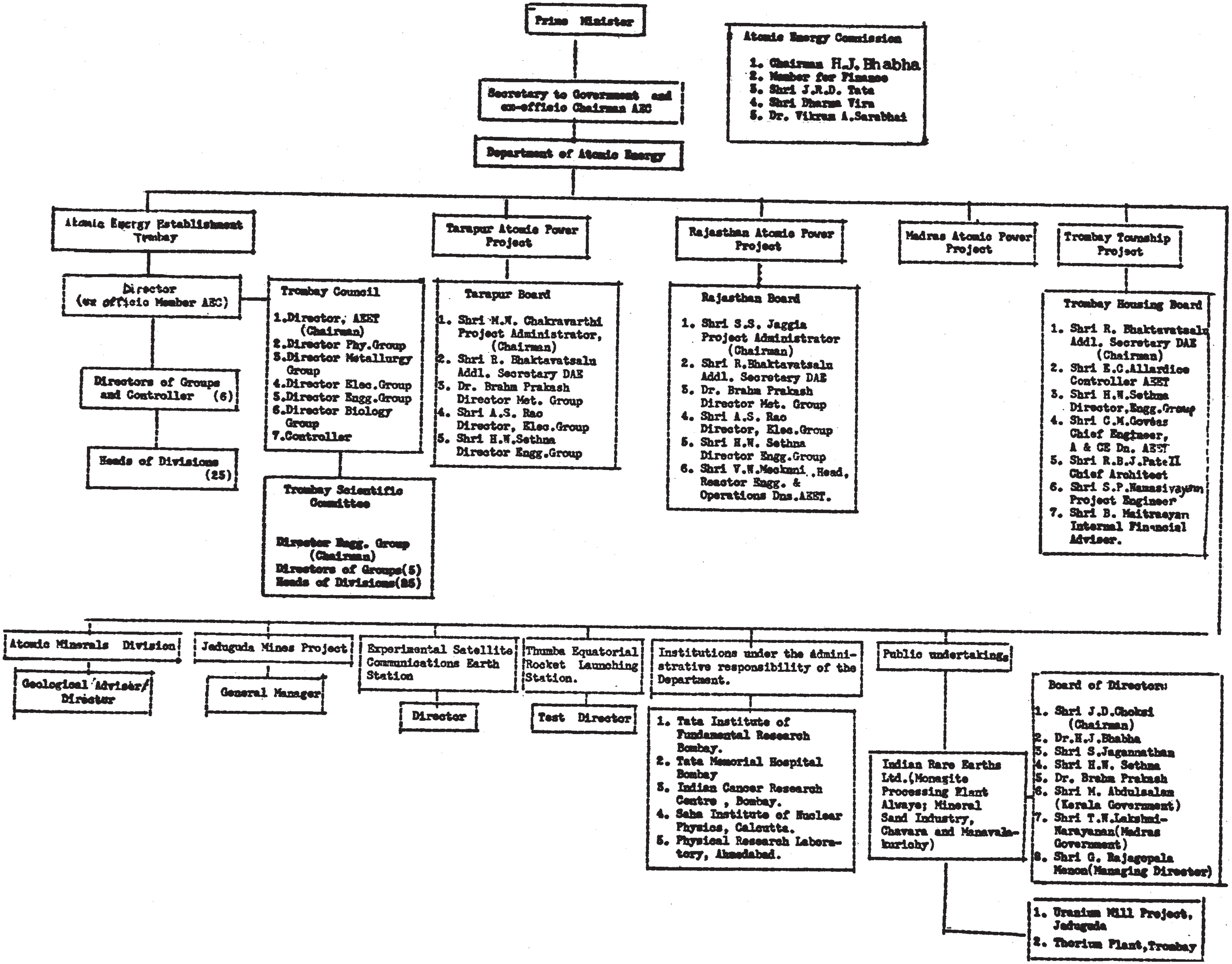
March 7, 1967

APPENDIX I

Some important landmarks in the development of Atomic Energy in India

1945	April	Tata Institute of Fundamental Research
1948	April	Atomic Energy Act of 1948 received assent of Governor General
	August	Atomic Energy Commission set up
1950	August	Indian Rare Earths registered as a limited company
1954	January	AEC decides to set up Atomic Energy Establishment, Trombay
	August	Department of Atomic Energy created
1955	March	AEC decides to build Apsara reactor
	August	First U.N. International Conference on the Peaceful Uses of Atomic Energy opens in Geneva under the presidentship of Dr Bhabha
1956	February	Work on CIR reactor with Canadian assistance
		Radiochemistry Laboratory set up
	May	Decision to set up Uranium Metal Plant and Fuel Element Fabrication Facility
	October	Travancore Minerals Ltd. registered as a limited company
1957	August	Training School started
1958	March	Constitution of AEC revised
	June	AEC reconstituted
	July	Decision to build Plutonium Plant
	August	Planning Commission approves the building of India's first atomic power station at Tarapur
1960	February	AEC decides to build Uranium Ore Mill at Jaduguda
	May	Erection of Zerlina reactor begins
	September	Heavy Water Reconcentration Plant commissioned

1962	February	Administrative responsibility for Indian Cancer Research Centre and Tata Memorial Hospital both at Bombay transferred to the Department to facilitate rapid development and expansion of medical facilities and research in cancer and other diseases with the help of isotopes, etc.
		Indian National Committee for Space Research constituted.
	March	Constitution of AEC further amended
	August	Decision to build second atomic power station at Rana Pratap Sagar, Rajasthan
	September	Atomic Energy Act 1962 comes in force
	December	Kalpakkam selected as site for third atomic power plant
1964	January	Six more rockets launched from Thumba
	July	Three meteorological rockets launched from Thumba
	November	Three Nike-Apache rockets launched from Thumba in the international synoptic launching series


Prime Minister
Secretary to Government and ex-officio Chairman AEC
Atomic Energy Commission
1. Chairman H.J. Bhabha
2. Member for Finance
3. Shri J.R.D. Tata
4. Shri Dharma Vira
5. Dr. Vikram A.Sarabhai
Department of Atomic Energy
Atomic Energy Establishment Trombay
Director (ex officio Member AEC)
Directors of Groups and Controller (6)
Heads of Divisions (25)
Trombay Council
1.Director, AEET (Chairman)
2.Director Phy.Group
3.Director Metallurgy Group
4.Director Elec.Group
5.Director Engg.Group
6.Director Biology Group
7.Controller
Trombay Scientific Committee
Director Engg. Group (Chairman)
Directors of Groups(5)
Heads of Divisions(25)
Tarapur Atomic Power Project
Tarapur Board
1. Shri M.N. Chakravarthi Project Administrator, (Chairman)
2. Shri R. Bhaktavatsalu Addl. Secretary DAE
3. Dr. Brahm Prakash Director Met. Group
4. Shri A.S. Rao Director, Elec.Group
5. Shri H.N.Sethna Director Engg.Group
Rajasthan Atomic Power Project
Rajasthan Board
1. Shri S.S. Jaggia Project Administrator (Chairman)
2. Shri R.Bhaktavatsalu Addl. Secretary DAE
3. Dr. Brahm Prakash Director Met. Group
4. Shri A.S. Rao Director, Elec.Group
5. Shri H.N. Sethna Director Engg.Group
6. Shri V.N.Meckoni, Head, Reactor Engg. & Operations Dns.AEET.
Madras Atomic Power Project
Trombay Township Project
Trombay Housing Board
1. Shri R. Bhaktavatsalu Addl. Secretary DAE (Chairman)
2. Shri E.C.Allardice Controller AEET
3. Shri H.N.Sethna Director,Engg.Group
4. Shri C.M.Goveas Chief Engineer, A & CE Dn. AEET
5. Shri R.B.J.Patel Chief Architect
6. Shri S.P.Namasivayam Project Engineer
7. Shri B. Maitraeyan Internal Financial Adviser.
Atomic Minerals Division
Geological Adviser/ Director
Jaduguda Mines Project
General Manager
Experimental Satellite Communications Earth Station
Director
Thumba Equatorial Rocket Launching Station.
Test Director
Institutions under the administrative responsibility of the Department.
1. Tata Institute of Fundamental Research Bombay.
2. Tata Memorial Hospital Bombay
3. Indian Cancer Research Centre, Bombay.
4. Saha Institute of Nuclear Physics, Calcutta.
5. Physical Research Laboratory, Ahmedabad.
Public undertakings
Indian Rare Earths Ltd.(Monazite Processing Plant Alwaye; Mineral Sand Industry, Chavara and Manavalakurichy)
Board of Directors:
1. Shri J.D.Choksi (Chairman)
2. Dr.H.J.Bhabha
3. Shri S.Jagannathan
4. Shri H.N. Sethna
5. Dr. Brahm Prakash
6. Shri M. Abdulsalam (Kerala Government)
7. Shri T.N.Lakshmi-Narayanan(Madras Government)
8. Shri G. Rajagopala Menon(Managing Director)
1. Uranium Mill Project, Jaduguda
2. Thorium Plant,Trombay