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Dissertation on
Time Variations of Cosmic Ray Intensity
'A Study of Solar Anisotropy of Galactic
Cosmic Ray Intensity'

Studies in time variation of cosmic
rays at a station on the geomagnetic
equator

Presented

by

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STATEMENT

The author has continuously monitored the meson component of cosmic ray intensity at Kodaikanal (Geomag. Lat. 10° N, Long. 147° E and altitude of 2.2 kms) during the period 1958 to 1961. Simultaneously a neutron monitor was in operation at the same station. The author has made use of these data and data from neutron monitors at Churchill (Canada), Huancayo (Peru), Mawson (Antarctica), Mt Norikura (Japan), Mina Aguilar (Argentina) and data from cubical meson telescopes at Churchill and Mawson to study, on a daily basis, the long-term changes of the characteristics of the daily variation from 1958, when the solar activity was at its maximum, to 1962 when it was approaching a minimum.

Extending the work of Rao et al, the response characteristics of these detectors were determined by the author under two different types of asymptotic latitude dependence of the strength of the anisotropy and several assumptions regarding its energy dependence. Both the diurnal and semi-diurnal components of daily variation measured by neutron as well as meson detectors from a net-work of stations are used on a daily basis, extending the study on a limited scale by Rao & Sarabhai using just two detectors, to determine the characteristics of anisotropy of cosmic ray intensity. Preliminary results of this study with data from three stations were presented by the author at the International Cosmic Ray Conference held in December 1963 at Jaipur, India. The

analysis is continued further with data from six detectors and the results are presented in this work. The conclusion that there is a day to day change in the characteristics of the anisotropy, including its energy spectrum of variation, confirms the earlier study by Rao & Sarabhai.

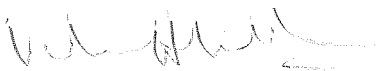
For the first time, a calculation is made, similar to that of Brunberg, of the possible effects of the opening angles on the response characteristics of two hypothetical telescopes of semiangles of 25° and 60° in the east-west plane and 45° in the north-south plane, situated at Kodaikanal and at Churchill. Two exponents of variation spectrum, namely 0 and -1, are considered and it is found that the wider angle telescope has less amplitude for the diurnal as well as the semidiurnal components. The decrease in the semidiurnal component is more than that in the diurnal component at both places for the two cases of energy dependence. This decrease is of the order of a few percent of the amplitude of the smaller angle telescope and is more pronounced at high latitudes. The decrease as measured by a telescope of larger opening angle is more for the zero exponent of the variation spectrum than for the negative exponent. A complete list of references is given at the end of this thesis.

Main conclusions of the present study regarding the characteristics of the anisotropy are:

- (1) The longitude dependence of the anisotropy cannot be represented by a single sinusoidal function because the difference between the direction of maximum of the anisotropy and its direction of minimum is found to be 8 - 10 hours instead of 12 hours. Therefore, more than one modulating mechanism is necessary to explain this result.
- (2) The variation spectrum of anisotropy on each day, determined by a method so as to fit best the data from a number of detectors, is not the same on all days. The days are broadly grouped according as

 - (a) low energy particles are proportionately less modulated than medium energy particles (positive variation spectrum),
 - (b) particles of all energy are equally modulated (zero variation spectrum), and
 - (c) particles of low energy are more modulated than particles of high energy (negative variation spectrum).
- (3) The days with positive exponent for the variation spectrum have the maximum of the anisotropy which occurs most frequently in the direction of 1400 hours in space beyond the influence of geomagnetic field, while the days with zero and negative spectrum have the maximum at 1600 hours. The direction of minimum of anisotropy occurs most frequently along 0600 hours for all the three different variation spectra.

- (4) The value of the peak to peak amplitude is less and the variance, from day to day, of the time of maximum and the time of minimum of the anisotropy is more during days with exponents of +1 or -1 for the variation spectrum than on days with zero exponent.
- (5) The most probable direction of maximum of anisotropy during 1958 to 1962 has remained essentially constant except for a slight shift to later hours in 1960. During this period the most probable direction of minimum of anisotropy has remained constant.
- (6) In the years 1961-62, as compared to the years 1958-60, there is a reduction in the number of days with positive exponent of the variation spectrum, while the number of days with zero and negative exponents shows an increase. There is a reduction in the peak to peak strength of anisotropy during 1961-62 as compared to 1958-60.



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CHAPTER-I

INTRODUCTION

PART I. ANISOTROPY AND MODULATION OF GALACTIC COSMIC RAYS IN INTERPLANETARY SPACE

1.1. Time variation of cosmic ray intensity

Time variations of cosmic ray intensity and their interpretation on the basis of cosmic electrodynamics and plasma physics have demonstrated the potentialities of their study in investigations of geo and astrophysics. Time variations of cosmic ray intensity are also of interest to geomagnetism and in understanding the cosmic ray transition effects in the atmosphere (Elliot¹, Sarabhai & Nerurkar², Dorman³, Singer⁴, Webber⁵, Dorman⁶).

Studies of anisotropy of galactic cosmic rays, through the daily variation measured in sidereal and solar time, have been conducted for the following principal effects:

- (1) Sidereal anisotropy due to a possible non-uniform distribution of cosmic ray sources in the galaxy or the streaming of cosmic rays along the galactic magnetic field or the relative motion of the solar system in the galaxy.
- (2) Solar anisotropy caused by magnetic fields in interplanetary space.

The present thesis is primarily concerned with solar anisotropy of galactic cosmic rays, its relationship with the electromagnetic conditions of interplanetary space and its changes with solar activity.

1.2. Nature of daily variation and anisotropy of cosmic ray intensity

Studies, earlier to the year 1960, of daily variation of cosmic ray intensity and its relation to cosmic ray anisotropy have been reviewed by Elliot¹. Later studies of anisotropy and their interpretation on the basis of different models of interplanetary states have been reviewed by Sarabhai and Nerurkar², and recently by Jorman³.

The present work deals with a study of the characteristics of solar anisotropy by means of daily variation of cosmic ray intensity as observed by a world-wide net-work of cosmic ray detectors. The study of solar anisotropy is especially interesting as it conveys information of not only the gross features of interplanetary magnetic fields, which are controlled by plasma motions, but also of the movements of blast waves and shock fronts (Rao & Sarabhai⁷). The anisotropy is characterized by its energy dependence, its strength and its profile in interplanetary space. The latter is best studied by the time of maximum and the time of minimum

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of daily variation of cosmic ray intensity, as observed by a telescope on the spinning earth. The strength of the anisotropy is reflected in the amplitude of daily variation.

1.2.1. Day to day variability of anisotropy

Studies of the strength and direction of anisotropy have generally been conducted considering the daily variation averaged over a period of time. Determinations of the energy dependence of anisotropy have been made by several workers with time-averaged data (Kuzmin⁸, Pommerantz et al⁹, Rao et al¹⁰, Kane¹¹). Studies with time-averaged data result in a much lower value of amplitude of daily variation (.1 to .4 %) as compared to the values which are observed on a daily basis (upto 3%). Also, the determination of the energy spectrum of anisotropy in terms of a single exponent for all days, obtained by using time-averaged data, is often misleading. However, the dominant direction of anisotropy is well brought out by measurements even with time-averaged data.

Studies have been made of the characteristics of the anisotropy, on a daily basis, by several workers (Piror et al¹², Remy & Sittkus¹³, Sittkus¹⁴, Sarabhai & Narurkar¹⁵). A detailed study of the profile and the energy dependence of the anisotropy, on individual days, with data from meson detector at MIT and neutron monitor at Deep River, has been made by Rao and Sarabhai⁷, for about five months during 1961.

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They find that

- (1) the time of occurrence of the maximum and the minimum of cosmic ray intensity is not random, but each has a high probability to occur at certain local times,
- (2) the times of maximum at the two stations, found either from the first harmonic or from the curve, composed of the first two harmonics, track each other well which is not the case with the amplitudes,
- (3) the most probable difference in time between the maximum of intensity and the minimum of intensity is about 8 hours,
- (4) the direction of maximum of the anisotropy shifts to earlier hours following some Forbush decreases. The direction of minimum of anisotropy follows the shift with a lag of few days after the change in the direction of maximum.

It has been suggested that the daily variation on individual days can, in general, be related to an anisotropy of galactic cosmic rays in interplanetary space. The characteristics of the anisotropy undergo significant changes from day to day. The most probable value of $T_{\max} - T_{\min}$ which is 8 hours suggests the existence, in general, of a

negative virtual source, perpendicular to a pair of oppositely directed positive and negative sources.

The present work concentrates on a study, on a daily basis, of the characteristics of anisotropy, its changes from day to day and from year to year, during the declining phase of solar activity, from 1958 to 1962.

1.2.2. Isotropic changes of cosmic ray intensity - 'slope effect'

Isotropic changes of cosmic ray intensity can produce a spurious component of daily variation (Kane¹⁶, Sanistrom¹⁷). A general method to eliminate the effects of such changes from daily variation has been discussed by Chapman & Bartels¹⁸. The procedure has been applied to study the cosmic ray anisotropy using data from 13 stations located on different meridians on the latitude belt 30° - 60° (Sekido¹⁹).

For data from a single station, the method of moving average is generally used to remove the long-term trend in the cosmic ray intensity. By this method the 'slope effects' on the daily variation are satisfactorily eliminated, while 'curvature effects' and effects due to short-term world-wide changes of intensity still persist.

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These residual effects are generally rather small and can be ignored in a study of daily variation on a day to day basis as demonstrated by Rao and Sarabhai⁷.

1.2.3. Diurnal and semidiurnal components

The study of anisotropy has most commonly been conducted only with reference to the diurnal component of the daily variation but several authors (Indian, Japanese, Russian and Swedish) have recognised the value of analysing the daily variation inclusive of both diurnal and semidiurnal components. The necessity of including the semidiurnal component for a complete study of anisotropy arises from the following:

- (1) A semidiurnal component persists even after pressure correction, in time-averaged data from some equatorial stations (Sarabhai et al²⁰, Katzman & Venkatesan²¹, Kane & Thakore²²). Thus the semidiurnal component is real and non-meteorological in origin.
- (2) The amplitude of the semidiurnal component of daily variation on individual days is found to be about .6 times the amplitude of the diurnal component and is statistically significant on most of the days.

- (3) The frequency distributions of the difference between the time of maximum and the time of minimum of the daily variation of cosmic ray intensity, measured by MIT meson detector and Deep River neutron monitor, have their most probable frequencies at 8 - 10 hours. On the other hand, for an anisotropy of sinusoidal form, the difference between the time of maximum and the time of minimum should be only 12 hours (Rao & Sarabhai⁷).

Some authors have concluded, using time-averaged data, that the semidiurnal component is not caused entirely, by an external anisotropy (Katzman & Venkatesan²¹, Rao et al¹⁰). However, several factors point to the existence of a non-meteorological origin of the semidiurnal component.

- (1) The amplitude of the semidiurnal component depends on the azimuthal direction in the case of particles incident at an angle of 45° to the zenith. For observations made in England the amplitude for particles coming from the south is about three times as great as that for particles coming from the north (Elliot & Wolbear²³).
- (2) It has been shown that a characteristic difference of six hours is obtained, between the times of maxima of the semidiurnal variation of cosmic ray

intensity, recorded by east and west pointing telescopes at low latitudes, on days on which the observed solar diurnal variation can be ascribed to a source, located outside the geomagnetic field (Rao & Sarabhai²⁴).

- (3) The semidiurnal component undergoes systematic changes with solar activity and geomagnetic planetary index K_p (Sarabhai et al.²⁰, Sekido²⁵, Sanstrom²⁶, Anluwalia²⁷).

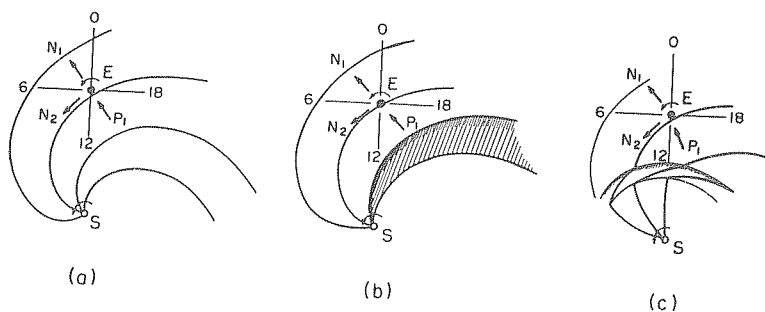


Fig. 1.1. The interplanetary magnetic field and the position of the virtual positive and negative sources of cosmic ray producing daily variation of cosmic rays (a) when there exists an ideal corotation of the solar magnetic field, (b) when a corotating boundary of a turbulent region or a magnetic cavity is approaching the earth, and (c) when the boundary advances radially as in a blast wave.

Fig.1.1, from Rao & Sarabhai⁷, illustrates the significance of $T_{\max}$ and $T_{\min}$ of the curve built-up from diurnal and semidiurnal components of daily variation. The advantage, in studying the anisotropy by means of $T_{\max}$ and $T_{\min}$, is in one's ability to follow the moving discontinuities in magnetic field configurations in interplanetary space.

In the present work both the diurnal and semidiurnal components are taken into consideration for the study of the anisotropy.

1.2.4. Local and external sources of anisotropy

The observed daily variation cannot always be related to an external anisotropy. This has been demonstrated by experiments made with inclined telescopes pointing, towards the east and west directions (Rao & Sarabhai²⁴). If the daily variation at equatorial stations is related to a solar anisotropy of galactic intensity, the direction of maximum and minimum intensity would appear 3 - 5 hours later in the west telescope than the east. Rao and Sarabhai²⁴ have shown that while on most of the days the daily variation can be explained by an external anisotropy, on days with high K_p it cannot be explained

and a 'local source' requires to be invoked. Norman⁶, considering the disturbed magnetic field of the earth by the impinging of solar plasma, points out that the departure from the dipole field and the consequent anisotropy of the magnetic field may be the cause of the 'local source' which will be all the more important, when the geomagnetic field is violently disturbed. It is found, during investigations by the author, that there are quite a few days (5 to 8%) on which the daily variation cannot be explained in terms of a solar anisotropy.

1.3. Solar cycle changes of daily variation

1.3.1. Eleven and twenty-two year changes in the daily variation

The solar daily variation undergoes large long-term changes that are world-wide in character, as found from the study of the hard component at Huancayo, Cheltenham and Christchurch for the period 1937-52 (Sarabhai & Kane²⁸, Sarabhai et al.²⁹, Thambyapillai & Elliot²⁹, Dattner & Venkatesan³⁰). These studies were extended upto 1959 by Forbush & Venkatesan³¹. Their results support the earlier finding of a systematic variation in the phase of the diurnal component with a period close to 22 years.

Parsons & Panton³² find the modulation effects, during 1963-66, for the diurnal component at Southern stations (Hobart and Mawson) to be the same as those of stations in the northern hemisphere (Tokyo, Hafelekar, Manchester and London). Sandstrom³³ finds that the shift in the time of maximum is independent of the asymptotic direction of viewing of the detector. The 22 year cycle is seen in the semidiurnal component also (Sarabhai et al²⁰).

The form of the daily variation, when studied without recourse to harmonic analysis, reveals interesting sequence of changes.²⁰ There is only one maximum at noon during 1937-43. The maximum shifts to early morning by 1952. However, two distinct maxima are observed during 1945-60. The pattern of addition and attenuation of the contributions to the form of daily variation by the two types of maxima appears to be reversed after 11 years. Data from middle latitude stations do not show such a pattern which agrees with the results of Feinburg³⁴. Kane³⁵ has discussed the implication of temperature correction to the changes in the form of daily variation and finds that the effect of 22 year cycle is maintained, while the 11 year changes in the form of the daily variation are considerably reduced.

1.3.2. Possible contribution of sidereal anisotropy

The study of the annual vector mean amplitude and local time of maximum of the diurnal component from Huancayo ionisation chamber by Sarabhai et al²⁰, Venkatesan and Gaitner³⁶, Forbush and Venkatesan³¹, Steinmaurer and Sheri³⁷ and Kane³⁵ shows that the changes in the amplitude and the time of maximum during solar minimum of 1964 are much more drastic than during the minimum of 1944. The shift in the time of maximum was of the order of 150° or 10 hours. Dorman's⁶ computation of the direction of the effective source of diurnal variation, assuming that the anisotropy is created outside the action of the earth's dipole field for the period 1932 to 1958 using data from several stations, shows that the most significant changes of phase occurred at minimum solar activity in 1933 and 1964, whereas at the minimum of 1944 the change in phase was negligible. When these data are corrected for temperature variation in the atmosphere, it is found that the shift in the time of maximum during 1964 reduces from 150° to $30^\circ - 60^\circ$ (Dorman⁶).

It should be emphasised that it is impossible in this way to account completely for this anomalous behaviour, because still stronger anomalous variations have been observed by Conforto and Simpson³⁸ in the nucleonic component which is not affected by changes in atmospheric temperature. These

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authors using the neutron monitor data from two locations - Huancayo and Climax, ion chamber data from Freiburg and counter telescope data from Rome have found that in 1953 and 1955, the time of maximum of the solar diurnal variation remained roughly constant, whereas during 1954, the monthly mean diurnal wave vector is displaced counter-clockwise in the harmonic scale.

Anomalous behaviour of daily variation compared to previous and later years has been found by Fossamer and V. Heerden³⁹, Elliot & Rothwell⁴⁰, Parsons⁴¹, Hassel and El-sherbini⁴², Baliga & Thanbyapillai⁴³, Gardichevskaya & Zhukovskaya⁴⁴ in 1954 using, mainly, neutron data. Dorman⁶, considering temperature correction for these data, proposes that (i) at maximum solar activity only one source, to the left of the earth-sun line, is mostly effective, (ii) and two sources are operative during minimum solar activity - on a low-latitude source, the other a high-latitude source. The low-latitude source is situated to the left of the earth-sun line and is caused, mainly, by modulation of low-energy particles ($\sim 30 - 40$ GeV). The high-latitude source, lying to the right of the earth-sun line, is effective for particles of higher energies ($50 \sim 100$ GeV).

To explain the results of Conforto and Simpson³², Dorman⁶ assumes that the second source of high-energy particles is due to a preferential flux of particles from the centre of

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galaxy. This source, together with the low-energy solar anisotropy, is sufficient to explain the rotation of the vector of diurnal variation at Huancayo. Thus it is suggested that during the lowest sun-spot minimum of 1964 there are two principal sources of the diurnal variation of cosmic radiation that differ in character - solar and galactic. Also the observed period of 22 years for the long-term changes of daily variation may be fortuitous (Dorman⁶) and variations of phase, may in principle, be observed in successive minima, if these turn out to be sufficiently low and long-lasting and if the lowest activity accidentally occurs in months when there is an essential difference in phases of diurnal effects caused by solar and galactic sources of anisotropy.

A part of 22 year cycle change of daily variation is studied in the present work which covers the period of the declining phase of solar activity (1958-1962).

1.4. Day-to-day changes - Solar-terrestrial relation- ships

The day-to-day changes of isotropic cosmic ray intensity and geomagnetic disturbances, which are under solar control, can be used to distinguish the different states of the electromagnetic conditions in the neighbourhood of the earth. Mac & Sarabhai⁷ have pointed out that the geomagnetic planetary index K_p , and H , the night-time value of the horizontal component

of the geomagnetic field near the dip equator, should be connected with the interaction of solar plasma with the magnetosphere. Disturbed geomagnetic conditions ($K_p > 25$, designated as K_p^+) indicate the impinging of solar plasma with the magnetosphere, regardless of the nature of interaction. However, depending on the assumed model, one can interpret low K_p as indicating either rarified plasma or absence of turbulence in it. On the other hand, high H (at Guam, designated as H^+) except during the initial phase of a magnetic storm, indicates steady state conditions of interplanetary plasma, inclusive of the possibility of its relative absence. On the other hand, the relation of the depressed values of H to the characteristics of the plasma is not well understood. It has been suggested that because of the ambiguities in the current interpretations concerning K_p and H , more knowledge can be derived about interplanetary plasma by considering them simultaneously rather than individually.

A decrease of cosmic ray intensity is identified (Rao & Sarabhai⁷) when the daily mean neutron intensity at Deep River is less than the mean of previous day by at least .5%. The recovery is supposed to have taken place when the daily mean intensity reaches the average value for the two days prior to the decrease.

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Using the above criteria a phenomenological classification is made, for the following four states:

1) β State This state often occurs after the initial phase of a Forbush decrease associated with a magnetic storm. The mean intensity may continue to be depressed even though the magnetosphere is relatively undisturbed so that K_p is low for the earth at the centre of this region. Often towards the end of a β state, the cosmic ray intensity is observed to be recovering while K_p simultaneously increases, indicating that as the region ends the earth enters a turbulent region or a region of increased momentum density of solar plasma. This is in contrast to the decrease of cosmic ray intensity with increasing K_p in a δ state, described next.

2) δ State This region is identified by a sharp decrease of cosmic ray intensity (implying that a blast wave or a shock transition overtakes the earth). The magnetosphere is violently disturbed giving a high K_p and a geomagnetic storm usually takes place. This is followed by quick recovery (in 3-6 days) of cosmic ray intensity with a decrease of K_p to low values. The completion of the magnetic storm leading to a recovery to normal H indicates a decay of the diamagnetic shell as the earth remains in interplanetary space with relatively steady wind conditions so that the shell is not regenerated.

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3) α State This region is identified when the earth is in interplanetary space with a relatively undisturbed plasma wind which approximates to the ideal picture of Parker. The cosmic ray intensity does not show major changes from one day to another. K_p is small and H is high since the magnetosphere is not disturbed to any great extent.

4) γ State This is provisionally the residuary state in their (Rao & Sarabhai⁷) classification and probably represents the earth being in turbulent plasma. K_p is frequently high but has no associated cosmic ray decrease as is seen to occur during the passage of a blast wave or a shock transition.

The characteristics of the anisotropy determined from data of Deep River and MIT in these states are given below (Rao & Sarabhai⁷): In α state the magnitude of the anisotropy is large and the direction of maximum is mostly between 0800 and 1800 hours local time. $T_{\max}$ is the least variable and on 85% of the days there is 0 exponent for the variation spectrum. In β state the anisotropy is similar to that in α state but weaker. A characteristic feature of the γ state is that the amplitude of the daily variation is small. Further $T_{\min}$ occurs with equal frequency in the morning, day and evening. They (Rao & Sarabhai⁷) point out that in the γ state the facts are consistent with the earth being situated in a region, where

large packets of plasma with irregular magnetic fields are loosely strung by a spiralling solar magnetic field. Sarabhai⁴⁵ has suggested that this is likely to occur when fast plasma wind blows into slower wind in front of it.

1.4.1. Studies of anisotropy during Forbush decreases

The onset of a Forbush decrease, in general, occurs at the same universal time at all stations, but there can be delays in the onset ranging from 0 to 6 hours. The highly anisotropic onset of the Forbush decrease associated with the sudden commencement magnetic storm on October 21, 1957 was investigated by McCracken and Parsons⁴⁶. Several hours (~ 8) before the onset of the main Forbush decrease a perceptible preliminary decrease was observed that differed at different stations. This was found to be caused by a flux of primaries in a cone of directions within the limits $45^\circ - 90^\circ$ west of the earth-sun line. The distribution of the onset times of intensity-decreases during the magnetic storms of August 21, 1956, October 21 and November 25, 1957 over widely separated stations (Robart, Mawson, Ottawa and Sulphur Mountain) was investigated by Fenton et al⁴⁷.

In Fig. 1.2a the location of the stations and their mean asymptotic directions of viewing are shown at 0000 hours U.T. Figure b, c and d give the direction of decrease for different stations for these three storms. It is clear from

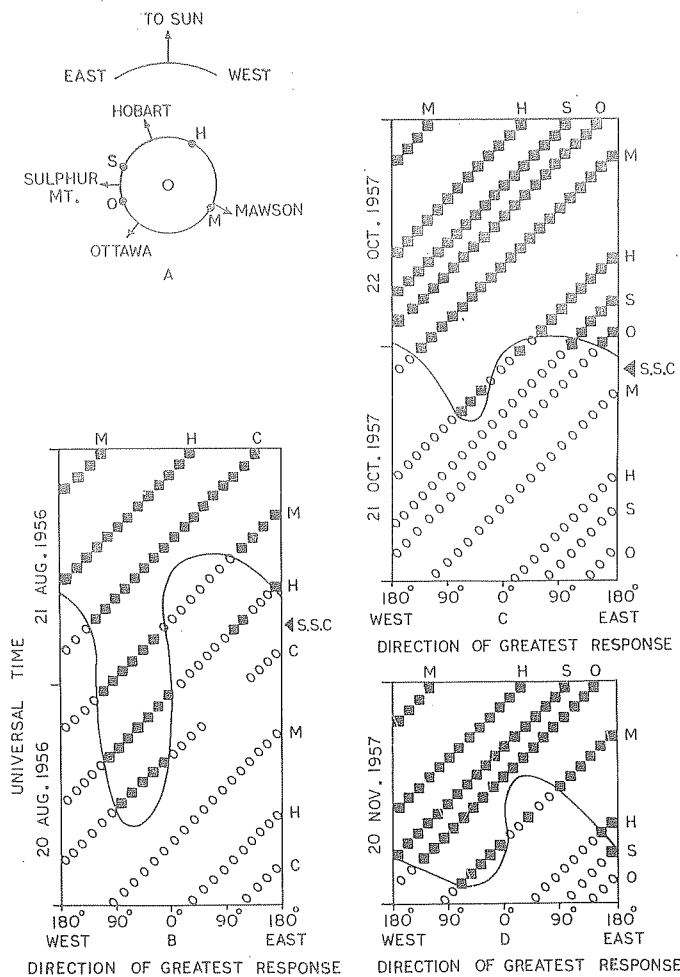


Fig. 1.2. Anisotropic onset of Portulaca decreases

the figure that the onset times differ significantly for different stations. The most effective decrease occurs at stations which have asymptotic cones of acceptance along 90° west of the earth-sun line while the largest delay in the onset of the decrease is observed in the direction $0^\circ - 90^\circ$ east of the earth-sun line.

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Lockwood and Razian^{48, 49} studying the differences in the onset times of large Forbush decreases during the period 1957-61, observe (i) that the onset of the Forbush decrease is always earlier at stations looking to the west of the earth-sun line regardless of the location of the solar flare on the sun causing the Forbush decrease. (ii) If the solar plasma responsible for the Forbush decrease originates from the western hemisphere of the sun, the onset of the decrease precedes that of the S.C. type magnetic storm, (iii) that the super-imposed anisotropic decreases are from the west and the increases are from the east of the earth-sun line.

Intensity increases, super-imposed on the main Forbush decrease, have been observed to occur at the same universal time at all stations (Koshida & Wada⁵⁰, Komio et al⁵¹, Sarabhai & Palmeira⁵², Lockwood⁵³, Rose and Lapointe⁵⁴). An explanation of these increases has been attempted by considering the effect on cosmic ray particles of the depressed magnetic field of the earth during magnetic storms (Komio et al⁵¹, Obayashi⁵⁵, Korman⁶). Korman, taking into account the longitude dependence, suggests that the increase cannot be explained completely by axially symmetric geomagnetic disturbances and part of

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the effect is due to the asymmetry in the earth's magnetic field during Forbush decreases. Lockwood and Razlan^{48,49} find that the magnitude of the increase is the largest for detectors whose asymptotic cones of acceptance lie to the east of the earth-sun line at the time of increase.

The investigation of the nature of anisotropy during geomagnetically disturbed days can give an insight regarding the advancing fronts of interplanetary plasma and magnetic fields. The time of maximum of the anisotropy is found, by several investigators, to shift to earlier hours and the amplitude is found to increase during Forbush decreases (Sekido & Yoshida⁵⁵, Sekido & Kodama⁵⁷, Samistrom⁵⁸, Glokova⁵⁹). The shift in the direction of the anisotropy continues on days following Forbush decreases. Dorman and Inozemtseva⁶⁰ study this effect using data from neutron telescopes at sea-level and underground in addition to data from world-wide network of neutron monitors. They find that a shift occurs in the time of maximum of the diurnal variation towards morning hours both for the north and the south directions. As the intensity recovers to the normal level a reverse shift of phase to a later time takes place. During the storm of July 1959, the shift in the phase of the diurnal variation in hard-component is found to be more for high energy primaries, before as well as after the storm (Kuzmin⁶⁰).

At least in two studies of anisotropy during Forbush decreases, the time of maximum of diurnal variation is reported to have shifted round the clock. Duggal and Pomerantz⁶¹, analysing the event of July 1961 at polar stations, find that the diurnal component shifts to earlier hours and returns to the original direction by a round-the-clock movement. Rao & Sarabhai⁷ study the event of 30th September 1961 and its twenty-seven day recurrent storm of 26th October. It is found that $T_{\max}$ measured by MIT neutron monitor and Deep River neutron monitor shifts to earlier hours in steps till it reaches the original direction. There is a delay of four days for the direction of minimum of anisotropy to be affected after the direction of maximum of anisotropy has undergone a change. The delay is too long to be explained by a Parker-type blast-wave advancing radially.

It is not surprising that conclusions are common for the anisotropic variations of intensity during Forbush decreases and for the anisotropy causing the daily variation. Anisotropic increases and decreases are observed when the direction of viewing is $30^\circ - 60^\circ$ east and $30^\circ - 90^\circ$ west of the earth-sun line respectively. These are the same as the directions of maximum and minimum of anisotropy that causes the daily variation, the difference of $T_{\max}$ and $T_{\min}$ being 8 - 10 hours. The shift to earlier hours of the

direction of these anisotropic increases and decreases is similar to the shift in the time of maximum and in the time of minimum of daily variation.

1.5. Experimental evidence relating to plasma, magnetic fields and galactic cosmic rays in the solar system

A knowledge of the conditions of plasma and magnetic fields in the interplanetary space is of great help in understanding the solar modulation processes of galactic cosmic rays.

Measurements on the ionisation of type I comet tails indicate the continuous presence of solar corpuscular emission (originally estimated as of density ~ 100 particles/cc. and velocity ~ 1000 km/sec). Several attempts for the measurements of interplanetary plasma have been made using space vehicles (Gringauz et al⁶², Bridge et al⁶³, Neugebauer & Bayler⁶⁴, Snyder et al⁶⁵). Only recently, however, we have clear evidence of conditions truly outside the magnetosphere. We now have measurements from the deep-space probe, Mariner II, launched towards Venus which went upto a distance of .25 A.U. from the earth towards the sun. It is found that the solar wind is always present in interplanetary space with a velocity of $300 \sim 700$ km/sec. More recent results from IMP-I confirm this broad conclusion⁶⁶.

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Several direct measurements have been attempted of interplanetary magnetic fields (Coleman et al^{67,68}, Heppner et al⁶⁹, Smith et al⁷⁰). The Mariner II measurements are devoid of several ambiguities which were present in the earlier measurements. Preliminary analysis by Smith et al⁷⁰, during the period August - September 1962, of magnetometer data collected from Mariner II indicates a persistent interplanetary field varying between 2 and 10 gamma. The interplanetary field appears to lie mainly in the ecliptic plane, although there is a substantial, fluctuating transverse component. Typically, variations as large as 5 to 10 gamma in the field component radial from the sun are measured. Changes in magnetic field appear to be well correlated with plasma measurements. Recent results from IMP-1 confirm the picture of an interplanetary field in the plane of the ecliptic and twisted by the rotation of sun, agreeing with the model of Parker⁷⁹.

Inferences regarding the interplanetary magnetic fields are also made from studies of polar cap absorption events, from studies of solar proton events and from studies of cosmic ray flares (Reid & Leinbach⁷¹, Obayashi & Nakura⁷², Obayashi⁷³, Hoffman & Winckler⁷⁴, McCracken⁷⁵, Carmichael & Steljes⁷⁶). The general picture is one in which the magnetic

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lines of force connect the vicinity of the earth with an active region in the western part of the sun. Small scale inhomogeneities of the order of .01 A.U. (McCracken⁷⁵) are required to explain the isotropy and time-delay of the solar flare protons of low-energy (~ 1 MeV). Deductions from Explorer XII measurements yield dimensions of the order of .04 A.U. for the diffusion centres (Bryant et al⁷⁷). Studies of long period fluctuations of geomagnetic field during magnetic storms point to the existence of inhomogeneities of the same order (Sarabhai & Pai⁷⁸).

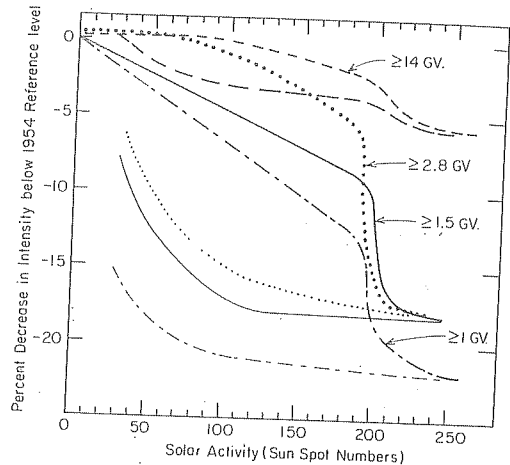
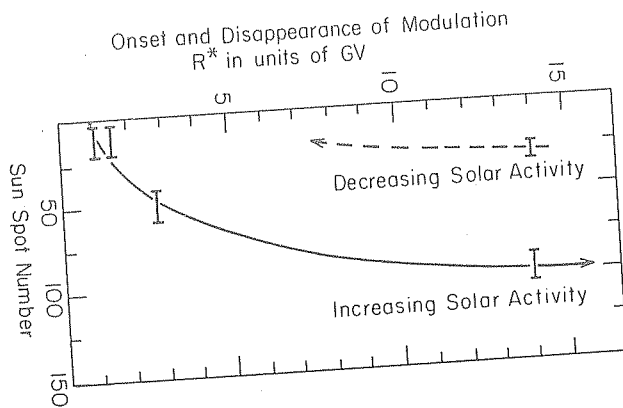
From the study of time variations of solar flare particles of February 1956, Meyer et al⁸² suggest that there should be a heliocentric magnetic barrier beyond the orbit of the earth (~ 1.4 A.U.). The field between the sun and this barrier should be sufficiently regular to explain the impact zone phenomena. The inhomogeneities in a thickness of 3 - 4 A.U. beyond this barrier give the proper decay time for solar flare particles. In addition, Parker^{79, 80}, with the help of this model, is able to explain some features of the daily variation and also the eleven year variation of cosmic ray mean intensity in the low energy region and with some modification on the high energy region (Norman⁶).

Several direct measurements of cosmic ray intensity in the interplanetary space far from the earth have been made

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with space probes (Fan et al⁸¹, Fan et al⁸², Arnold et al⁸³, Neher⁸⁴). Deductions from Mariner II measurements of cosmic ray intensity lead to a decrease of 3% in a distance of .25 A.U. from the earth towards the sun. These measurements give the integrated number of cosmic ray particles from energies of a few hundred MeV and are of great value in understanding the conditions of solar plasma, magnetic field and modulation processes.

A study of great significance in the understanding of large-scale modulation processes in interplanetary space has been made by Simpson¹⁰¹ using neutron monitor data of equatorial and high latitude station for a period of 11 years. He has shown that the dependence of cosmic ray intensity on the sun-spot number is not the same during the period when the sun-spot number is increasing as compared to the years when it is decreasing. A comparison of Climax neutron monitor data with the data of Huancayo neutron monitor shows that the onset of modulation is first for the low energy particles. Progressively higher energy particles are modulated as the sun-spot activity increases, while the changes in the lower energy particles have already ceased. The reverse phenomena happen during the decreasing phase of the solar activity. In Fig. 1-3 are illustrated the changes in the modulation process with changes in sun-spot activity.



a

b

Fig. 1.3a. First order changes taking place in the cosmic ray intensity measured by neutron monitors at Huancayo (~ 14 GV), Climax (~ 2.8 GV), Chicago (~ 1.5 GV) and Ottawa (~ 1 GV magnetic rigidity cut-off).

b. At any time during the eleven year solar cycle there is a primary particle magnetic rigidity R^* above which no solar modulation is observed (Simpson¹⁰¹).

1.6. Models of plasma and magnetic fields in the solar system

Several configurations for interplanetary magnetic fields and various patterns for movements of solar plasma have been proposed by various authors and explanations given, on their basis, for the eleven year variations of cosmic ray intensity and Forbush decreases (Davis⁸⁵, Beiser⁸⁶, Morrison⁸⁷, Parker⁸⁸, Nagashima⁸⁹, Singer⁹⁰). Explanations of the cosmic ray anisotropy are also given by several workers (Alfven⁹¹, Nagashima⁹², Brunberg & Dattner⁹³, Herurker⁹⁴, Dattner & Venkatesan⁹⁵, Gorman³, Elliot⁹⁶).

Gorman³ has made use of Alfven's concept of plasma streams from the sun but his finding of a low energy cut-off for modulation due to the effect of magnetic field frozen in the stream distinguishes his model from earlier ones. He has postulated two kinds of streams with their origin in different centres of solar activity (one from solar faculae and high latitude formations and the other from active region near sun-spots), with different velocities (one ~ 1000 km/sec and the other ~ 1500 km/sec), and with different densities (one with ~ 2 particles/cc and the other ~ 200 particles/cc). The streams of the first

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kind are supposed to be those which persist longer in time, cause gradual commencement magnetic storms and show 27 day recurrence tendency during solar minimum. The stream of the second kind, it is suggested, lasts for a shorter time and causes S.C. type magnetic storms.

If equal number of streams 'n' be situated to the left and to the right of the earth, then the differential energy spectrum of variation for particles of energy E is given by:

$$\frac{\delta D(E)}{D(E)} = \begin{cases} \pm (1+\pi) \frac{\Delta E}{E} \frac{n\delta}{\pi^2} (1 + \log \frac{\pi}{8}) & \text{if } E \geq E_{\min} \\ 0 & \text{if } E < E_{\min} \end{cases}$$

where δ is the width of the stream in the meridian plane, γ is the exponent of the energy spectrum of unmodulated primaries. The required number of streams to explain the diurnal variation is 10. This model is able to explain some aspects of daily variation from time-averaged data and some aspects of Forbush decreases.

Any model that claims acceptance should take into consideration the recent measurements by space vehicles. The interplanetary magnetic field in the vicinity of the earth is of the order of 4 - 5 gauss, and lies on the average, in the plane of the ecliptic. Also interplanetary plasma is moving continuously outwards from the sun with velocities of 300 $\sim$ 700 km/sec.

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Parker⁸⁸, from dynamical considerations, has proposed that the solar corona expands continuously starting with a low velocity at its base but attaining supersonic velocity long before it reaches the orbit of the earth. The magnetic field lines of the sun are stretched outwards by the radially moving plasma and assume the form of an Archimedes spiral due to the rotation of the sun. Fig. 1-4 shows the magnetic lines of force in the equatorial plane of the sun on the assumption of a uniform velocity for the solar wind.

INTERPLANETARY MAGNETIC FIELDS •

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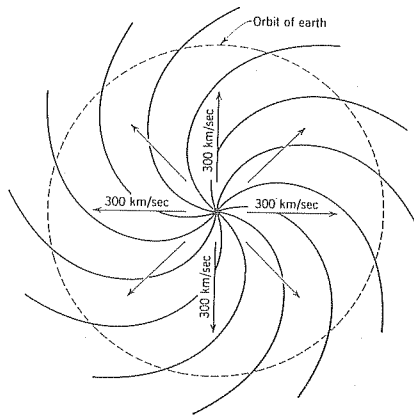


Fig. 1-4. The lines of force of the quiet-day interplanetary magnetic field resulting from extension of the general solar field by an idealized uniform 300 km/sec quiet-day solar wind directions.

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Ahluwalia and Dessler⁹⁷ have suggested that this configuration is likely to give rise to an anisotropy due to a drift of cosmic ray particles in a direction perpendicular to the magnetic lines of force. Stern⁹⁸ has examined this proposal and discussed the nature of interplanetary field and modulation mechanisms of diurnal variation. He finds that the application of Liouville's theorem leads to an isotropic flux when the quasi-stationary nature and irregularities of magnetic fields in the solar system are taken into consideration. In general, isotropy is attained in a region where the fields are conservative, if the flux of particles is isotropic outside the region. Anisotropy is created when there is an absorber (the sun as an absorber as in Elliot's⁹⁸ model) or when the magnetic field is changing with time so that

$$\text{Curl } \mathbf{E} = - \frac{\partial \mathbf{B}}{\partial t} \neq 0 .$$

Therefore, the model of large-scale smooth interplanetary magnetic field as envisaged by Ahluwalia and Dessler⁹⁷ in which $\frac{\partial \mathbf{B}}{\partial t} = 0$ cannot give rise to an anisotropy.

Parker⁸⁰ considering the case of stationary regular magnetic field and spherically symmetric constant solar wind, as in the case of Ahluwalia and Dessler⁹⁷, shows formally, that any electric drift perpendicular to

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the lines of force is exactly cancelled out by gradients in energy density and in particle density. Next he considers the case of outward moving irregularities, the number of them being so high that the cosmic ray particles execute random-walk through them. In the spherically symmetric case without source or sink, there is no net flux from any direction since the outward convection of cosmic ray particles is exactly compensated by an inward diffusion due to a gradient of cosmic ray intensity. However, as is pointed out by Parker, any departure from spherical symmetry will lead to a net streaming of cosmic ray particles.

A combination of the above two effects, namely regular spiral magnetic field in the inner part of the solar system (upto the orbit of the earth) and irregular magnetic fields of dimension 10^5 cm to 10^7 cm beyond the orbit of the earth, will give rise to an anisotropy in the inner part of the solar system. The inhomogeneities are necessary to wipe out the major portion of the density gradient which would otherwise be established by the electric field $-v \times B/c$. The imposition of the condition that there should be no net accumulation or depletion of particles within a sphere of radius r rules out any permanent radial component of anisotropy (The absorption by the

sun is not considered). The tangential component corresponds to a streaming velocity v which is the same as the velocity of rigid rotation about the sun. This gives rise to a constant amplitude of .4% for diurnal variation with a maximum in the 18 hours direction. The energy and latitude dependence of the anisotropy will be the same as in the case of the model of Ahluwalia and Bessler, namely,

$$\frac{\delta D(E)}{D(E)} = a E^0 \quad \text{and}$$

$$g(\lambda) = \cos \lambda.$$

The inner region with spiral magnetic fields extends to (~ 1.4 A.U.) and the region of turbulent magnetic fields is of width ~ 4 A.U. The inhomogeneities are carried radially outwards by the solar wind and convect out the galactic cosmic ray particles. Thus a lower intensity of galactic cosmic rays is established in the inner region. The model seems to explain most of the present day measurements of interplanetary plasma, magnetic fields and cosmic ray variations. However, as Parker himself points out, the spherically symmetrical boundaries are over-simplification of the physical situation. Further no explanation for either the semi-diurnal component or long-term changes of daily variation is attempted.

Consideration of the non-uniformity of the solar wind velocity due to longitudinal gradients of activity

in the solar corona and the change of activity with them, enables one to differentiate three or four different states according to the electromagnetic conditions of the interplanetary plasma (Sarabhai²⁰). A magnetic cavity (termed β region) is formed in interplanetary space either when in the solar corona an active zone produces a longitudinal gradient $\frac{\partial V}{\partial \theta} > 0$ or has a time-dependent activity $\frac{\partial V}{\partial t} < 0$. Corresponding to the two types of origin, the cavities are referred to as β_{θ} and β_t respectively. Similarly there are turbulent regions (γ_{θ}) due to a longitudinal gradient or (γ_t) produced by time-dependent activity. The β_{θ} cavity is expected to produce small cosmic ray effects while β_t cavity decelerates cosmic ray particles. However, as far as the geomagnetic effects are concerned, the two types of cavities act in the same way. A γ_t region would be expected to produce a blast-wave of the type already considered by Parker¹⁰⁰, but a γ_{θ} region would have a shock transition as an envelope at its leading edge. Both a γ_t region moving radially outwards and a γ_{θ} region overtaking the earth from west to east looking along the earth-sun line can be expected to produce cosmic ray storms and geomagnetic disturbances, as they strike the earth.

The α region is expected when the solar-wind velocity is uniform. Magnetic fields and cosmic ray anisotropy in this region have been investigated by Parker in detail.

Consideration of more zones of activity than one leads Sarabhai⁹⁹ to the conclusion that the heliocentric distance of the boundary of the turbulent region will decrease with increasing solar activity. There seems to be a fair chance of explaining the modulation of galactic cosmic rays on a day to day basis corresponding to different conditions of magnetic fields and plasma according to the relative position of the earth with respect to the region of coronal activity on the sun.

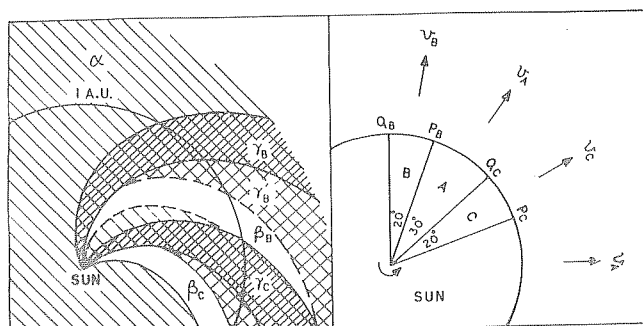


Fig. 1.5. Interplanetary states when two zones of solar activity are present.

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In Fig. 1.5 is shown a hypothetical picture of the sun and the interplanetary conditions when two zones of activity, B & C, are considered. The velocities V_A , V_B and V_C are assumed to be 300, 500, 500 kms/sec. On the left hand side of the figure are shown the α , β and γ states. It is to be noted that the onset of turbulence occurs at a comparatively less distance from the sun when more zones of activity are considered. Sarabhai has pointed out the significance of this effect to the study of 27 day recurrence tendency in geomagnetic and cosmic ray phenomena.

PART II. ANALYTICAL TECHNIQUES FOR A QUANTITATIVE STUDY
OF THE PRIMARY COSMIC RAY ANISOTROPY

1.7. The determination of the characteristics of
cosmic ray anisotropy

For a quantitative determination of the characteristics of cosmic ray anisotropy, such as its strength, energy dependence and profile in interplanetary space, it is necessary to consider the response of cosmic ray detectors to the primary anisotropy.

The calculation of the response of ionisation chambers and cylindrical neutron telescopes of various opening angles to primary anisotropy has been made by Brunberg¹⁰³, for detectors situated at Muscayo. Nagashima et al¹⁰⁴ have calculated the attenuation factors for the amplitudes of the harmonic components and drift angles in the dipole field of the earth for world-wide net-work of neutron monitors, assuming the anisotropy to be beyond or within the geomagnetic field. Their calculations take into account only the asymptotic directions corresponding to the vertical and have been used by Pomerantz et al⁹ to determine the variation spectrum during the 1957, considering only the amplitude of the diurnal variation. Rao et al¹⁰ have employed more sophisticated calculations of asymptotic

directions taking into account the finite solid angle of the detector, but use only data from neutron monitors at sea-level to determine the energy dependence of the anisotropy. The stations selected for this study have geomagnetic cut-off rigidities lower than 7 GV/c. Kane¹¹ has made use of data from a large number of stations for the determination of energy dependence of the anisotropy and compared the different methods. Kuzmin¹⁰⁵ and Skripin¹⁰⁶ using data from meson telescopes at sea-level and underground, at depths of 7, 30 and 60 meters water equivalent have determined the variation spectrum for the period 1954-59. All these authors have considered only the diurnal component and used data averaged over a long period of time. Rao & Sarabhai⁷ have used the diurnal and semidiurnal components of daily variation measured at MII and Deep River to study the characteristics of the anisotropy on a daily basis.

In the present study the author has studied the characteristics of primary anisotropy using cosmic ray data from a net-work of stations and in what follows reference is given to the work of different authors and to some of the basic data necessary for such a study.

1.8. The relation of the variation in the secondaries to the variation of primaries

In order to relate the observed daily variation

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of intensity to the primary cosmic ray anisotropy, the effect of the geomagnetic field, transition effects in the atmosphere and the geometrical sensitivity of the detector have to be taken into consideration. The change in the counting rate of the secondary component is linked to the variation in isotropic primary flux by the formula, due to Norman³,

$$\frac{dN}{N} = \int_{E_{\min}}^{E_{\max}} W(E, h) \cdot \frac{\delta D(E)}{D(E)} \cdot dE \quad (1.1)$$

where dN/N is the fractional variation in the observed counting rate, $D(E)$ is the differential energy spectrum of the primaries, $\frac{\delta D(E)}{D(E)}$ is the variation spectrum, W is the coupling constant between the secondary and the primary variation. $E_{\min}$ has the value of cut-off due to geomagnetic field or atmospheric absorption or the modulation process, whichever is higher.

In the case of anisotropic primary flux the secondary variation as measured by a detector on the spinning earth is given at any time 't' by

$$\frac{dN(t)}{N} = \int_{E_{\min}}^{E_{\max}} \int_{\theta} \int_{\alpha} W(E, h) \cdot \frac{\delta D(E, \lambda, \varphi)}{D(E)} \cdot P(\theta, \alpha) \cdot d\alpha \cdot d\theta \cdot dE \quad (1.2)$$

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Here, $\frac{\delta F(E, \lambda, \varphi)}{F(E)}$ is the variation spectrum of the anisotropic flux corresponding to the asymptotic latitude and longitude, λ and φ , respectively and incident at the detector from a zenith angle θ and an azimuth angle α . The function $F(\theta, \alpha)$ represents the dependence of the radiation on the zenith angle and the geometrical sensitivity.

1.8.1. Effects of the geomagnetic field

Determinations of trajectories of cosmic ray particles in the earth's magnetic field have been made by several investigators by numerical integration (Stormer¹⁰⁷, Jory¹⁰⁸, Lust et al¹⁰⁹) and by terella experiments (Malmfors¹¹⁰, Brunberg and Ostner¹¹¹) assuming a dipole field for the earth. McCracken et al¹¹² have recently determined the trajectories with a better representation of the geomagnetic field by means of spherical harmonic coefficients found by Finch and Leaton¹¹³. The values of asymptotic directions given by McCracken et al are therefore more accurate and are available for different zenith angles of incidence (0° , 16° and 32°) in east, north, west and south directions at a large number of stations.

Cut-off rigidities due to the earth's magnetic field have been calculated by Lemaitre and Vallarta¹¹⁴ and Alpher¹¹⁵ considering the dipole field of the earth.

These values have been revised by quenby and webber¹¹⁶ taking into account the local magnetic field and its orientation. This work has been extended by quenby and Wenk¹¹⁷ considering the quadrupole terms. McCracken and Proton¹¹⁸ have determined the cut-off rigidities from the calculations of the trajectories using the Finch and Leaton's¹¹³ simulation of the geomagnetic field. The values of quenby and Wenk¹¹⁷ and McCracken and Proton¹¹⁸ agree with the cosmic ray threshold rigidities obtained by global surveys.

The asymptotic direction and threshold rigidities of cosmic ray particles used in the present work are taken from the work of McCracken et al¹¹² and of quenby and Wenk¹¹⁷ respectively.

1.3.2. Transition effects in the atmosphere

The knowledge of coupling constants and the multiplicity in the energy range upto 15 GeV has been obtained from measurements of cosmic ray intensities by several latitude surveys at different levels of the atmosphere with neutron monitors and counter telescopes (Meher¹¹⁹, Treiman¹²⁰, Ponger¹²¹, Nagashima¹²², Simpson et al¹²³, Olbert¹²⁴, Dorman³, webber & quenby¹²⁵, Sandstrom et al¹²⁶). The values of webber and quenby correspond to the period of minimum of solar activity

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during 1964. For energies beyond 15 GeV, the values of multiplicity have to be deduced mainly by a knowledge of the production and the propagation of secondaries in the atmosphere. However, for practical purposes, extrapolation of the curves of Dorman or of Quenby and Webber is resorted to. This is partly subjective and for equatorial stations almost all the values of coupling constants have to be got by extrapolation. Theoretical computations of multiplicities at high energies for muons under various shield thicknesses have been done by Dorman¹²⁷ and are found to agree with the extrapolated values. Roederer et al¹²⁸ give coupling constants for muonic components based on their diffusion in the atmosphere. It is necessary to improve the values of the multiplicity functions by the development of more exact estimates of the production and the propagation of secondaries in the atmosphere. In the present study, therefore, values of multiplicities are taken from the work of Quenby and Webber¹²⁵.

1.8.3. Directional response of cosmic ray detectors

The directional response of meson telescopes of various geometry assuming various zenith angle dependence for the radiation has been determined by several workers (Newell¹²⁹, Newell and Presley¹²⁹, Parsons¹³⁰, Brunberg¹⁰³, Kane & Rao¹³¹). The response of neutron monitors has been

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experimentally determined by Phillips and Parsons¹³². They find that the decrease of neutron intensity with increase in zenith angle is more than what can be normally expected from Gross transformation under the usual assumptions (Janossy¹³³). This discrepancy arises mainly because the secondaries, due to scattering in the atmosphere, do not maintain the direction of primaries. Rao et al¹⁰ find by calculation that a slightly different assumption for the zenith angle response of neutron monitors does not significantly affect the studies of daily variation. The zenith angle response for neutrons used in this work is the same as that used by Lapointe and Rose¹³⁴ and for meson intensity, a $\cos^2$ dependence on zenith angle is assumed.

Using the above data the author has calculated the response characteristics of several detectors and studied by means of the diurnal and semidiurnal components the characteristics of the anisotropy on a daily basis from 1963 to 1962.

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PART III. STATEMENT OF THE PROBLEM

The present work has the object of identifying the characteristics of the anisotropy of cosmic ray intensity on individual days and of studying how these characteristics are distributed within an year as well as the changes of these distributions with declining solar activity from the year 1938 to 1962.

The characteristics considered are the strength, the direction of maximum, the direction of minimum, and the energy spectrum of anisotropy. This study includes for the first time, in the determination of optimum characteristics of anisotropy, the diurnal and the semidiurnal components of daily variation measured by a world-wide net-work of meson and neutron detectors. It is also the first study in which the energy dependence of the anisotropy is estimated on individual days.

The author has conducted experiments with two detectors at Kodaikanal, one, a cubical meson telescope and the other, a neutron monitor. In the present study, data from these detectors are used in addition to data from a net work of detectors, operated by different investigators who have kindly supplied their data to the author.

To determine the characteristics of the anisotropy the response characteristics of meson and neutron detectors, used in the present work, have been calculated. These calculations have been done under various assumptions regarding the energy dependence of the anisotropy, characterized by the exponents of its variation spectrum and also by the cut-offs for modulation on the low and ^{the} high energy sides. Further, the response characteristics have been calculated for two types of dependence of the strength of the anisotropy on asymptotic latitude.

In the context of using telescopes of different opening angles, a determination of the response characteristics is made for two hypothetical meson telescopes, situated (1) at an equatorial station and, (2) at a high latitude station. The calculations are made for two different cases of energy dependence.

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CHAPTER - II

EXPERIMENTAL TECHNIQUES AND PROCESSING OF DATA

Part A. EXPERIMENTAL TECHNIQUES

2A.1. Measurement of the Intensity of Meson Component

2A.1.1. Introduction

A cubical meson telescope and a neutron monitor pile were already in operation, as part of the programme of the IGY when the author took charge of the meson recording units at Kodaiikanal¹. This station is situated at a geomagnetic latitude of 1° N, longitude of 147° E and an altitude of 2.2 kms. The daily and seasonal temperature variations at this place are of the same order ($\sim 10^{\circ}$ C).

2A.1.2. The geometry of the apparatus

The meson recording system shown in Fig. 2.1 consists of a number of Geiger-Müller counters each of length 60 cms and diameter 3.8 cms. Sixteen such counters arranged with their length along the geomagnetic north-south line form one tray and there are three such trays, as shown in the figure. The separation between the top and middle tray is 43" and the separation between the middle and bottom tray is 24". Lead plates covering the entire

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sensitive area are packed to a total thickness of 7 cm between the middle and lowermost tray to filter the soft component.

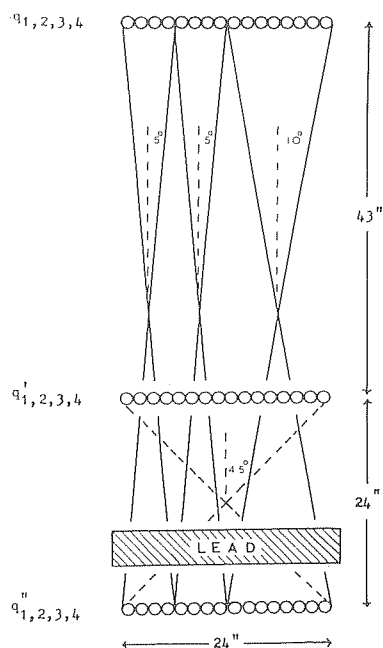


Fig. 2.1 Arrangement of counters.

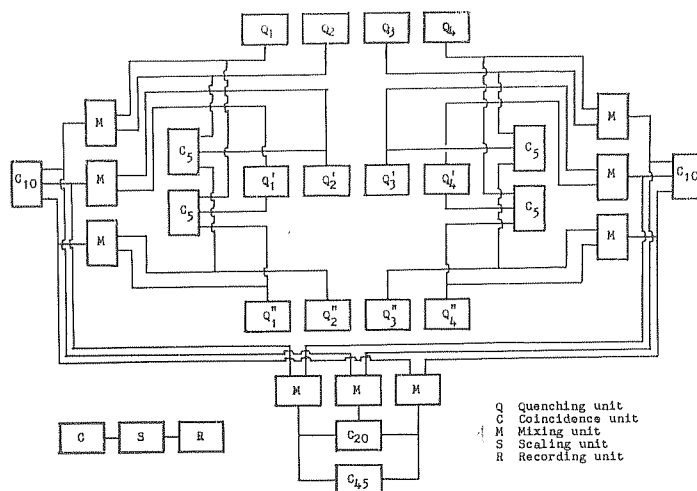


Fig. 2.2 Block diagram of electronic circuits.

Fig. 2.2 is a block diagram of the electronic circuits aligned to get telescopes of different opening angles. Four sub-trays Q_1, Q_2, Q_3, Q_4 of four counters each are formed out of the 16 counters. Triple coincidences between the top, middle and bottom sub-trays Q_1, Q'_1, Q''_1 yield telescopes of 5° in the east-west plane and 20° in

: 3 :

the north-south plane. Telescopes of $10^\circ \times 80^\circ$ are obtained from mixing the pulses from adjacent horizontal trays Q_1 and Q_2 or Q_3 and Q_4 . A cubical telescope is created out of double coincidence between the sixteen counters of the middle tray and the sixteen counters of the bottom tray. The sensitive areas of the telescopes of opening angles 5° , 10° and 45° are 840 square cms, 1680 square cms and .38 square meters respectively. The corresponding bihourly counting rates are 1100 counts, 4400 counts and 100,000 counts.

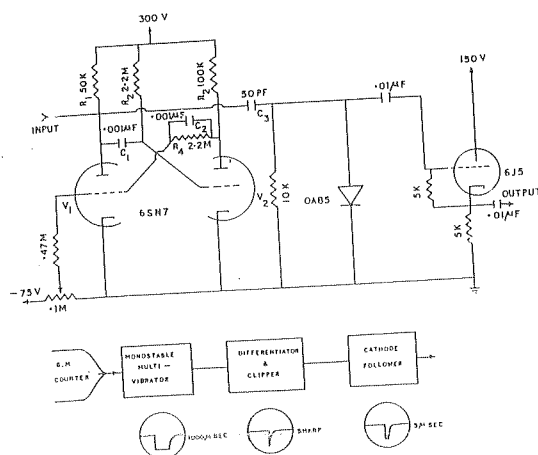
2A.1.3. Preparation of self-quenched counters

The Geiger-Müller counters used are of the self-quenching type. They are filled with argon and ethyl acetate in the proportion of 9 : 1 respectively to a total pressure of 10 cms of mercury. These counters have operation potential of ~ 1000 V, plateau of ~ 200 V, efficiency of 99.9 % and dead-time of ~ 100 micro sec. For time variation studies counters with long and stable life are necessary. The life of a counter is increased if the multiple pulses are avoided which arise because of the emission of electrons from the cathode of the counter during the positive ion bombardment. For this purpose, in addition to the self-quenching of the counters, an external electronic device

34.1.4. Electronic circuits

SECRET

QUENCHING UNIT



2 microsecond duration are obtained by a differentiating circuit, as shown in the figure. The positive pulse is clipped by a diode while the negative pulse is fed through a cathode follower to several mixer and coincidence units by means of shielded cables.

2A.1.4.2. Mixing circuit

The outputs of two cathode followers corresponding to two adjacent trays are mixed through diodes in order to combine the area of the two trays electronically. While mixing the pulses, these diodes prevent the interfeeding between the different quenching units.

2A.1.4.3. Coincidence unit

The coincidence circuit shown in Fig. 2.4 is of the Rossi-type and consists of sharp cut-off pentodes

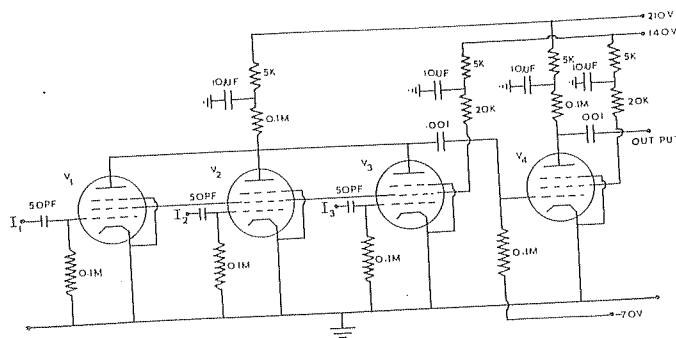


FIG.2-4 COINCIDENCE CIRCUIT

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with their plates connected together through a common resistance and with their grids so biased that they are normally conducting. When negative pulses from mixers or cathode followers arrive at all the grids within a short interval of time (~ 4 micro sec.), known as the resolving time, all the tubes are switched off and a large positive pulse is developed at the plate. If, at any time, one of the tubes is not switched off, the pulse developed at the plate is only $1/20$ th of the triple coincidence pulse. These pulses are fed to a pentode with its grid biased much below cut-off which can easily discriminate between these two different pulses. This pentode serves not only as a discriminator but as a pulse inverter giving negative pulses required for triggering the scaling circuits.

2.1.4.4. Scaling circuits

The scaling circuit shown in Fig. 2.5 consists of a number of Eccles-Jordan type bistable multivibrators connected in cascade. The scaling circuit facilitates the recording of output pulses by electromagnetic recorders which have rather low resolving times (~ 2 sec). This circuit has good stability and low sensitivity to extraneous interferences. The output pulse from one of the plates of the twin triode of the last stage of scaling unit is fed to a

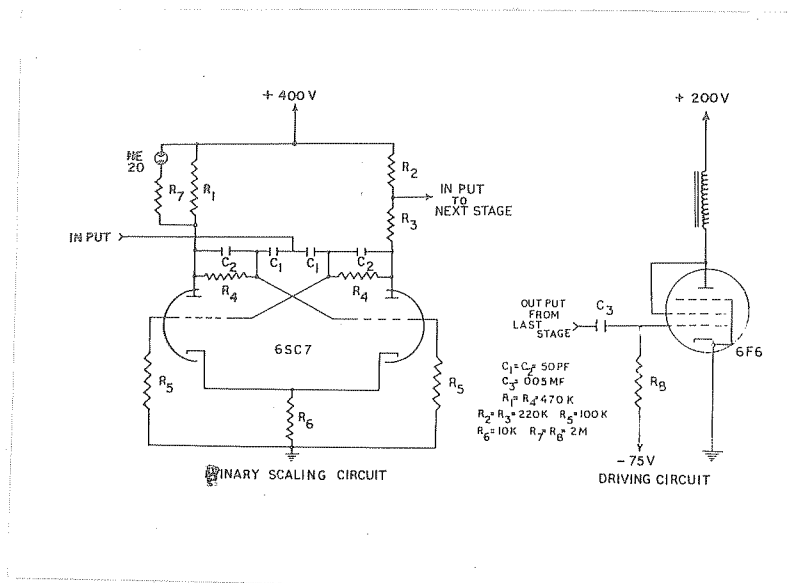


Fig. 2.5. Scaling circuit

recorder-driving circuit. It consists of a power pentode with its grid biased below cut-off and whenever a positive pulse arrives at its grid, an electromechanical recorder is activated.

2A.1.4.5. Automatic photographing device

The mechanical recorders are mounted as shown in Fig. 2.6a along with a clock and a calendar on a panel on one end of a light-proof box blackened from inside. The

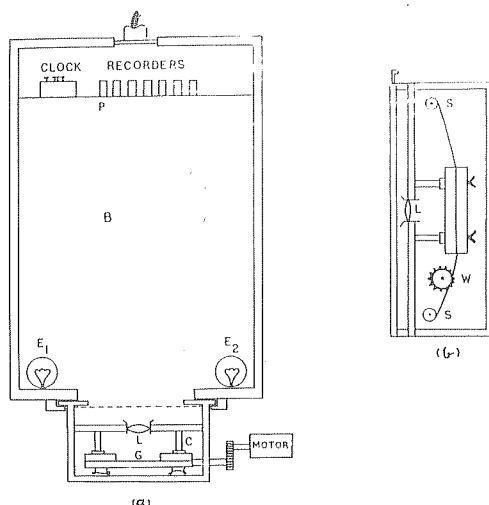


Fig. 2.6. Camera unit

box contains two bulbs to illuminate the panel when required. On the opposite side of the box is a camera shown in Fig. 2.6b which photographs the panel at required times on 35 mm film.

The sequence control system for photography is shown in Fig. 2.7. The clock contact gives a positive pulse of 150 volts at hourly intervals which triggers the first thyatron normally biased below cut-off. The current passing through this thyatron energizes a relay 'A', thereby causing the electric bulbs to flash. This relay cuts-off



the voltage on the plate circuit of the first thyatron to extinguish its discharge and this in turn switches off the lamps. The pulse from the plate of the first tube, after a delay time sufficiently long for photography, triggers the second thyatron, energising the relay 'B' on its plate circuit which starts the motor. After the film has moved by one frame, an internal switch of the motor cuts off H.T. connection from the plate of the second tube and the circuit reverts to the initial state.

2A.1.4.6. Power supplies

The electric supply at Kodaikanal fluctuates over wide limits from 90 to 250 volts in addition to frequent break-downs. Therefore to achieve reliability in the working of electronic circuits, stabilisation of D.C. voltages against both line voltage fluctuations and load variations becomes necessary. To stabilise against line voltage fluctuations, the mains voltage is fed to a constant voltage transformer of the saturated core type. The output A.C. voltage from this transformer fluctuates within $\sim 1\%$. To get stabilised D.C. voltage a regulating circuit shown in Fig. 2.8 is used. It gives a close control over the output voltage,

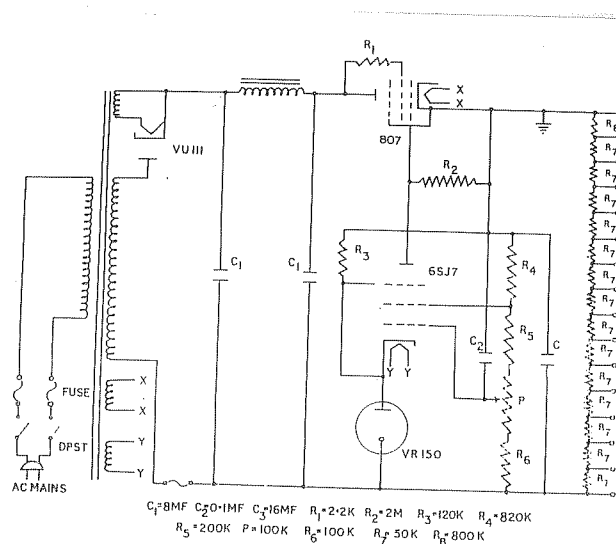


Fig. 2.8a. High tension power supply

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a high stabilising ratio and a low internal impedance. The circuit consists of a half wave rectifier with an L.C. type filter feeding about 2500 volts to the degenerative regulating network which gives an adjustable output, needed for G.M. counters, in the range 1200 to 1500 volts.

From another power supply, shown in Fig. 2.8b, 420 volts are got by degenerative regulation. Since a current of 150 mA is required, three tubes are used in parallel as shown in the circuit. Power supplies of similar design are

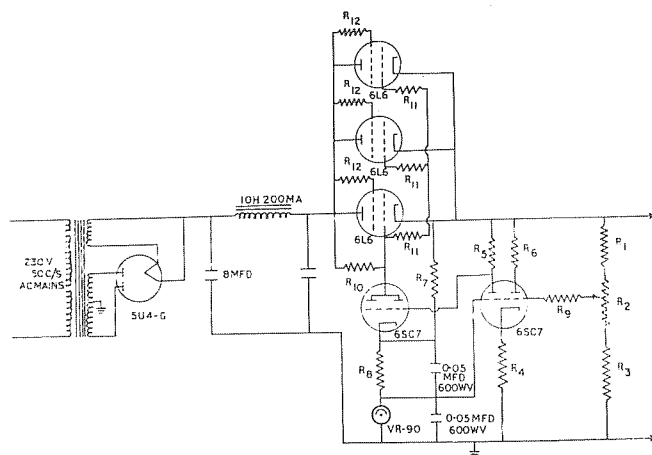


Fig. 2.8b. Low tension power supply

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used to get 300 V and 300 V D.C. output. From voltage regulator tubes negative voltages needed for biasing are obtained. The maximum current that can be drawn from these voltage regular tubes is of the order of 40 mA.

2A.2. Neutron Monitor pile

2A.2.1. Introduction

The neutron monitor pile at Kodanikanal is of the standard type recommended by SCHIV² and is essentially similar to that described by Chicago group. The proportional counters containing enriched boron trifluoride were prepared by Satya Prakash³ and the associated circuitry is well described in SCHIV report. This pile consists of two sections, WITH entirely independent recording system each section having two B¹⁰F₃ counters. For time variation studies the long life of the boron counter is well suited. In the proportional region in which the counter is working, pulses produced by neutron reactions are equal in value and considerably exceed the size of background pulses from ionising particles of cosmic rays.

The optimum thickness of moderating material and the moderator to be used to set up a neutron pile has been studied by several workers (Tongiorgi et al⁴,

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Montgomery et al.⁵, Cocconi et al.⁶, Adams and Bradnick⁷, Simpson et al.⁸). The lead thickness used in the neutron monitor pile at Kodaikanal is 3.2 cms which is greater than the local transition maximum but at the same time does not attenuate much of the star producing radiation. The paraffin surrounding the lead serves not only the purpose of stopping extraneous low energy neutrons but also acts as a moderator and reflects back the neutrons produced in lead which tend to escape.

2A.3.2. Electronic circuit

The pulses from the BF₃ counter are of the order of a millivolt and have to be amplified to the level of a few tenths of a volt for monitoring. Elmore and Sands⁹ have given an exhaustive account of the theory of amplifiers. The amplifier shown in Fig. 2.9 is capable of handling randomly distributed pulses at a high mean rate of occurrence and has a large signal to noise ratio. The gain of the amplifier is 400 and output pulses are of the order of .4 volts. As shown in the figure, these pulses are fed to a cathode-coupled monostable multivibrator which, when triggered, remains in the unstable state for a few hundred microseconds and gives a pulse big enough to drive a scaler. This discriminator circuit is used for effective

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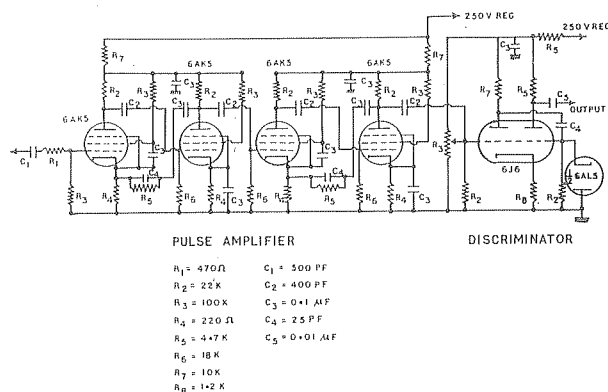


Fig. 2.9. Pulse amplifier and discriminator

elimination of background pulses. Also, it can be adjusted to any desired stable discrimination level. The scaling and recording devices are of the type described in sections 2A.1.4.4, and 2A.1.4.5.

2A.2.3. Power supplies

In the beginning stages the D.C. power supplies were of the type described in section 2A.1.4.6. Later on, in order to make the recording independent of the mains

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supply, 'Eveready' dry cells of the radio battery type, each of 45 volts have been put in series to get 200 volts. These cells are well insulated and are kept in moisture-proof box. The supply of 250 volts is obtained by putting 25 of WT-10 lead accumulators, in series, each giving 10 volts. These have a capacity of 10000 m amp. hours. The filament current is supplied by automobile batteries of the type 3FMFG-9 capable of handling the load for about 12 hours in case the mains supply is cut-off. All these storage cells are kept in floating operation.

Part B. PROCESSING OF DATA

23.1. Introduction

The present study concerns itself, mainly, with the determination of the characteristics of solar anisotropy through a study of daily variation of cosmic ray intensity. Therefore, it is necessary to eliminate the variations of intensity caused by other agencies in order to process the basic data for further analysis. The basic data of cosmic ray intensity are given as a time-series in terms of counts/2 hours centered, in most cases, at 0 hours, 2 hours, etc. in universal time and occasionally in local time. Of late, the data from detectors with moderately high counting rate are supplied at hourly intervals. The procedures described henceforth deal only with bihourly data.

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23.2. Data reduction23.2.1. Test of self-consistency of the data

The data can be tested for self-consistency in the following way if these are got from two identical but independent detectors. When the first series of readings are

$$C_1, C_2, \dots, C_n \dots \quad (2.1)$$

and the second series of readings are

$$D_1, D_2, \dots, D_n \dots \quad (2.2)$$

a third series is found by subtraction of series 2.1 and 2.2 as

$$E_1 = C_1 - D_1, E_2 = C_2 - D_2, \dots, E_n = C_n - D_n \dots \quad (2.3)$$

This new series $E_1, E_2, \dots, E_n$ should have a mean value zero and a variance twice that of the individual series. However, due to the differences in the geometrical set up and circuitry, there will exist for the series 2.3, a mean value 'd' which will be different from zero. The variance σ_1^2 and σ_2^2 of the two series may not be the same and the variance σ_3^2 of series 2.3 will be equal to the sum of the variance of the

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individual series. Assuming a normal distribution for the series E, the probability that E_1 exceeds $d \pm 2 \sqrt{3}$ on either side is 4.6 %. Consequently, if there are greater number of deviations in series E.3 than the expected 4.6 %, the data are considered not to be self-consistent and the individual series are further checked for any systematic error. This procedure has been applied by the author to process neutron data from Kodaiakamal.

2B.2.2. Normalisation of cosmic ray intensity

The following procedure is adopted whenever it is found that a finite number of binourly values from one series are either not reliable or not available. If 'i'th value in the first series, E.1, is missing, the normalised value corresponding to the i th value is determined from the five preceding values of both the series as

$$C_1 = D_1 \cdot \frac{C_{1-5} + C_{1-4} + C_{1-3} + C_{1-2} + C_{1-1}}{D_{1-5} + D_{1-4} + D_{1-3} + D_{1-2} + D_{1-1}} \quad \dots (2.4a)$$

where the fraction to the right of D_1 is called the normalising factor H_0 . On the other hand, if the sensitive area or the efficiency of the detector changes giving rise

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to a different mean level after the i th value, a new normalising factor R is found by using the formula

$$R = \frac{C_{i+5} + C_{i+4} + C_{i+3} + C_{i+2} + C_{i+1}}{D_{i+5} + D_{i+4} + D_{i+3} + D_{i+2} + D_{i+1}} \quad \dots (2.4b)$$

The series C after the i th value is normalised by multiplying it by R_0/R . This method corrects for any change in the mean level of the counting rate of the detector. Every break in the data is normalised by using a new normalising factor. After normalisation of the complete series, the average counting rate of all the identical detectors are determined.

2B.2.3. Corrections for meteorological effects

2B.2.3.1. Pressure correction

The pressure data are obtained by a sensitive barograph calibrated often with a Fortin's barometer. Special attention is devoted to the lag of the recording pen due to friction when the pressure changes abruptly. Pressure coefficients of -0.22 % per mm of Hg for meson intensity and -0.96 % per mm of Hg for neutron component are used. The cosmic ray intensity ' I ' is corrected for pressure by the use of the formula

$$\Delta I/I_0 = \beta (P - P_0) \quad \dots (2.5)$$

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In the case of discontinuous data, I_0 and P_0 correspond to the daily mean of cosmic ray intensity and daily mean pressure respectively. For a continuous series, fixed convenient values of I_0 and P_0 , not much different from the respective average values of I and P , are used.

2B.2.3.2. Temperature correction

Methods of temperature correction have been developed by Dorman and Feinberg¹⁰, Maeda and Wada¹¹. Dorman and Feinberg¹⁰ have divided, for the purpose of calculation, the whole atmosphere into eleven layers, each layer having its temperature coefficient, as shown in Table 2B.1. The total temperature correction is given by

$$\frac{\Delta N/\mu}{N/\mu} = \sum_1 K_1 \Delta T_1 \quad \dots (2.6)$$

where $\frac{\Delta N/\mu}{N/\mu}$ is the resultant variation in the meson intensity due to variation in air temperature at various layers. K_1 and ΔT_1 are, respectively, the partial temperature coefficient, and ^{the} mean amplitude of temperature variation for the 1 th layer.

An accurate correction for temperature fluctuations is possible only when a precise knowledge of temperature variations from the ground level to about 50 mb is available.

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Table 22.1

No.	1	2	3	4	5	6	7	8	9	10	11
h in m.b.	1000	900	800	700	600	500	400	300	200	100	50
$K_1 (\times 10^3)$	20	21	22	24	25	25	28	33	38	31	33

Radiosonde data are not available for most of the time and when these are available, mostly these do not cover upto 50 mb of the atmosphere. Moreover, their accuracy is not high due to radiation errors. Beers¹² finds that the amplitudes of temperature variations at 1 km and 2 km above the ground level are, respectively .22 and .11 times the amplitude at the ground level. For sea-level stations Rao and Sarabhai¹³ find that using this method about two thirds of the total temperature correction is taken into account. For Kodaikanal which is situated at an altitude of 2.2 km and near the equator, it can be assumed that the contribution of the atmospheric temperature variations is similar to that of Huancayo. For Huancayo, Quenby and Thambyahpillai¹⁴, have found that the average effect of temperature correction in the diurnal vector is $\sim .13\%$. Therefore it is reasonable to assume that at Kodaikanal the maximum contribution of temperature is to increase the average peak to amplitude by .26%. Effects of the same order have been obtained at high

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latitude stations (Dorman¹⁵). The effect is small compared to the value of peak to peak amplitudes on individual days ($\sim 1.5\%$) and is not likely to affect significantly the studies of daily variation on a daily basis (Rao and Sarabhai¹²). Therefore, in the present work, temperature correction is neglected for meson data.

23.2.4. Elimination of the long-term trend in cosmic ray intensity

The data corrected for pressure and temperature effects are subjected to the following procedure known as the method of moving averages. It separates the daily variation from changes which have periods of more than a day.

Average values of cosmic ray intensity are found as

$$\overline{C_{6.5}} = \frac{1}{12} \sum_{i=1}^{12} C_i \quad \dots (2.7)$$

where C_i s are the bihourly values and the bar denotes the average which is centered at 6.5 th bihourly or 13 hours.

Similarly

$$\overline{C_{7.5}} = \frac{1}{12} \sum_{i=2}^{13} C_i \quad \dots (2.8)$$

which is centered at 7.5 th bihourly or 15 hours and the

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mean of these two averages is centered at 7 th bihourly. As the calculations are continued for other bihourly values, successive means are obtained which are devoid of any periodic variations with periods of a day and harmonics of it. This series therefore represents the long-term trend of cosmic ray intensity. This trend is removed in the difference series $(C_7 - \bar{C}_7)$ which therefore contains only variation of short term with the period of a day and less.

Since the process of long-term removal uses a fixed step length of twelve bihourly values, variations such as Forbush decreases and flare increases, which are of shorter duration as compared to the step-length, give a distortion in the moving average. It contributes a spurious component to the daily variation obtained after removal of long-term trend on these days and this is discussed by Kane¹⁶. However, the short term isotropic variations which occur in U.F., e.g. Forbush decreases, can be removed and the diurnal and semidiurnal components of the daily variation can be separated out if we select three stations at the same geomagnetic latitude but separated in longitude by 120° from each other. Assuming the anisotropy causing the daily variation not to change during the course of a day, one gets

$$\bar{C}_1 = \frac{1}{3} (C_{11} + C_{21} + C_{31}) \quad \dots (2.9)$$

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where the bar denotes the average bihourly value for the three stations at the same U.T. The series $(\bar{C}_1)$ contains only U.T. variations but is free of diurnal and semidiurnal variations. Consequently on subtracting each bihourly value from the corresponding mean, only the diurnal and semidiurnal effects remain in $(C_1 - \bar{C}_1)$. This method first applied in the study of geomagnetism has to be modified to consider the longitude of the asymptotic cones of acceptance of the detectors in the study of daily variation of cosmic ray intensity (Rao¹⁷).

2B.3. Harmonic analysis

Every function satisfying certain conditions can be expressed as an infinite series of circular functions

$$F(t) = a_0 + \sum_{n=1}^{\infty} (a_n \cos nt + b_n \sin nt) \dots \quad (2.10)$$

where, a_n, b_n are the coefficients of the n^{th} harmonic.

Chapman and Bartels¹⁸ have discussed the method of analysing a function $F(t)$ which is defined at π equidistant points in the interval $t = 0$ to $t = 2\pi$ into a series of harmonic components. They have shown that in approximating this function with a finite series of $(2k + 1)$ coefficients, the harmonic analysis makes

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the value of $\sum_{t_i=0}^{2\pi} (t) = a_0 + \sum_{n=1}^k (a_n \cos nt_i + b_n \sin nt_i)^2$

a minimum, the coefficients are determined uniquely, i.e. the inclusion or dropping out of some harmonic components does not affect the values of the remaining coefficients. This follows from the property of orthogonality of sine and cosine functions.

In the case of bihourly measurements the value of r is 12 and the maximum number of harmonic coefficients that can be determined for each day is also 12. The following expression is used to determine the coefficients when measurements are available at r equidistant intervals.

$$a_0 = \frac{1}{r} \sum_{i=1}^r c_i$$

$$a_n = \left(\frac{2}{r} \right) \sum_{i=1}^r c_i \cos nt_i$$

$$b_n = \left(\frac{2}{r} \right) \sum_{i=1}^r c_i \sin nt_i$$

... (2.11)

The amplitude, r_n , and the phase φ_n of the n th harmonic are found from the relation

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$$r_n \cos (nt - \phi_n) = (a_n \cos nt + b_n \sin nt)$$

from which it follows that

$$r_n = \text{square root of } (a_n^2 + b_n^2)$$

$$\phi_n = \text{arc tan } (b_n/a_n). \quad \dots (2.12)$$

The daily variation of cosmic ray intensity is sufficiently described by the first two harmonics. Therefore after determining the coefficients a_1, b_1, a_2, b_2 , the curve

$$V_1 = a_1 \cos t_1 + b_1 \sin t_1 + a_2 \cos 2t_1 + b_2 \sin 2t_1$$

is obtained and the hour $T_{\max}$ at which the curve has a maximum, $T_{\min}$ at which the curve has a minimum and 'A' the peak to peak range of the curve are determined.

These values were obtained using IBM 1630 computer for all values of i . While using an electronic computer, it is better to supply and store in its memory the values of all $\cos t_1, \sin t_1, \cos 2t_1$ and $\sin 2t_1$. This saves the time which otherwise the machine will require for evaluating every time the cosine and sine functions by expanding them into series.

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From the theory of probability it is found that the distribution of a_n , b_n are Gaussian if the bihourly values have also the same distribution. The standard error of the various harmonic components are

$$\sigma_{a_n}^2 = \sigma_{b_n}^2 = \frac{\sigma_1^2}{6}$$

where σ_1 is the standard deviation of bihourly values.

$$\begin{aligned} \sigma_{r_n} &= \sigma_{a_n} \\ \sigma_{p_n} &= \frac{\sigma_{r_n}}{r_n} \end{aligned} \quad \dots (2.13)$$

22.4. Frequency distributions

In the present work, studies of day to day and year to year changes in the characteristics of daily variation have been made extensively with the help of frequency distributions. In a frequency distribution the number of occurrence is given for all values of a variable x in the interval x_1 to x_2 . When the intervals are discrete, the graph is called a histogram. In histograms the frequency is represented by either the ordinates or preferably by the area bounded by the histogram, the ordinates and the abscissa.

2B.4.1. Moments of histograms

The moments of histograms about an arbitrary origin is defined in the following way, where P_i is the frequency of occurrence of the variable x_i and N is the total number of occurrences.

$$\begin{aligned}\gamma_1 &= (1/N) \sum_i P_i x_i \\ \gamma_2 &= (1/N) \sum_i P_i x_i^2 \\ \gamma_n &= (1/N) \sum_i P_i x_i^n \quad \dots \quad (2.14)\end{aligned}$$

2B.4.2. The Chi square test

Any of the parameters like the first moment or the second moment can be used to distinguish one histogram from another. However, the most powerful method for comparison of histograms is the Chi square test evolved by Karl Pearson¹⁹. If there are 'n' independent normal variables, x_1, x_2, x_n with mean zero and standard deviation $\sigma_1, \sigma_2, \dots, \sigma_n$ then χ_n^2 is defined as

$$\chi_n^2 = \sum_{i=1}^n (x_i / \sigma_i)^2 \quad \dots \quad (2.15)$$

The probability y that this value lies between χ^2 and $\chi^2 + 1$ χ^2 is given by

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$$P(\chi^2) = e^{-\frac{\chi^2}{2}} \cdot \left(\frac{\chi^2}{2} \right)^{\frac{n-2}{2}} / (2)^{n/2} \cdot \left(\frac{n-2}{2} \right)! \dots (2.16)$$

and tables are available in standard books of statistics²⁰ where the value of the probability to be greater than or equal to a given value of χ^2 for n degrees of freedom are printed.

Let n_{1i} , n_{2i} be the frequencies at the i th interval of two frequency distributions having total frequencies N_1 and N_2 respectively. The expected frequencies at i th interval are

$$\begin{aligned} E_{1i} &= (n_{1i} + n_{2i}) \cdot N_1 / (N_1 + N_2) \\ E_{2i} &= (n_{1i} + n_{2i}) \cdot N_2 / (N_1 + N_2) \dots (2.17) \end{aligned}$$

and the value of chi square is given by

$$\chi^2 = \sum_{i=1}^k \left(\frac{(n_{1i} - E_{1i})^2}{E_{1i}} + \frac{(n_{2i} - E_{2i})^2}{E_{2i}} \right) \dots (2.18)$$

where k is the number of intervals so adjusted that there are not less than five occurrences in any of them and $k-1$ is the degree of freedom of the chi square.

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If χ^2 determined from any two histograms exceeds the value of χ^2 for 5% probability corresponding to the same degrees of freedom given in tables, there is a risk of 1 in 20 in rejecting the null hypothesis that the two histograms are from the same population. The essential point to be noted is that the comparison is valid only for the regrouped histograms with not less than five occurrences in any interval. Another point is that the χ^2 test does not give any indication as to whether the differences between two distributions are due to a single value in one histogram differing very much from the corresponding values of the other histogram or a number of values in one histogram differing moderately from the corresponding values in the other one. Further, one histogram may differ from another in a negative manner on one side of a central point and in a positive manner on the other. Still if the differences are small, the χ^2 test may not reveal this obvious lack of conformity because the sign is not taken into account.

20.5. IBM 1620 electronic computer

All the processing of data are done with an IBM 1620 electronic computer and its accessory units²¹. This computer has a memory of 20000 in magnetic core storage. It executes a single instruction in a few microseconds.

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Input information can be given either through a typewriter, punched tape or punched card, though the last is preferred because of its comparative speed and flexibility. The machine accepts FORTRAN language programmes, which follow the algebraic way used in solving problems. For a programme written in this language, 8000 positions are used for sub-routines (e.g. cosine, sine, exponentials, logarithms, square root, addition, subtraction, multiplication and division). Any constant or variable, however small it may be, occupies 10 storage positions. Consequently long and complicated problems involving large amount of memory have to be split up into smaller programmes in order to be fed to the computer in succession. However, this language is easy to write and is flexible. The machine also accepts programmes written in both SPS and machine language, but these programmes are difficult to write and check, even though these are faster and require less of storage space.

From the data sheets the required information is punched in cards by means of punching machines in the format provided in the programme. The information contained in the card is interpreted with the help of an accounting machine or a document writing system. A sorting machine is of great help in arranging the cards in any required manner. These cards are fed into the card-read-punch IBM 1682 in

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the order required by the instructions in the programme. The output is either typed, or if required for further calculations with the computer, is punched in cards. It takes about seven seconds to get the harmonic coefficients and the built-up curve with $T_{\max}$, $T_{\min}$ and A for each day after correcting for the meteorological effects and removing the long-term trend.

C H A P T E R - I I I

RESULTS AND DISCUSSION

Part A. THE RESPONSE OF MESON AND NEUTRON DETECTORS TO ANISOTROPY OF COSMIC RAY INTENSITY

3A.1. Introduction

The variation of secondary cosmic ray intensity, after correction for meteorological changes, depends on many factors such as the directional response of the detector, the nature of the secondary component detected, the height of the atmosphere above the instrument, the geographic location and also on the nature of variation of primary cosmic ray intensity. Let $D(E, \lambda, \varphi)$ be the differential energy spectrum of primary cosmic rays of energy E , in a direction λ and φ which are the latitude and longitude respectively of the asymptotic velocity vectors measured in the geographic co-ordinate system. After bending in the geomagnetic field, the particles arrive at the top of the atmosphere at a zenith angle θ and azimuth angle α . It is assumed that this direction is maintained by the secondary particles reaching the detector. The number of secondary particles of all energies which are produced by a single primary particle and detected at a height 'h' in the direction of θ and α , is given by the multiplicity, $n(E, h, \theta)$. This multiplicity function can be separated into two functions, $S(E, h) \cdot f_1(\theta)$. Since

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the elementary sensitive area 'da' of the detector is a function $f_2(\theta, \alpha)$ of zenith and azimuth angles, and the elementary solid angle is equal to $\sin \theta \, d\theta \cdot d\alpha$, the counting rate of the detector is given by

$$N = K \int_{E=E_0}^{E_0} \int_{\theta=0}^{\pi/2} \int_{\alpha=0}^{2\pi} S(E, h) \cdot D(E, \lambda, \varphi) \cdot F(\theta, \alpha) \cdot \sin \theta \cdot d\theta \cdot d\alpha \cdot dE \quad \dots (3A.1)$$

where K is a constant and $F(\theta, \alpha) = f_1(\theta) \cdot f_2(\theta, \alpha)$. $F(\theta, \alpha) \sin \theta$ gives the zenith angle response of the detector. The fractional variation in the secondary flux, $\delta N/N$, due to a variation in the primary flux, $\delta D(E, \lambda, \varphi)$, is given by

$$\delta N/N = \frac{1}{N} \int_{E_{\min}}^{E_{\max}} \int_{\theta=0}^{\pi/2} \int_{\alpha=0}^{2\pi} S(E, h) \cdot \delta D(E, \lambda, \varphi) \cdot F(\theta, \alpha) \cdot \sin \theta \cdot d\theta \cdot d\alpha \cdot dE \quad \dots (3A.2)$$

The expected variation in secondaries due to primary anisotropy has been calculated by Brunberg¹ for ionisation chambers and neutron telescopes of cylindrical geometry at Musucayo. Nagashima et al.² have determined the response characteristics of world-wide network of neutron monitors under several assumptions regarding the variation spectrum of the anisotropy, using asymptotic directions corresponding

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only to the vertical. Lapointe and Rose³ have determined, for zero exponent of the variation spectrum, the cone of acceptance, which is the solid angle beyond the geomagnetic field that contributes effectively to the counting rate of a detector, of neutron monitors at different latitudes from equator to pole. All these authors have used mainly data of asymptotic directions obtained from terrella experiments of Brunberg and Dattner,²³ which correspond to a dipole field for the earth. McCracken et al.⁴ have used the sixth degree simulation of the geomagnetic field and have obtained the response characteristics of neutron monitors situated at 28 different places on the globe for values of the exponent of the variation spectrum ranging from +.4 to -1.0 and assuming a cosine function for the dependence of the strength of the anisotropy on asymptotic latitude. For the purpose of calculations, they have considered zenith angles of 0, 15 and 30 degrees in the four principal azimuths.

In order to make a detailed study of anisotropy, it is found necessary to make additional calculations using more values of the exponent, $E_{\min}$ and $E_{\max}$ of the variation spectrum and considering different types of dependences for the strength of anisotropy on asymptotic latitude. The calculations have been done by using formula 3A.1 and 3A.2

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and are presented in the following sections together with the results.

3A.2. The response of a detector to cosmic ray flux

3A.2.1. zenith angle response of cosmic ray detectors

3A.2.1.1. Meson telescopes

The geometrical sensitivity, i.e. the product of the sensitive area and the solid angle, of a two counter telescope has been discussed by Newell⁶, Newell and Pressly⁶. The cases of telescopes with cylindrical, cubical and rectangular parallelepiped geometries have been discussed by Brunberg¹, Parsons⁷ and Kam & Rao⁸ respectively. Kam and Rao have found the formula for geometrical sensitivity of a rectangular telescope in terms of its length 'l', breadth 'b' and separation between the extreme trays 'a' as

$$G.S. (\theta) = a^2 \cdot \sin \theta \cdot \cos \theta \left[\Delta \cdot \delta \cdot (\alpha_2 - \alpha_1) - \Delta \tan \theta (\sin \alpha_2 - \sin \alpha_1) + \delta \cdot \tan \theta (\cos \alpha_2 - \cos \alpha_1) - (\tan^2 \theta / 4) (\cos 2\alpha_2 - \cos 2\alpha_1) \right] \quad \dots (3A.3)$$

where $\alpha_1 = l/a$, $\alpha_2 = b/a$. α_1 and α_2 are the limiting values of azimuth angles and depend on θ . In order to get the geometrical sensitivity centered along the directions corresponding to the sides of the telescopes, the author has found the following limits to be used in formula in 3A.3.

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When the azimuth direction is parallel to the shorter side of the telescope,

for $0 \leq \theta < \text{Arctan}$

$$\alpha_1 = 0$$

$$\alpha_2 = \pi/4$$

For $\text{Arctan} \delta \leq \theta < \text{Arctan} (\delta\sqrt{2})$

$$\alpha_1 = \arccos (\delta \cot \theta)$$

$$\alpha_2 = \pi/4$$

When the azimuth direction is parallel to the longer side of the telescope,

for $0 \leq \theta \leq \text{Arctan} \delta$

$$\alpha_1 = \pi/4$$

$$\alpha_2 = \pi/2$$

Two cases are to be distinguished according as $\delta\sqrt{2}$ is greater or less than Δ .

Case 1. $\delta\sqrt{2} > \Delta$

for $\text{Arctan} \delta \leq \theta < \text{Arctan} \Delta$

$$\alpha_1 = \pi/4$$

$$\alpha_2 = \pi/2$$

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for $\text{Arctan } \Delta \leq \theta < \text{Arctan } (\delta\sqrt{2})$

$$\alpha_1 = \pi/4$$

$$\alpha_2 = (\pi/2) - \text{Arccos } (\Delta \cot \theta)$$

for $\text{Arctan } \delta\sqrt{2} \leq \theta < \text{Arctan } (\Delta^2 + \delta^2)$

$$\alpha_1 = \text{Arccos } (\delta \cot \theta)$$

$$\alpha_2 = (\pi/2) - \text{Arccos } (\Delta \cot \theta)$$

Case ii. $\delta\sqrt{2} < \Delta$

for $\text{Arctan } \delta \leq \theta < \text{Arctan } (\delta\sqrt{2})$

$$\alpha_1 = \pi/4$$

$$\alpha_2 = \pi/2$$

for $\text{Arctan } (\delta\sqrt{2}) \leq \theta < \text{Arctan } \Delta$

$$\alpha_1 = \text{Arccos } (\delta \cot \theta)$$

$$\alpha_2 = \pi/2$$

for $\text{Arctan } \Delta \leq \theta < \text{Arctan } (\Delta^2 + \delta^2)$

$$\alpha_1 = \text{Arccos } (\delta \cot \theta)$$

$$\alpha_2 = (\pi/2) - \text{Arccos } (\Delta \cot \theta)$$

The dependence of meson intensity on zenith angle is generally expressed as $\cos^2 \theta$. Barret et al.⁹ find that

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for mesons measured underground, produced by primaries of considerably high energies, $n = 3$. For meson intensity at sea-level, which is produced by primaries of mean energy ~ 25 GeV, a value of $n = 2$ agrees fairly well with experimental results. Consequently calculations are made for meson telescopes under the approximation $f(\theta) = \cos^2 \theta$.

3A.2.1.2. Neutron monitors

Phillips & Parsons¹⁰ have found experimentally that the geometrical sensitivity of a neutron monitor, conforming with the standard ICY pattern, varies with the zenith angle approximately as $\cos \theta + 1/3 \sin \theta$. Cross transformation, under the usual assumptions and also under the approximation that the counting rate of a neutron monitor in a parallel beam of high energy nucleons is independent of the zenith angle of arrival of the nucleons, leads to a zenith angle dependence (Janossy¹¹) of

$$f(\theta) = (1 + h/L \cos \theta) \cdot \exp(-h/L \cos \theta) \dots (3A.5)$$

where 'L' is the attenuation length. Rao et al¹² show that in the study of daily variation, a slightly different function for zenith angle dependence does not make a significant difference. Consequently, zenith angle response is assumed to be given by a simpler function expressing the intensity at inclined directions in terms of the intensity

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in the vertical direction as

$$f(\theta) = \exp \left(-(h/L) (\sec \theta - 1) \right) \quad \dots (3A.6)$$

which is the same as ^{that} used by Lapointe and Hesse³.

3A.2.2. Multiplicity

The concept of multiplicity function or specific yield function has been utilised by many workers to relate the variation in the secondary component to the variation in the primary cosmic ray intensity (Hoher¹³, Treisman¹⁴, Simpson et al¹⁵, Ponger¹⁶, Dorman¹⁷, Quenby & Webber¹⁸, Kane¹⁹, Sandstrom et al²⁰). Dorman has defined the coupling constant $W^1(E, h)$ for the type '1' of the component as

$$W^1(E, h) = \frac{\delta(E) \cdot m^1(E, h)}{\int_{E_0}^{\infty} \delta(E) \cdot m^1(E, h) dE} \quad \dots (3A.7)$$

where the denominator is the total counting rate of the detector. Coupling constant, which is generally expressed as percentage, is a measure of the percent variation in the flux of a particular secondary component produced by primary cosmic rays having a fractional variation of $\delta\phi(E)/\phi(E)$. Dorman has calculated the values of coupling constants for various detectors.

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Queaby and Webber¹⁸ have defined the 'gross' yield function $m^1(p, h)$ as

$$\delta N(h)/\delta p = m^1(p, h) \cdot \delta j(p)/\delta p. \quad \dots (34.8)$$

where $j(p)$ is the total number of all charge components in the primary radiation of rigidity p . Latitude surveys of cosmic ray intensity made at different heights of the atmosphere during the sun-spot minimum of 1954-55, when the variation in primary radiation was small, have been used to calculate the gross specific yield function by the following formula

$$\left(\frac{dN^1(h)}{dp} \right) / \left(\frac{dj(p)}{dp} \right)_{p_c} = m^1(p_c, h) \quad \dots (34.9)$$

where p_c is the vertical geomagnetic cut-off rigidity.

Obviously this method is not applicable to rigidities beyond 15 GV/c and in that region extrapolation is required to get the values of multiplicity. For this purpose, a relationship between $\frac{dN}{dp}$ and p is assumed, by then, to be a power law of the form

$$\frac{dN}{dp} = K p^{-\gamma_1} \quad \dots (34.10)$$

The values of γ_1 have been obtained from the slope of these curves at 15 GeV for neutrons and at 25 GeV for mesons.

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The author has used the values of yield functions from the graphs and from the tables of dN/dp given by them. The value of K is so determined that the counting rate N adds upto 100%. The multiplicity for detectors at Kodaikanal (770 mb) are obtained by interpolation between the curves corresponding to sea-level and to 680 mb. The constants that are used to calculate dN/dp for neutrons beyond 15 GV/c and for mesons beyond 25 GV/c for some stations are given in the following table 3A.1. Here suffixes N and C stand for neutron monitor and cubical meson telescopes respectively. The capital letters used are H for Hananayo, C for Port Churchill, M for Mt. Morikura, N for Dawson and K for Kodaikanal.

Table 3A.1.

Constants used for the extrapolation of the multiplicity function

Constants	H_N	C_N	C_C	N_N^*	M_N	M_C	K_N^*	K_C^*
γ_1	1.69	1.50	1.32	1.66	1.50	1.32	1.62	1.39
K^*	447	203	766	400	203	766	353	115

* denotes values extrapolated by the author

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The extrapolation is partly subjective. For equatorial stations almost all the values have to be got by this process. Theoretical computations of multiplicities at high energies for muons under various shield thicknesses have been done by Gorzan⁴⁷ and are found to agree with the extrapolated values. Still, it is desirable to have more accurate values for multiplicity, which can be done in future when more sophisticated theories are developed.

3A.2.3. Asymptotic directions

In order to relate the direction of arrival, θ and α , at the top of the atmosphere of a charged particle having a rigidity 'P' to the directions of asymptotic velocity vectors, λ and φ , the determination of the trajectory in the geomagnetic field is required. Stormer²¹, Malmfors²², Brunberg and Gutner²³, Jory²⁴, Lust et al²⁵ have calculated the trajectories of charged particles either by numerical integration assuming a dipole field for the earth or by torella experiments simulating the dipole field. McCracken et al⁴ have determined the trajectories using a better representation of the earth's magnetic field by means of spherical harmonic coefficients found by Finch and Leaton²⁶ for the epoch 1955.

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In the present work the values of asymptotic directions used are essentially those of McCracken et al. Primary energies are chosen from 1 to 20 GeV in intervals of 1 GeV, from 20 to 40 GeV in steps of 5 GeV, from 40 to 100 GeV in steps of 10 GeV and 150, 200, 300, 400, 500 and 600 GeV. The azimuths chosen are east, north, west and south and the zenith angles are in steps of 8° upto 48° in the case of neutron monitor and upto 55° in the case of cubical meson telescopes. Since the values given by McCracken et al are not available for all values of primary energies, the author has interpolated them in the case of some energy intervals. For zenith angles of more than 32° , asymptotic directions obtained from the graphs of Brunberg and Lattner²³ are converted into geographic co-ordinates and are normalised with respect to the values of McCracken et al⁴ to be used in the calculations.

3A.2.4. Out-off rigidities

The evaluation of the cut-off rigidity in the earth's magnetic field is closely connected with the determination of the trajectories. It is found that the dipole simulation is insufficient to explain the results of the global surveys of cosmic ray intensity. However, since the major contribution for daily variation is from energies of the order of 25 GeV, it is sufficient to use the vertical

out-off rigidities given by Quenby and Wenk²⁷ under more exact representation of the earth's magnetic field and get the rigidities in the inclined directions using the ratios given by Alpher²⁸ which take into account the Störmer cone, the main cone, the penumbra and the shadow cone.

3A.3. Response of detectors to cosmic ray anisotropy

3A.3.1. The nature of primary anisotropy

It is not possible to uniquely determine the characteristics of anisotropy from a given set of observations. However, certain forms based on experience and models of anisotropy can be assumed and tested whether observations are consistent with a particular form. To evaluate the effect of primary anisotropy on daily variation the following assumptions have been made;

- 1) The profile of the anisotropy is supposed to be represented
 - (a) in longitude by the first two harmonic components, viz.,

$$A_1 \sin \varphi + B_1 \cos \varphi + A_2 \sin 2\varphi + B_2 \cos 2\varphi$$
 - (b) in latitude by the source strength $g(\lambda)$ which
 - (i) falls off as $\cos \lambda$
 - (ii) remains constant.

- 2) The energy dependence of the strength of the anisotropy is represented by a power law of the form,

$$\delta D(E)/D(E) = aE^x \text{ in the energy region}$$

$$E_{\min} \leq E \leq E_{\max} \text{ and}$$

$$\delta D(E)/D(E) = 0 \text{ when } E < E_{\min} \text{ or } E > E_{\max}.$$

- 3) The anisotropy does not undergo a change during the course of a day.
- 4) To simplify the calculations the values of $\delta(\lambda)$, $E_{\min}$, x and $E_{\max}$ are assumed for the second harmonic to be the same as those of the first harmonic.

3a.3.2. Variational coefficients

Variational coefficients $V(\varphi)$ are those numbers which relate the variation measured by a detector to the strength of the anisotropy from a solid angle Ω_1 beyond the geomagnetic field (Hao et al.¹²). These are determined by a method essentially similar to that of Brunberg¹. The total solid angle above the detector is divided into four quadrants centered along the east, north, west and south directions and further divided into annular regions with boundaries $\theta = n \times 8^\circ$ ($n = 0, 1, 2, 3, 4, 5, 6$). It is found that for neutron monitors and cubical neutron telescopes the consideration of zenith angles larger than 48° and 68° respectively is not necessary. In the case of ionisation chambers and telescopes of large opening angles, larger zenith angles will, of course, be needed.

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The contribution to the counting rate and its variation due to particles coming from the solid angle subtended by an annular quadram between $\theta = 0$ and θ° is calculated using formulas 3A.1 and 3A.2 for primary particles of energy E . This contribution comes from a region, beyond the geomagnetic field, bounded by φ_1 and φ_2 which are the asymptotic longitudes corresponding to $\theta = 0$ and $\theta = \theta^\circ$. The contribution is plotted as the area with its base along the abscissae φ_1 and φ_2 . This procedure is continued for other zenith angles, azimuth angles and energy intervals and the graph is plotted in a cumulative way.

The asymptotic directions are not available for energies very near the geomagnetic cut-off. In such cases the first interval of energy used is the difference between the cut-off energy and the least energy for which data of asymptotic directions are available. The contribution of this energy interval to the counting rate corresponds to particles coming from asymptotic longitudes between φ and 360° .

The contribution corresponding to every θ° interval of asymptotic longitude is called the variation coefficients and is plotted as ordinate against the corres-

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ponding asymptotic longitude. Here the intervals of asymptotic longitude are discrete and so the graph has the form of a histogram. Normalization of the histogram is done by making the sum of the ordinates equal to 100%, when

1. $E_{\min} = 0$, $\pi = 0$ and $E_{\max} = 600$ GeV and

2. $G(\lambda) = \text{constant}$.

The variational coefficients depend on the nature of the energy dependence of the anisotropy and on the characteristics of the detector. The solid angle which contributes significantly to the variation in the counting rate of a cosmic ray detector has been defined by Rao et al.¹² as the asymptotic cone of acceptance of the cosmic ray detector for a given variation spectrum.

3.3.3. Application to the study of the daily variation

Let the anisotropy be an arbitrary function of η and expanded as a Fourier series

$$f(\eta) = \sum_{j=1}^{\infty} r_j^* \cos j(\eta - C_j^*) \quad \dots (3A.11)$$

where η is the angle measured to the left of the sun-earth line P_j^* and C_j^* are arbitrary amplitude and phase constants. Since $\eta = \psi + 181 - 180$,

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$$f(\varphi) = \sum_{j=1}^{\infty} r_j^* \cos j(\varphi + 15^\circ - 180^\circ - c_j^*) \dots (3A.12)$$

Since

$$\Delta B/N = \sum_{n=0}^{71} f(n \times 5) \cdot V(n \times 5) \dots (3A.13)$$

where n is a variable

$$\Delta B(I)/N = \sum_{j=1}^{\infty} r_j^* \cdot \alpha_j \cos [j(15^\circ - c_j^*) + \gamma_j] \dots (3A.14)$$

' α 's and ' γ 's are defined by the following equations:

$$X_j = \sum_{n=0}^{71} V(5n) \cdot \cos j(5n + 2.5) \dots (3A.15)$$

$$Y_j = \sum_{n=0}^{71} V(5n) \cdot \sin j(5n + 2.5) \dots (3A.16)$$

$$\tan \gamma_j = Y_j/X_j, \quad \alpha_j^2 = X_j^2 + Y_j^2 \dots (3A.17)$$

The angle of drift, γ_j , can be expressed in hours, τ_j , by

$$\tau_j = \gamma_j/(j.15) \dots (3A.18)$$

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It is seen from formulae, 3A.13 and 15, that this method of relating the observed variation of cosmic ray intensity to that of the primary does not introduce any spurious harmonics. These formulae reveal that X_j and Y_j are the coefficients of the cosine and sine terms of the j^{th} harmonic obtained when the polar diagram of the detector is subjected to Fourier analysis.

3A.4. Comparison of the response characteristics of different detectors

In Fig. 3A.1 are shown the response diagrams of some of the stations for two values of the exponent α of the variation spectrum.

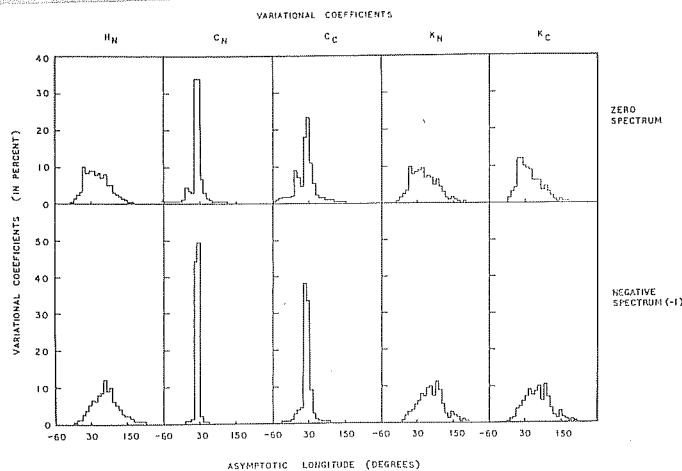


Fig. 3A.1. Variational coefficients

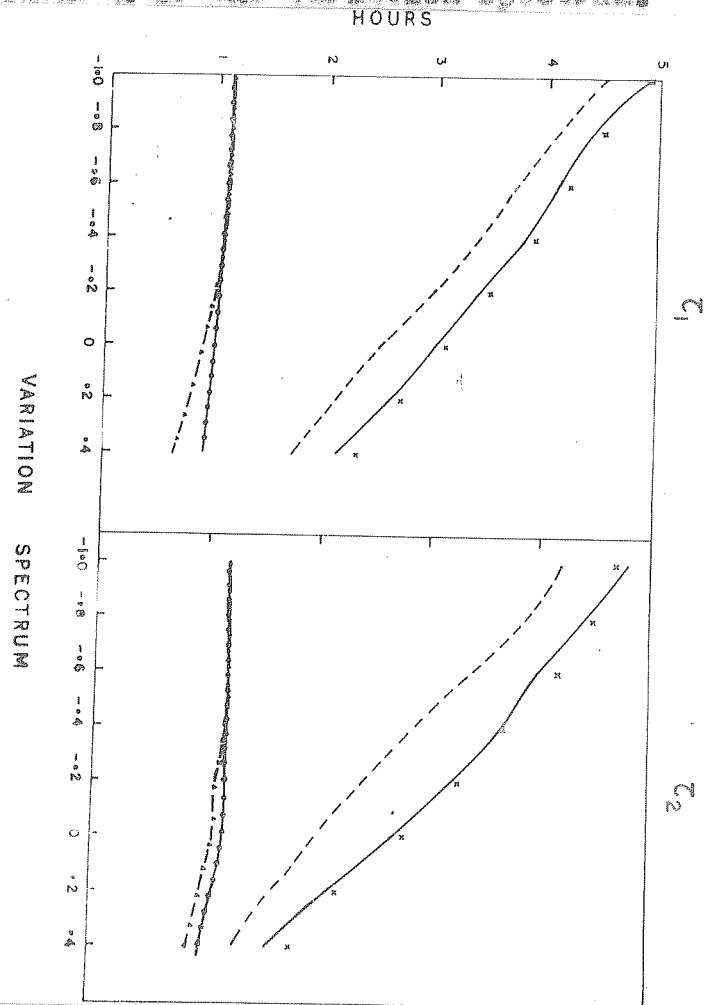


Fig. 3A.2. The drift angles in geomagnetic field.

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It is seen from the Fig. 3a.1 that:

- 1) the high latitude detectors C_H and C_C
 - (a) have sharp response curves with narrow cones of acceptance and
 - (b) have constant drift angles for different values of the exponent of the variation spectrum of daily variation,
- 2) equatorial stations H_H , K_H and K_C have
 - (a) broad response curves with cones of acceptance extended more along the asymptotic longitude and
 - (b) drift angles which are sensitive to changes in the energy dependence of the primary variations and which have higher values as the exponent of the variation spectrum of cosmic ray intensity becomes more negative.

In Fig. 3a.2, the results are more clearly brought out, where drift angles of the first and second harmonics are shown. It is seen that the drift angles, τ_1 and τ_2 for high latitude detectors are independent of spectrum, while those of equatorial stations strongly depend on the exponent of the spectrum.

The following tables 3a.2 to 3a.5 are prepared for different exponents of the variational spectrum of cosmic ray intensity (+1.0, 0 and -1.0), while the dependence of the source strength of the asymptotic latitude is expressed as $Q(\lambda) = \text{constant}$ and $Q(\lambda) = \cos \lambda$.

TABLE 3A.2

 α_1

$E_{\min}(\text{BeV})$		C_N		C_C		U_N/C_N		C_C/C_N	
		Spectrum	Spectrum	Spectrum	Spectrum	Spectrum	Spectrum	Spectrum	Spectrum
		+4	0	-1.0	+4	0	-1.0	+4	0
0	A	410	74.5	2.30	320	90.4	12.200	395	81.7
	B	383	70.6	2.20	261	73.6	11.000	265	58.1
6	A	410	74.5	2.30	230	61.7	4.800	395	81.7
	B	383	70.6	2.20	184	52.0	4.300	265	58.1
10	A	410	74.5	2.30	193	44.9	2.000	375	75.0
	B	383	70.6	2.20	136	35.0	1.800	249	62.3
15	A	410	74.5	2.30	156	34.2	0.900	345	64.3
	B	383	70.6	2.20	111	25.3	0.820	235	43.0
30	A	331	52.2	0.75	110	17.4	0.168	260	45.4
	B	291	49.5	0.70	71	12.9	0.153	182	25.3
50	A	255	51.7	0.34	91	12.8	0.060	224	29.3
	B	254	34.3	0.28	57	9.5	0.055	138	17.0
$E_{\max}(\text{BeV})$									
500	A	410	74.5	2.30	320	90.4	12.200	395	81.7
	B	383	70.6	2.20	261	73.6	11.000	265	58.1
100	A	276	64.7	2.26	308	85.7	8.170	270	73.6
	B	265	61.3	2.16	260	71.4	7.370	190	52.3
50	A	187	46.8	2.16	275	79.5	8.170	190	52.3
	B	195	46.8	2.06	239	65.8	7.370	142	42.6

A for $g(\lambda)$ = constant. B for $g(\lambda) = \cos \lambda$.

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TABLE 3A.3

 α_2

E _{min} (BeV)	H _N		C _N		C _C		H _N /C _N		C _C /C _N	
	Spectrum		Spectrum		Spectrum		Spectrum		Spectrum	
	+4	0	-1.0	+4	0	-1.0	+4	0	-1.0	+4
0	225	33.8	1.10	245	77.7	12.000	230	57.3	3.30	1.17
	A									
	205	31.8	1.10	210	66.6	10.800	171	44.1	2.60	0.98
	B									
6	225	33.8	1.10	154	49.1	4.670	230	57.3	3.30	1.46
	A									
	205	31.8	1.10	121	45.0	4.200	171	44.1	2.60	1.27
	B									
10	225	33.8	1.10	118	32.4	1.890	211	50.7	2.30	1.91
	A									
	205	31.8	1.10	90	28.0	1.700	155	38.0	1.80	2.59
	B									
15	225	33.8	1.10	91	21.9	0.780	184	40.1	0.90	2.46
	A									
	205	31.8	1.10	68	19.0	0.700	132	28.0	0.70	3.01
	B									
30	217	27.5	0.46	47	7.6	0.097	119	23.6	0.22	4.61
	A									
	212	25.3	0.43	33	6.8	0.087	80	14.1	0.17	6.42
	B									
50	177	20.7	0.27	36	4.8	0.027	97	12.3	0.07	4.91
	A									
	182	17.1	0.20	25	4.3	0.024	64	7.4	0.06	7.28
	B									
E _{max} (BeV)										
600	225	33.8	1.10	245	77.7	12.000	230	57.3	3.30	1.17
	A									
	205	31.8	1.10	210	66.0	10.800	171	44.1	2.70	0.98
	B									
100	143	32.2	1.10	265	76.6	8.00	190	55.0	3.30	0.56
	A									
	147	30.3	1.10	234	65.4	7.200	144	42.2	2.67	0.63
	B									
50	109	28.2	1.10	256	74.7	7.980	181	50.0	3.20	0.43
	A									
	112	26.7	1.10	226	63.5	7.200	123	38.0	2.61	0.50
	B									

A for $G(\lambda) = \text{Constant}$.B for $G(\lambda) = \cos \lambda$.

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E_{min} (BeV)		C_H			C_C			$H_H - C_H$			$C_H - C_C$		
		Spectrum			Spectrum			Spectrum			Spectrum		
		+4	0	-1.0	+4	0	-1.0	+4	0	-1.0	+4	0	-1.0
0	A	2.04	3.04	4.8	0.93	1.05	1.13	0.73	0.93	1.12	1.11	1.98	3.7
	B	2.08	3.09	4.8	0.93	1.06	1.13	0.63	0.90	1.12	1.15	1.94	3.7
6	A	2.04	3.04	4.8	0.89	1.03	1.10	0.73	0.93	1.12	1.16	1.98	3.7
	B	2.08	3.09	4.8	0.83	1.00	1.10	0.63	0.90	1.12	1.25	2.09	3.7
10	A	2.04	3.04	4.8	0.85	1.00	1.10	0.71	0.92	1.10	1.19	1.98	3.7
	B	2.08	3.09	4.8	0.78	1.00	1.10	0.61	0.90	1.10	1.30	2.09	3.7
15	A	2.04	3.04	4.8	0.81	1.00	1.20	0.68	0.90	1.20	1.33	2.04	3.6
	B	2.08	3.09	4.8	0.71	1.00	1.20	0.58	0.85	1.20	1.47	2.09	3.6
20	A	0.92	1.40	1.3	0.51	0.62	1.00	0.44	0.79	0.90	0.41	0.50	0.8
	B	1.04	1.49	2.2	0.31	0.70	1.00	0.38	0.58	0.90	0.73	0.79	1.2
50	A	0.64	0.80	1.2	0.43	0.53	0.37	0.35	0.60	0.43	0.21	0.20	0.9
	B	0.73	0.84	1.3	0.14	0.60	0.37	0.06	0.45	0.43	0.53	0.34	0.9
E_{max} (BeV)													
600	A	2.04	3.04	4.8	0.93	1.05	1.13	0.73	0.93	1.12	1.11	1.98	3.7
	B	2.08	3.09	4.8	0.93	1.05	1.13	0.65	0.90	1.12	1.15	1.94	3.7
100	A	3.20	3.70	4.8	1.35	1.11	1.10	1.00	1.23	1.13	1.85	2.60	3.7
	B	3.10	3.70	4.9	1.39	1.10	1.10	1.00	1.20	1.14	1.70	2.60	3.8
60	A	4.13	4.70	5.1	1.41	1.14	1.10	1.30	1.20	1.15	2.70	3.60	4.0
	B	4.13	4.70	5.2	1.45	1.10	1.10	1.20	1.20	1.15	2.70	3.60	4.1

A for $g(\lambda) = \text{Constant}$.B for $g(\lambda) = \cos \lambda$.

TABLE 3A.5

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		H_N		C_N		C_C		$H_N - C_N$		$C_N - C_C$			
		Spectrum		Spectrum		Spectrum		Spectrum		Spectrum			
		+ .4	0	-1.0	+ .4	0	-1.0	+ .4	0	-1.0	+ .4	0	-1.0
0	A	1.6	2.6	4.7	1.0	1.1	1.2	0.7	1.0	1.2	0.6	1.5	3.5
	B	1.6	2.7	4.7	1.0	1.1	1.2	0.9	1.1	1.2	0.6	1.5	3.5
6	A	1.6	2.6	4.7	0.9	1.1	1.2	0.7	1.0	1.2	0.7	1.5	3.5
	B	1.6	2.7	4.7	1.0	1.1	1.2	0.9	1.1	1.2	0.6	1.5	3.5
10	A	1.6	2.6	4.7	0.9	1.1	1.2	0.7	1.0	1.2	0.7	1.5	3.5
	B	1.6	2.7	4.7	1.0	1.2	1.2	0.8	1.1	1.2	0.6	1.5	3.5
15	A	1.6	2.6	4.7	0.8	1.1	1.3	0.6	1.0	1.3	0.3	1.5	3.4
	B	1.6	2.7	4.7	1.0	1.2	1.3	0.8	1.1	1.3	0.6	1.5	3.4
30	A	0.9	1.5	1.9	0.1	0.4	1.0	0.0	0.8	0.9	0.3	1.1	0.9
	B	1.1	1.6	2.2	0.4	0.4	1.0	0.3	0.7	0.9	0.7	1.5	1.2
50	A	0.7	1.0	1.3	0.0	0.1	0.5	- .1	0.0	0.4	0.7	0.9	0.8
	B	0.8	0.9	1.4	0.1	0.1	0.5	0.0	0.0	0.4	0.7	0.8	0.9
$E_{\max}(\text{BeV})$													
600	A	1.6	2.6	4.7	1.0	1.1	1.2	0.7	1.0	1.2	0.9	1.5	3.5
	B	1.6	2.7	4.7	1.0	1.1	1.2	0.9	1.1	1.2	0.6	1.5	3.5
100	A	2.9	3.7	4.7	1.5	1.2	1.2	1.1	1.2	1.2	1.4	2.5	3.5
	B	2.7	3.7	4.7	1.5	1.1	1.2	1.2	1.2	1.2	1.9	2.6	3.5
50	A	3.9	4.7	5.0	1.5	1.2	1.2	1.3	1.2	1.2	2.4	3.5	3.8
	B	3.9	4.7	5.0	1.5	1.1	1.2	1.3	1.2	1.2	2.4	3.5	3.8

A for $\alpha(\lambda) = \text{Constant}$.B for $\alpha(\lambda) = \cos \lambda$.

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Modulation below a particular energy $E_{\min}$ does not arise as a consequence of scattering of primary particles by magnetic fields in the models of Dorman¹⁷ and Parker²⁰. The existence of daily variation upto energies of the order of 100 - 300 GeV ($E_{\max}$) is found from underground experiments (Kuzmin³⁰, Fenton et al³¹). Therefore in the present work several values of $E_{\min}$ and $E_{\max}$ are considered and the results are obtained when

- 1) $E_{\min}$ has values 0, 5, 10, 15, 30, 50 GeV, while $E_{\max}$ has a constant value of 600 GeV, and
- 2) $E_{\max}$ has values 600, 100, 50 GeV, while $E_{\min}$ has a constant value of zero.

In table 3A.2 are shown the values of α_1 of all the three stations H_N , C_N , C_C and also the ratio α_1^1 / α_1^2 of H_N/C_N and C_C/C_N . In table 3A.3 are shown the values of α_2 for all the three stations and the ratio of α_2^1 / α_2^2 for H_N/C_N and C_C/C_N . Table 3A.4 gives in addition to the values of the drift angle for the first harmonic in all the three stations, the difference in the drift angles for H_N and C_N and also for C_C and C_N . Similar values are given in table 3A.5 for the drift angles of the second harmonic. It is found from tables 3A.4 and 3A.5 that

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the drift angles of high latitude detectors are insensitive to changes of $E_{\min}$ and $E_{\max}$, while detectors at equatorial stations show larger drift angles for lower $E_{\max}$.

Some of the results are illustrated in the form of graphs in Fig. 3A.3, where α_1 and α_2 corresponding to the diurnal and the semidiurnal components respectively are plotted against x under the assumption that the source strength depends on the asymptotic latitude as $\cos \lambda$. The response of C_N for the diurnal component is

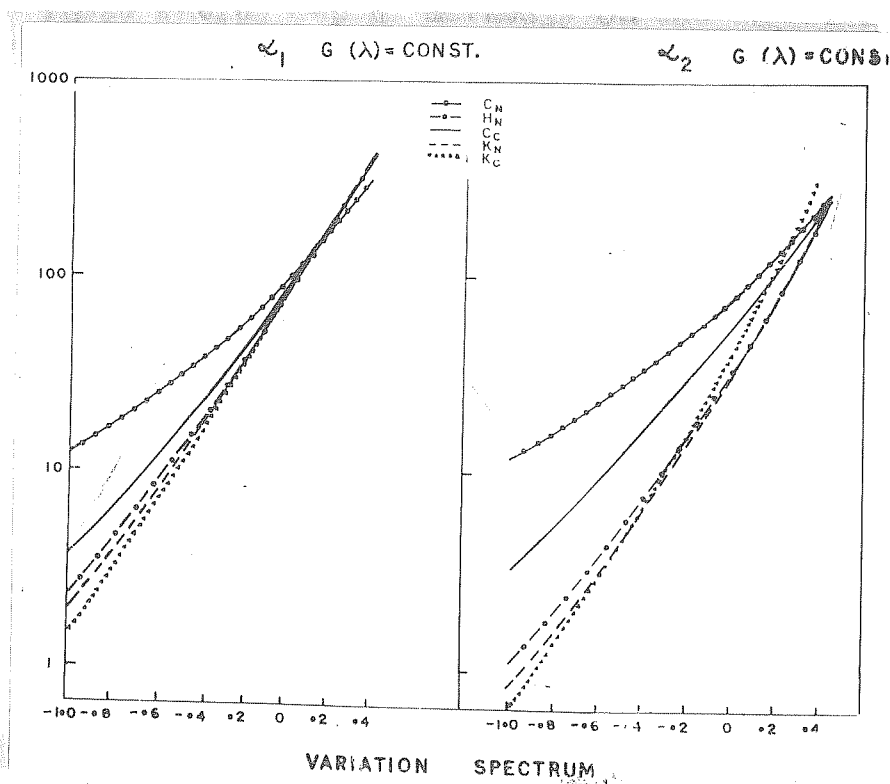


Fig. 3A.3. Attenuation factors for the diurnal and the semidiurnal components.

markedly different from the response of the equatorial stations and C_C for large negative values of the exponent of the spectrum. The response for the semidiurnal component is even more sensitive to the spectrum. C_C has a response intermediate between those of C_N and detectors at equatorial stations.

In Fig. 3h.4 the expected ratios of the first and harmonic of H_N/C_N and C_C/C_N are plotted against different values of the exponent of the variation ranging from +1.0 to -1.0. These ratios depend markedly on the exponent of the spectrum at low values of E_{min} (0 & 5 GeV), the ratio decreasing as the exponent becomes more negative. For higher values of E_{min} (10 and 15 GeV), the spectral dependence is less marked. At the highest value of E_{min} (30 GeV), the ratio slightly decreases and then increases.

Similar calculations have been made for the response characteristics of detectors at Mawson and Mt. Norikura. It is found that the detectors at Mawson have similar response as those of Churchill and the response of H_N is similar to other equatorial detectors.

In order to study the nature of variation of primary cosmic ray intensity, the detectors used should have as widely different characteristics as possible.

Here it is shown that not only the relative strengths of the first and second harmonics as measured by high latitude detectors are very much different as compared to measurements made at equatorial stations but the individual amplitudes and drift angles are influenced in a dissimilar way by the energy dependence of the primary variation. It is seen from table 3A.6 that while all the stations are

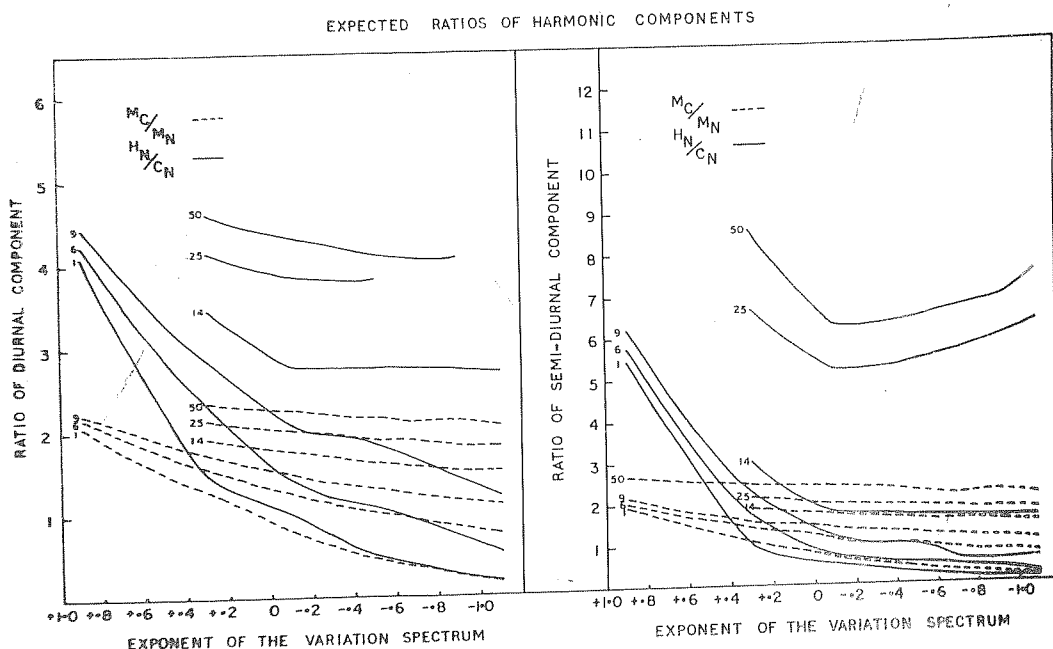


Fig. 3A.4. Expected ratios of harmonic components

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not exactly looking at the equatorial plane, these are also not far away from it. As a result, these stations are unsuitable for a study of the dependence of the source strength of anisotropy on the asymptotic latitude.

Table 3A.6.

Mean asymptotic latitude

Exponent of variation spectrum	C_N	C_C	M_N	M_C
0	35°	48°	-40°	-48°
-1	29°	39°	-26°	-42°

3A.6. The effect of opening angles of cosmic ray telescopes

Calculations are made for meson telescopes of semi-opening angles 25° , 60° in the east-west plane and constant semi-vertical angle 45° in the N-S plane for hypothetical detectors located at Kodaikanal and at Churchill. The results are presented in table 3A.7 for two cases of energy dependence of the anisotropy viz. when the exponent of the variation spectrum is zero and when the exponent of the variation spectrum is -1. It

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is seen that

- 1) the 25° angle telescope always shows higher amplitude than the 60° angle telescope,
- 2) this increase in amplitude for smaller angle of opening is more at high latitudes than at the equator,
- 3) the relative increase in amplitude is more in the second harmonic than in the first harmonic, and
- 4) the effect is more at zero spectrum than for negative spectrum.

It is found that the effect of the opening angle on the drift angle in geomagnetic field is negligible.

Table 3A.7

Telescope	Exponent x	Kodaikanal		Churchill	
		α_1	α_2	α_1	α_2
$25^\circ \times 45^\circ$	0	78.0	46.6	85.7	62.7
$60^\circ \times 45^\circ$	0	78.9	38.4	78.9	55.1
$25^\circ \times 45^\circ$	-1	73.3	64.1	96.0	87.4
$60^\circ \times 45^\circ$	-1	73.3	33.2	93.8	85.2

PART B. STUDY OF THE ANISOTROPY OF COSMIC RAY INTENSITY
OUTSIDE THE INFLUENCE OF THE GEOMAGNETIC FIELD

33.1. Introduction

Most of recent studies of the characteristics of the anisotropy of cosmic ray intensity make use of data averaged over a period of time and consider only the diurnal component (Kuzmin³⁰, Duggal et al³², Sandstrom et al³³, Rao et al¹², Kane³⁴). However, the variation from day to day in the amplitude and in the time of maximum of the daily variation of cosmic ray intensity is too much to be attributed to statistical fluctuations. This necessitates a study on a day to day basis which has been done by Rao & Sarabhai³⁵ using data of about five months in 1961 obtained from the meson detector at MIT (1000 counts/sec) and the Deep River neutron monitor (18 counts/sec). They have considered only two exponents of the variation spectrum of the anisotropy for classifying days on the basis of the ratio of peak to peak amplitudes of daily variation measured by these two detectors. The results from this study have already been discussed in sections 1.2.3 & 1.4.

The present analysis is a new approach to a quantitative determination of the parameters of the anisotropy

of cosmic ray intensity on individual days. The method is of general applicability and the error of determination would be reduced as larger number of stations with high counting rates are used and as short-term U.I. variations are eliminated.

A study making use of the amplitudes and phases of the diurnal and the semidiurnal components of daily variation of cosmic ray intensity measured by H_N , C_N and C_C on each day, was reported by the author at the International Cosmic Ray Conference held at Jaipur, India³⁶. Preliminary results of this study, from the year 1958 to 1962 during the declining phase of solar activity, were then presented. The number of days on which data were available simultaneously at the three stations was small and the range of the variation spectrum used was not sufficiently broad. Therefore in the present work the calculations are extended using data from three more stations (M_N , M_N and M_C) and the determination of the characteristics of the anisotropy is made with broader ranges for the exponent of the variation spectrum for the period 1958-62. The determination is carried out on a day, only when data from at least one neutron monitor and meson telescope at high latitude and data from at least one low latitude station are available.

As a first step in this analysis, the response characteristics of the detectors (H_N , H_C , C_N , M_N , C_C and M_C) are determined and the attenuation factors α_1 and α_2 and the drift angles τ_1 and τ_2 for the diurnal and the semidiurnal components are calculated as outlined in 3A.3.3.

3B.2. The method of best fit

3B.2.1. Determination of the anisotropy beyond the geomagnetic field

Let a_{11} , b_{11} be the 0 hour and 6 hour components of the diurnal variation and let a_{21} , b_{21} be the 0 and 3 hour components of the semidiurnal variation for the 1th detector. Let X_{jik} , Y_{jik} be the values of the components of the attenuation factor α_{jik} . Here j stands for the order of the harmonic components and k denotes the serial number of assumptions regarding the dependence of the anisotropy on latitude and primary energy. The X and Y components are calculated with reference to local or Greenwich meridian according as the diurnal and the semidiurnal components are obtained in L.T. or U.T. respectively. The formulae relating the X 's and Y 's to α 's have been given in section 3A.3.3.

The anisotropy outside the geomagnetic field can be obtained if correction is applied for the bending of primary particles in geomagnetic field and for the

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transition effects in the atmosphere. This is done by rotating the observed vectors of first and second harmonics by τ_{jik} in clockwise direction in a harmonic dial, while increasing the amplitude by $1/\alpha_{jik}$. The components of the diurnal and the semidiurnal vectors in space are given by the following formulae,

$$\begin{aligned}
 a_{jik}^* &= \frac{a_{j1} \cdot X_{jik} - b_{j1} \cdot Y_{jik}}{\alpha_{jik}^2} \\
 b_{jik}^* &= \frac{a_{j1} \cdot Y_{jik} + b_{j1} \cdot X_{jik}}{\alpha_{jik}^2} \\
 &\dots (33.1)
 \end{aligned}$$

where * denotes the values in space. These components in space derived from the data of different detectors under the correct assumption (k) of energy dependence should be identical in the absence of observational errors. That is, for a particular value of k

$$\begin{aligned}
 a_{j1}^* &= a_{j2}^* = a_{j3}^* \dots a_{jn}^* = a_j^* \\
 b_{j1}^* &= b_{j2}^* = b_{j3}^* \dots b_{jn}^* = b_j^* \\
 &\dots (33.2)
 \end{aligned}$$

where, the bar denotes the average value for n stations.

However, observational errors are unavoidable, and could be assumed, in the lower limit as the Poisson statistical error which is given by the square root of the counting rate of a detector. Also the exact nature of energy dependence cannot be realised in practice, partly due to physical reasons and partly due to the discrete nature of the assumptions. Consequently the sum of the squares of the deviations from the mean, weighted in inverse proportion to the square of the statistical error of each detector, is a measure of the goodness of fit of the assumption, the optimum spectrum giving the lowest scatter. The scatter S^2 is calculated as

$$S_k^2 = \sum_{i=1}^n \sum_{j=1}^2 \frac{(a_{jik}^* - \bar{a}_{jk}^*)^2 + (b_{jik}^* - \bar{b}_{jk}^*)^2}{\sigma_{jik}^2} \quad \dots (38.3)$$

where, the denominator is given by

$$\sigma_{jik}^2 = \frac{(n^2 - 2n) \alpha_{jik}^2 \cdot \sigma_1^2 + \sum_{i=1}^n \alpha_{jik}^2 \cdot \sigma_1^2}{n^2} \quad \dots (38.4)$$

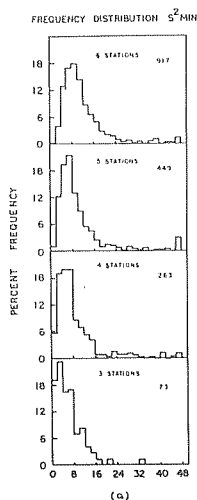
The formula 3B.4 is derived by assuming that the bihourly counting rate has a Gaussian distribution leading to the same distribution for the harmonic coefficients a_{j1} and b_{j1} with standard error σ_{j1} (Chapman & Bartels⁴⁵).

a_{jik}^* and b_{jik}^* are linear functions of a_{j1} and b_{j1} and therefore have Gaussian distributions with standard error σ_{jik} (Topping⁴⁶).

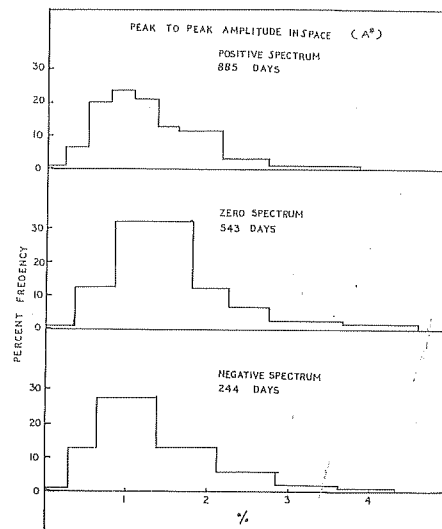
Once the optimum spectrum is determined, the optimum values of the diurnal and the semidiurnal components in space a_{j1}^* , b_{j1}^* are easily obtained. Using these values, the time of maximum, the time of minimum and the peak to peak strength of the anisotropy of cosmic ray intensity beyond the influence of the geomagnetic field are calculated.

3B.2.2. Determination of the variation spectrum

Frequency distributions of $S_{\min}^2$, which is the value of the lowest scatter corresponding to the optimum spectrum, are shown in Fig. 3B.1a on days on which 6, 5, 4 and 3 stations are working. From the smooth curves fitted to these distributions, lower and upper limits have been fixed so that 95% of the days used in the analysis remain within these limits and 2.5% of the days are beyond these limits on either side. The values of these limits depend on the number of detectors used on each day. The lower limits are 1, 1.6, 2.2 and 3.1 and the upper limits are



a



b

Fig. 3B.1a. Histograms of S^2_{min}

Fig. 3B.1b. Histograms of peak to peak strength of anisotropy in space on days with different variation spectra.

15, 31, 31 and 26 respectively, when data from 3, 4, 5 and 6 stations are available. A day is rejected or accepted according to the criterion that S^2_{min} on that day is beyond or within these limits. The chance of rejecting a normal day on which

the daily variation can be accounted for by an external anisotropy is only 5%. An examination of the days which got rejected on this basis reveals that on these days either Forbush decreases had occurred or one or more of the stations showed erratic behaviour. It is believed that this check, in addition to those mentioned in Chapter-II B, is sufficient to ensure consistency in the determination of the energy dependence of the anisotropy.

The different assumptions regarding the nature of the anisotropy are distinguishable from one another with 95% confidence, if the corresponding values of S^2 are separated by at least the width (ΔS^2) of the acceptance region. If the optimum spectrum on any day has its $S_{\min}^2$ separated from all other values of S^2 by ΔS^2 , then that spectrum is considered to fit unambiguously the observed daily variation.

The exponents of the variation spectrum used in this study are +1.0, 0 and -1.0, while the values of $E_{\max}$ and $E_{\min}$ used are 600 GeV and 0 respectively. The latitude dependence of the source strength of the anisotropy is assumed to be $Q(\lambda) = \text{constant}$. The standard errors in the harmonic coefficients have been obtained by comparing data from pairs of stations of similar response to primary anisotropy (H_N and N_N , C_C and N_C , C_N and M_N). Comparison

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is done separately for the coefficients of first and second harmonics. The standard errors thus determined, being overestimates of the true statistical errors, make all the values of S^2 proportionately low and therefore, the results or the conclusions drawn from them are not affected. The values of standard errors experimentally determined are given below in table 3B.1.

Table 3B.1

Experimentally determined standard errors (S)

Harmonics	H_N	H_C	C_N	M_N	C/C	M_C
First	.25	.29	.59	.27	.34	.17
Second	.18	.21	.46	.21	.24	.12

3B.2.3. Check for consistency of the calculations

It was intended to check whether the determination of the variation spectrum by the method of best fit is self-consistent. Three frequency distributions of $T_{\max}^1 - T_{\max}^2$ where 1 and 2 refer to M_C and M_N , are found from basic data corresponding to three sets of days which have exponents +1.0, 0 and -1.0 assigned to them by the method of best fit.

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The corresponding values of the most probable frequency obtained from these histograms are 1, 5 and 8 hours respectively for the three exponents. The calculated differences in the drift angles of primary particles in the geomagnetic field, when the variation spectrum has exponents +1.0, 0 and -1.0, are 1, 3 and 5 hours respectively. Thus the predictions seem to agree with the observations. Therefore, it is concluded that the determination of the energy dependence of anisotropy is self-consistent.

38.3.4. Normalization of the strength of the anisotropy for various variation spectra

For comparison of the peak to peak strength of anisotropy on days with different exponents of variation spectra, a normalization procedure is necessary, because of the manner in which the variational coefficients, as described in section 34.3.2., are obtained. The number of days in each year is found when the range of δ^2 does not exceed 5 on each day. The total number of days thus found during 1958-62 are 114, 124 and 43 respectively for positive, zero and negative optimum spectra. The mean values of A^* found on these days are .013, 1.06 and 13.7 respectively for the three spectra. It is assumed that the peak to peak amplitudes are equal on those days, when values of δ^2 corresponding

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to different exponents of the variation spectrum are nearly equal so that data alone cannot distinguish between the different spectra. This condition is satisfied while calculating the mean values of A^* . Therefore these values are equivalent though differing from one another by constant factors. The values of the normalisation factors obtained are 55, .94 and .07 respectively for the three cases of energy dependence of the anisotropy.

33.3. Study of the day to day changes of the anisotropy

33.3.1. Peak to peak strength in space

In Fig. 33.1b are shown the normalised histograms of A^* determined on individual days during the period 1988-89, for positive, zero and negative exponents. Chi square tests show that these histograms differ at 5% level of significance. The weighted mean of the A^* histograms on days with positive, zero and negative exponents are 10.9, 13.0 and 13.5 respectively. Therefore it is suggested that the days with positive and negative exponents of variation spectra have peak to peak strength of anisotropy less than that for days with zero exponent. This agrees with the results of Rao & Sarabhai³⁵.

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3B.3.2. Energy spectrum

In table 3B.2 is shown the distribution of days with respect to the exponent of variation spectrum determined by means of both the diurnal and the semidiurnal components of the daily variation of cosmic ray intensity for the period 1958-62, after the removal of days on which none of the three spectra gave a good fit.

Table 3B.2.**Classification of days according to variation spectra**

Determination of the variation spectrum using	Period studied	% No. of days with			Total days
		+ve spect.	0 spect.	-ve spect.	
1) the diurnal and the semidiurnal components.	1958-62	63.1	32.6	14.4	1672
2) the diurnal component.	1958 & 62	28.6	47.5	24.7	531
3) unambiguous classification, taking into account the di- urnal and the semidiurnal components.	1958-62	14.2	4.8	1.9	1672

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The difference in the distributions corresponding to the two determinations (1) and (2) can be explained as follows: In the first determination it is assumed that the entire semidiurnal component observed on each day is caused by an anisotropy of cosmic ray intensity situated outside the geomagnetic field. Further, it is assumed that the anisotropy has the same latitude dependence and the same energy dependence (i.e. same $E_{\min}$, x and $E_{\max}$) for its first and second harmonic. In the second determination the semidiurnal component is not taken into account.

It is found experimentally that the semidiurnal component, as measured by detectors at both high and low latitudes, are of comparable magnitude on individual days. On the other hand, calculations of the response characteristics show that a low latitude detector, as compared to one at high latitude, has a wider cone of acceptance and its diurnal and semidiurnal components are more attenuated. This attenuation is found to be more for the semidiurnal component than the diurnal component. The comparable magnitudes of the semidiurnal components for the two detectors could arise, if the source strength of the semidiurnal component decreases faster than $\cos \lambda$ where λ is the asymptotic latitude or there is a positive exponent for the variation spectrum. Since in the first determination neither a separate energy dependence

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nor separate latitude dependence for the second harmonic was assumed, as distinguished from those of the first harmonic, the overall determination favours an anisotropy with a positive exponent. This then results in larger number of days with positive spectrum when both the harmonics are considered.

Using the criterion described in section 3B.2 the spectra on certain days have been classified unambiguously. These distributions are shown in the last row of table 3B.2 and it is concluded that the days with positive spectrum do exist.

3B.3.3. Directions of maximum and minimum of anisotropy

In Fig. 3B.2 are shown the frequency distributions of $T_{\max}^*$ and $T_{\min}^*$ for days with positive, zero and negative spectrum. The days with positive spectrum have the most probable frequency at 14 hours direction in space as found by fitting a smooth curve. The distributions of $T_{\max}^*$ on days with zero and negative spectrum have their most probable frequencies at 13 hours direction space. The variance of the frequency distribution of $T_{\max}^*$ is 33.7, 18.7 and 28.8 hours² respectively for positive, zero and negative exponents.

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The variance is thus the largest on days with positive spectrum and the least on days with zero spectrum. Chi square tests reveal that these differences are significant at 5% level.

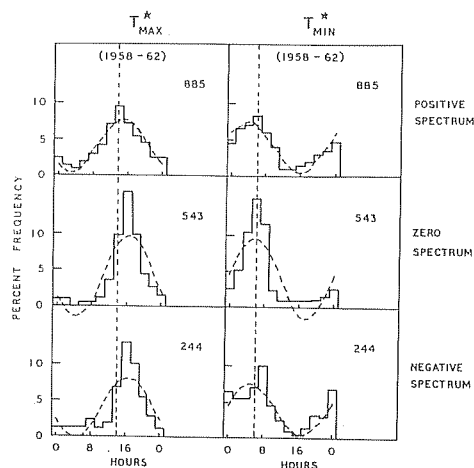


Fig. 33.2. The directions of maximum and minimum of anisotropy in space for different variation spectra.

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In order to estimate the effect of the variability in the semidiurnal component on $T_{\max}^*$, determinations of the frequency distributions of $T_{\max}^*$ for different exponents of the variation spectrum are made using the diurnal components alone during the years 1958 and 1962. Still, the distribution of $T_{\max}^*$ for days with positive exponent and for days with negative exponent of the variation spectrum have greater variance than the distribution of $T_{\max}^*$ corresponding to days with zero spectrum. Therefore it is suggested that the greater spread in the distribution of $T_{\max}^*$ on days with positive and negative spectra is a property of the anisotropy on these days.

This is in accordance with the conclusion, arrived at by Rao and Sarabhai³⁵, that most of the days in the α state, which have proportionately more number of days with zero exponent for the variation spectrum, have $T_{\max}$ between 0800 to 1800 hours. While other states, which have the number of days with -1 exponent for the variation spectrum in higher proportion and which are caused by non-uniform velocity of the solar wind, have $T_{\max}$ distributed in all quadrants.

35.4. Conclusions

Thus an examination of daily variation on individual days points to:

- 1) the existence of cosmic ray anisotropy with positive, zero and negative exponents for the variation spectrum,
- 2) less variabilities in the time of maximum and the time of minimum of anisotropy on days with zero exponent than on days with either positive or negative exponents of the variation spectrum, and
- 3) stronger anisotropy on days with zero exponent than on days with positive or negative exponents.

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Part C. LONG-TERM CHANGES OF DAILY VARIATION DURING THE PERIOD 1928-52.

3C.1. Introduction

Changes in the characteristics of daily variation of cosmic ray intensity in relation to different types of solar activity have been studied by several investigators and a 22 year cycle in the time of maximum of daily variation has been established (Sarabhai & Kane³⁷, Sarabhai et al³⁸, Elliot and Thanbyaipillai³⁹, Venkatesan and Satiner⁴⁰, Forbush and Venkatesan⁴¹, Glokova⁴²). When data of moon component are corrected for changes in atmospheric temperature, the effect of the 22 year cycle is reduced but its main features are found to persist (Dorman⁴³, Kane⁴⁴). These studies have been made with time-averaged data and the diurnal component alone has been investigated except for the study by Sarabhai et al³⁸, in which the form of the daily variation is considered.

In the present work, T_{max} , T_{min} and A of the daily variation are found on each day, as described in section 2B.3, from the built-up curve containing the first two harmonics. These parameters represent the daily variation better than the diurnal component alone and have been used effectively by Rao and Sarabhai³⁵. The frequency distributions of these

parameters are obtained in the form of histograms on groups of days and are used for the study of the characteristics of these groups. In these histograms the percent frequencies are plotted as ordinates against the corresponding values of the parameter. The number in the right hand corner of each figure shows the total number of days in the group. Dashed lines are drawn in order to illustrate the changes, if any, more clearly. The histograms of $T_{\max}$ and $T_{\min}$ are fitted with smooth curves from which the time of most frequent occurrence is determined. Comparison of the histograms for significant differences are made by the Chi square test.

Studies by means of $T_{\max}$, $T_{\min}$ and A , without considering the relationship of the variation of the secondary component to that of the primary, give only the trend of the long-term changes. Calculations necessary for linking the variation in the secondary component to the variation in the primary, have been presented in section 3B.1 and a detailed study of the anisotropy, on a daily basis, has been discussed in 3B.3. In this section, all the results of the study concerning the long-term changes are presented. In table 3C.1 are given the geographic and geomagnetic coordinates of the different detectors used in this work. Also the respective Poisson standard errors in bihourly values are indicated.

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Table 3C.1

Station	Location				Poisson Standard error (%) in bihourly values
	Geographic		Geomagnetic		
	Lat.	Long.	Lat.	Long.	
H _N	612	W75	-1	354	.17
C _N	N59	W94	69	323	.63
C _C	N59	W94	69	323	.30
N _N	N33	E138	26	204	.00
M _N	368	E83	-73	104	.38
M _C	368	E83	-73	104	.19
K _N	N10	E77	+1	147	.51
K _C	N10	E77	+1	147	.30
Mina Aguilar Neutron	523	W66	-12	3	.15

3C.2. Long-term changes in the direction of maximum of anisotropy

3C.2.1. T_{max} at high latitude stations

In Fig. 3C.1 are shown the histograms of T_{max} of daily variation measured by detectors H_N, H_N, C_N, C_C, M_N and M_C. The results are not corrected for the bending of primary particles in the geomagnetic field. From the smooth

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curves fitted to the histograms of the high latitude stations, C_N , C_C , M_N and M_C , the times of most frequent occurrence are obtained as shown in table 3C.8.

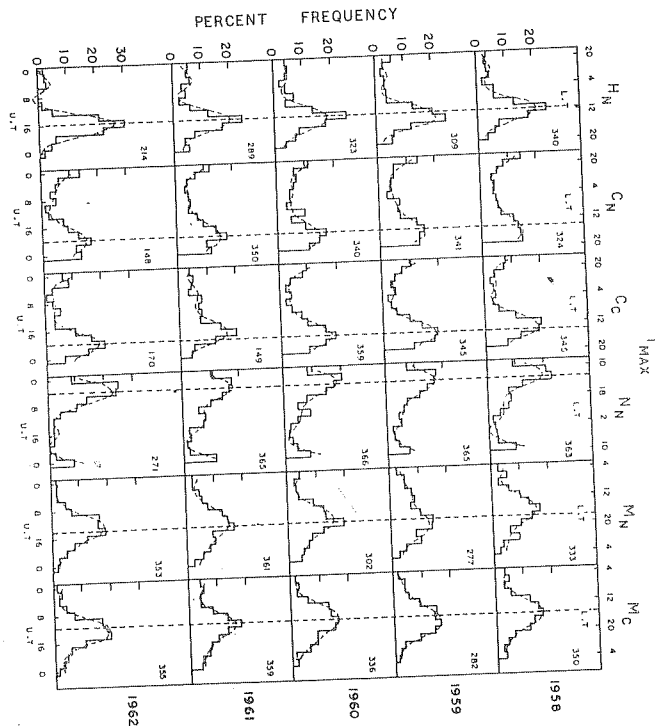


Fig. 3C.1. Histograms of T_{max} in each year from 1958 to 1962.

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Table XC.2

$T_{\max}$ at high latitude stations
(in hours U.T.)

Year	C_N	M_N	C_C	M_C
1958	22	12	20	12
1959	20	16	20	14
1960	20	12	20	12
1961	20	12	18	12
1962	20	12	20	12

It is seen that the time of most frequent occurrence of $T_{\max}$ remains the same from 1958 to 1962 except during 1959 when there is a shift in $T_{\max}$ as observed in M_N and M_C to later hours. The neutron data at Churchill (C_N) show a shift in 1959 as compared to 1958. C_C shows a shift only in the year 1961. However, more weightage is given to data from M_N and M_C , taking into account the higher statistical accuracy (Table XC.1) and larger number of days on which data are available from this station. Therefore it is suggested that there is a shift to later hours in $T_{\max}$ at high latitude stations. Since these stations have drift angles in the

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geomagnetic field which are insensitive, to the energy dependence of the daily variation, represented by the parameters α , $E_{\max}$ and $E_{\min}$ as shown in ^{section} 31.4, the change in $I_{\max}$ at these stations reproduces faithfully the change in the direction of source in space. It is concluded that the direction of most frequent occurrence has remained constant except during 1959.

32.2. $I_{\max}$ at low latitude stations

Results of studies made with the help of detectors at low latitudes are shown in Figures 32.2a, 2b and 2c. From the smooth curves fitted to the histograms the values of $I_{\max}$ are found at these stations corresponding to the most probable frequency and are given in Table 32.3.

Table 32.3

$I_{\max}$ (12 hours U.T.) at low latitude stations

Year	H_N	E_N	H_E	E_C	Minn Aguilar
1958	16	14	4	14	16
1959	18	14	4	16	18
1960	15	14	4	14	16
1961	16	14	4	14	16
1962	16	14	4	14	16

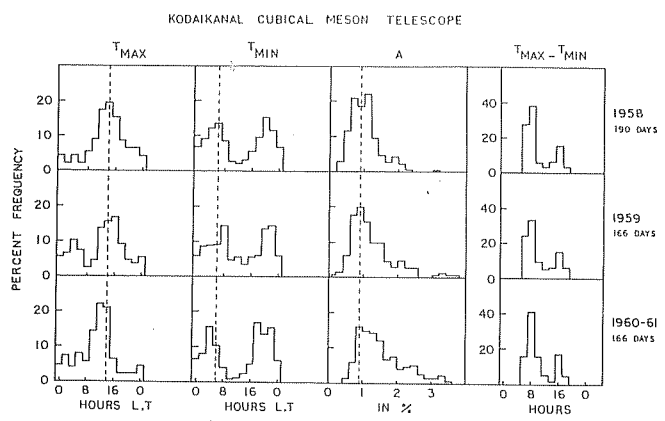


FIG 3C.2a

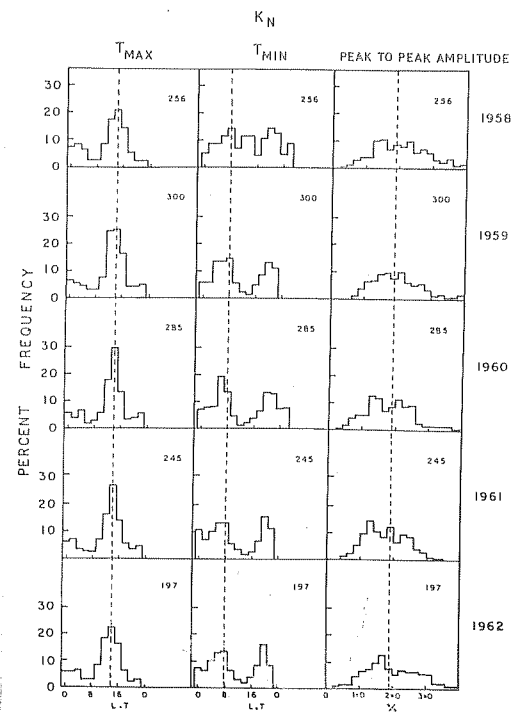


Fig 3C.2b

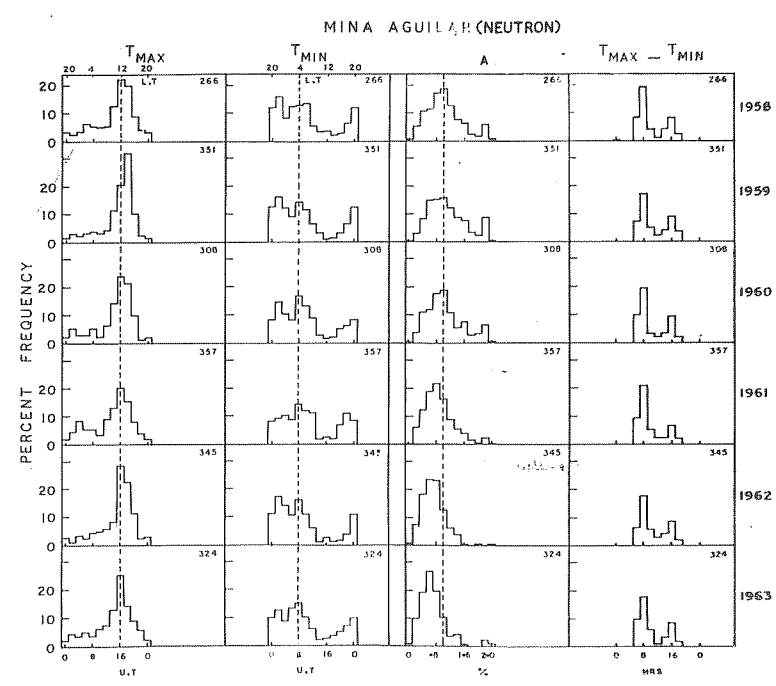


Fig 3C.2c

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It is seen that also at equatorial stations the most probable value of $T_{\max}^*$ remains constant in all years from 1958 to 1962 except during 1959, when there is a shift in $T_{\max}^*$ to later hours in the data of majority of stations (K_H , K_C and Mina Aguilar). K_H and K_H do not show such a change.

3C.2.3. $T_{\max}^*$ in space

Using the optimum values of $T_{\max}^*$ obtained by the method of best fit described in section 3B, the frequency distributions of $T_{\max}^*$ on days on which the variation spectrum of anisotropy has positive, zero or negative exponents, are shown in Fig. 3C.3. It is found that $T_{\max}^*$

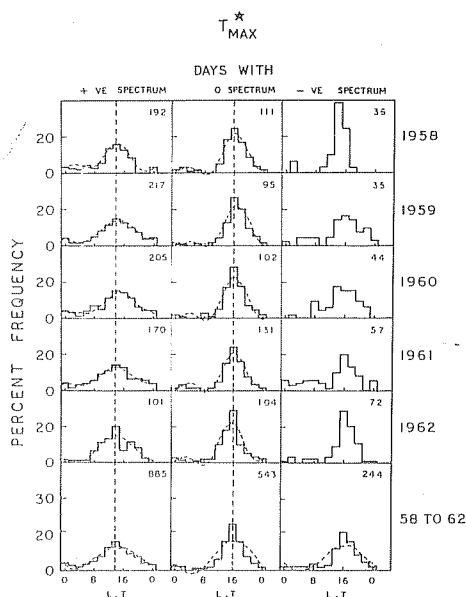


Fig. 3C.3. $T_{\max}^*$ in space.

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has remained constant throughout the period of study except in 1959, when it has increased by about an hour as determined by fitting a smooth curve. It is seen in table 3C.5 that days with positive exponent for variation spectrum have increased by 5% in 1959 with a corresponding decrease in the number of days with zero exponent as compared to 1958, while the number of days with exponent -1 has remained constant.

The change of $T_{\max}$ to later hours at equatorial stations can happen due to either of the two causes given below or due to both of them:

- (1) The direction of source in space shifting to later hours or
- (2) an increase in the value of one or more of the parameters x , $E_{\max}$ or $E_{\min}$.

The evidence presented in ^{Sections} 3C.2.1, 2.2 and 2.3 suggests that the shift to later hours of $T_{\max}$ is due, partially, to a shift in the direction of source to later hours and partially to an increase in the number of days with positive exponent.

3C.3. The long-term changes in the direction of minimum of cosmic ray intensity

In Fig. 3C.4 are shown the frequency distributions of $T_{\min}$ for H_N , N_N , C_N , M_N , C_C and M_C for each year during the period of study. There is no change from year to year

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in the time at which the maximum frequency of T_{min} occurs. This is also the case for the frequency distribution of T_{min} at the equatorial detectors K_p , K_c and Minas Aguilar shown in Fig. 30.8 (a, b, c).

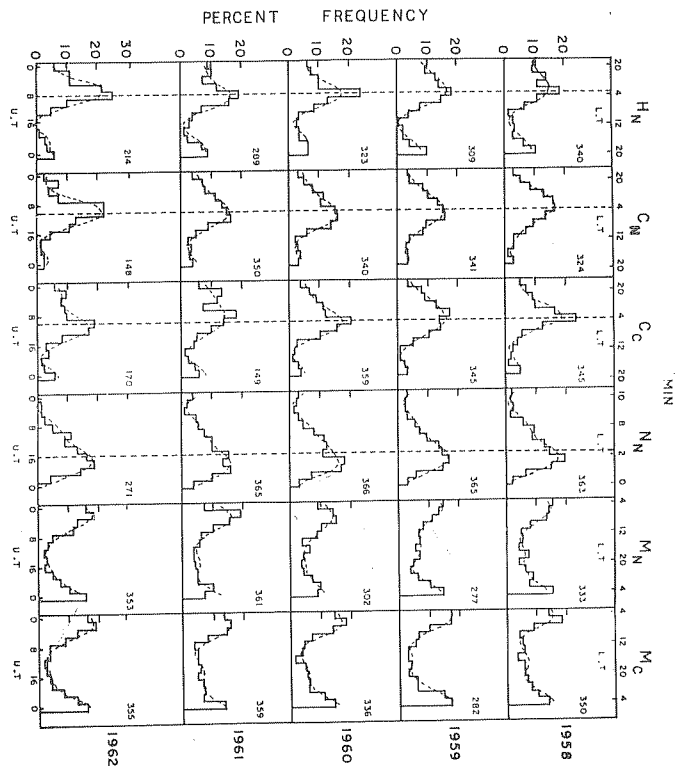


Fig. 30.8. Histograms of T_{min} .

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The histograms of the direction of minimum of anisotropy in space, $T_{\min}^*$, are shown in Fig. 3C.5 for days on which the exponent of the variation spectrum is positive, zero or negative. It is seen that the direction of minimum of anisotropy remains constant through out the period of study.

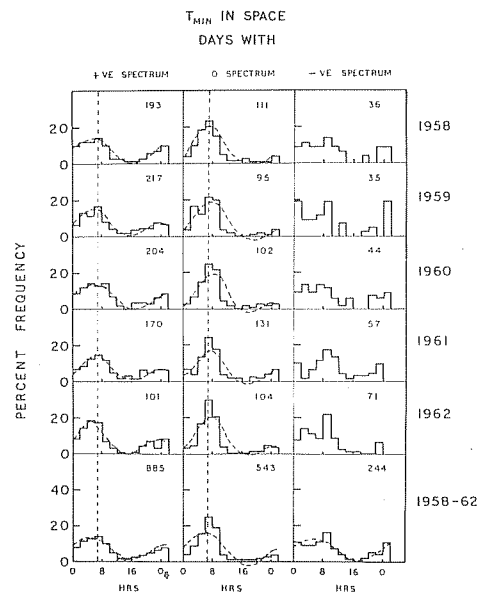


Fig. 3C.5. $T_{\min}$ in space.

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3C.4. Long-term changes of $T_{\max} - T_{\min}$

In Fig. 3C.5 are shown the histograms of $T_{\max} - T_{\min}$ for the three stations H_N , C_N and C_C . These distributions and also those of $T_{\max} - T_{\min}$ for equatorial

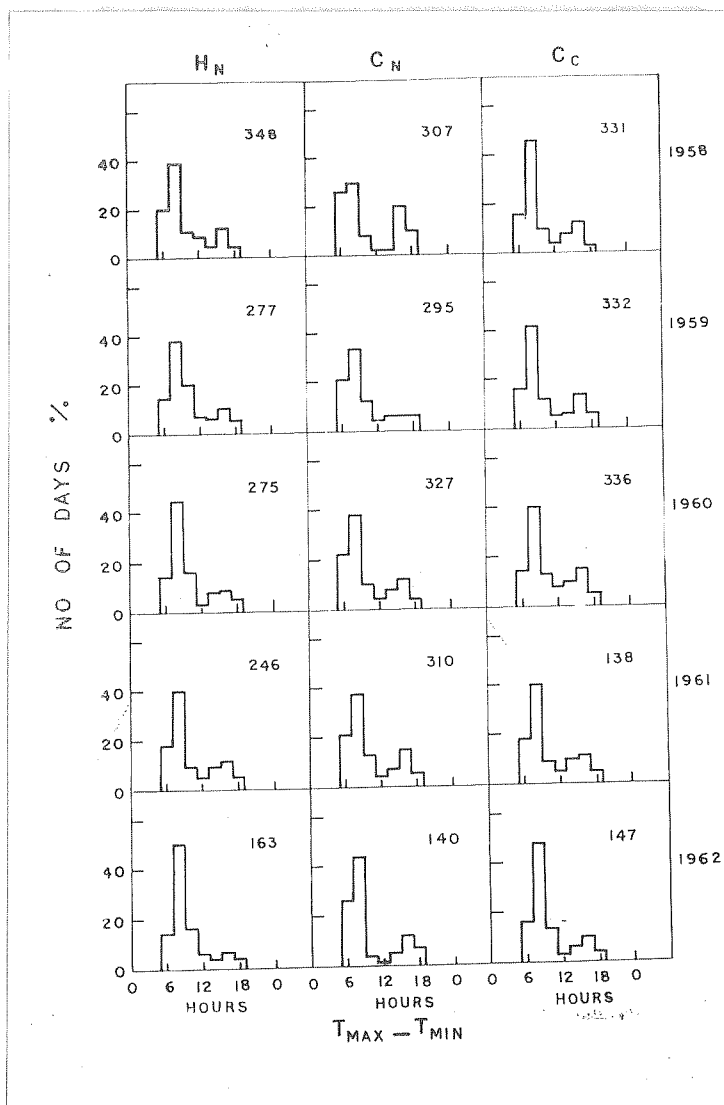


Fig. 3C.5. $T_{\max} - T_{\min}$

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stations, shown in Fig. 3C.2 have their most probable frequencies not at 12 hours but at about 8 hours. This most probable time-difference between the time of maximum and the time of minimum of cosmic ray intensity remains roughly the same for all detectors from 1958 to 1962.

A separate determination of the distribution of $I_{\max} - I_{\min}$ is made, directly from bihourly data of M_H , C_C and M_H , without recourse to harmonic analysis. These distributions are shown in Fig. 3C.7. The data are not corrected for the long-term trend of cosmic ray intensity. It is seen that, even though the shape of the distributions is now different from those of Fig. 3C.6, still the most probable frequency does not occur at 12 hours but at 10 hours. These results indicate that the modulating mechanisms which give rise to a pure sinusoidal anisotropy are not sufficient to explain completely the dependence of anisotropy on longitude. An additional modulating mechanism is therefore necessary.

3C.6. Long-term changes of the energy dependence of the anisotropy

3C.6.1. The long-term changes in the ratio of peak to peak amplitudes obtained at a pair of stations

In Fig. 3C.8 are shown the histograms of the ratio of peak to peak amplitude of daily variation measured on

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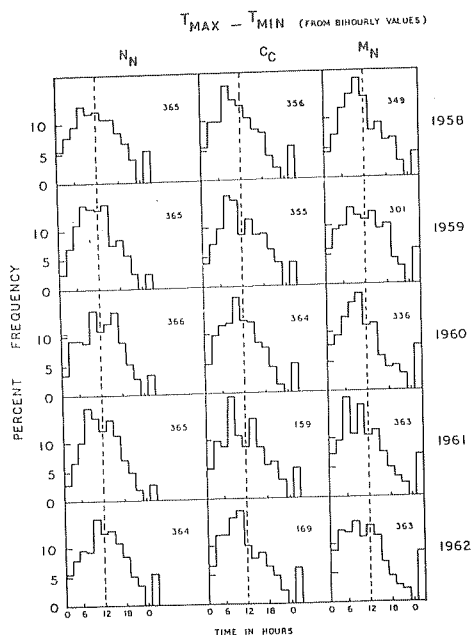


Fig. 30.7. $T_{max} - T_{min}$ from bihourly values

individual days by a pair of detectors. The pairs of stations used are N_N/C_N , C_C/C_N , N_N/M_N and M_C/M_N . Comparison by χ^2 test reveals that the histograms in 1958 are different from the corresponding ones in 1962 with probabilities of only 30 ~ 40%. For further study of these differences, the first moment, i.e. the mean value, of these frequency distributions are given in table 30.4.

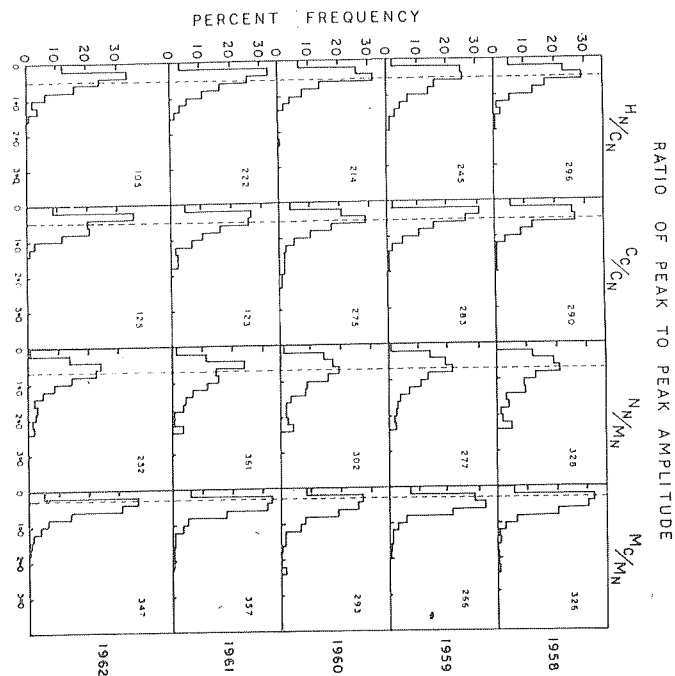


Fig. 3C.8. The ratio of peak to peak amplitudes.

Table 3C.4

Mean values of the histograms of the ratio
of peak to peak amplitude

Year	H/C	C/C	N/M	M/C
1958	.62	.63	.83	.55
1959	.60	.64	.81	.55
1960	.61	.62	.85	.56
1961	.61	.48	.87	.63
1962	.64	.53	.85	.60

It is seen that there is a decrease in the mean of the frequency distributions for the majority of stations, H_N/C_N , C_C/C_N and H_C/H_N , in the years 1961-62 as compared to the years 1958-60. One pair, H_N/H_N does not show this decrease. As shown in section 3A.4, this decrease points to a decrease in one or more of the parameters, x , E_{max} and E_{min} of the variation spectrum during the years 1961-62 in comparison with 1958-60.

Only a qualitative change of the energy dependence of the anisotropy can be studied by means of the ratio of peak to peak amplitudes. A quantitative study is not possible because the ratio of peak to peak amplitudes is a function of all the three parameters x , E_{min} and E_{max} which may change from day to day independently of one another.

3C.5.2. Detailed study of the variation spectrum

3C.5.2.1. Determination of the variation spectrum using both the diurnal and the semidiurnal components

From the study of the optimum spectrum on each day by the method of best fit described in section 3B.2, the percent number of days with positive, zero and negative exponents for the variation spectrum are presented in table 3C.5. This table also gives the total number of days used in the determination in each year. Days (6 - 8%) on which none of the

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three spectra fitted well are rejected, the risk of rejecting a normal day being 5%.

Table 30.5

Classification of days according to variation spectra
(Diurnal & Semidiurnal components)

Year	Percent number of days with			Total days
	+ve spectrum	0 spectrum	-ve spectrum	
1958	56.9	32.6	10.6	341
1959	62.5	27.4	10.1	326
1960	58.4	29.1	12.5	318
1961	47.5	34.6	15.9	340
1962	36.7	37.8	25.5	254

30.5.2.2. Determination of the variation spectrum using the diurnal component only

The percent number of days with the three exponents of variation spectrum is determined by the method of best fit making use of only the diurnal component and is given in table 30.6 for the years 1958 and 1962.

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Table 3C.6

(Diurnal component only)

Year	Percent number of days with			Total days
	+ve spectrum	0 spectrum	-ve spectrum	
1958	33.3	44.7	22	286
1962	23.7	50.2	26	245

This table agrees with the results shown in table 3C.5, where both the components of daily variation are taken into consideration. The decrease in the number of days with positive exponent in 1962 as compared to the number in 1958 is now only 10% as against 20% seen in table 3C.5.

3C.5.2.3. Unambiguous determination of the variation spectrum

The results presented in tables 3C.5 and 6 do not distinguish whether the anisotropy on a day can be represented by a single exponent unambiguously, but correspond to that exponent which has the highest probability.

Using the criterion described in section 3B.2.2, the spectrum on certain days is classified unambiguously with 93% confidence into three groups. The distribution of days with different exponents of variation spectra determined

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using both the diurnal and semidiurnal components in the calculations are given in table 3C.7.

Table 3C.7

(Unambiguous determinations of the variation spectrum)

Year	% No. of days with unambiguous spectrum	Classification of days (expressed as percentages of the total number of days with unambiguous spectra in each year)		
		+ve spect.	0 spect.	-ve spect.
1958	20.5	78.3	19.7	5.7
1959	21.9	76.3	21.0	2.6
1960	19.4	72.1	23.5	4.4
1961	24.7	64.0	24.7	11.2
1962	17.1	42.4	34.0	26.6

From the results of the sections 3C.5.1, and 2 it is concluded that:

- (a) in the years 1958-61, there is definite evidence for the existence of days with positive exponent as well as days with zero exponent of the variation spectrum.
- (b) the number of days with positive exponent decreases while the number of days with zero or negative exponent of the variation spectrum increases during 1962 as compared to 1958-61.

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- (c) in the year 1960, the number of days with positive exponent is more than any other year during the period of study.

3C.6. Long-term changes of the strength of the anisotropy

3C.6.1. Change in peak to peak amplitude measured by the network of detectors

The distributions of peak to peak amplitude using data from a net-work of stations are presented in Fig. 3C.9

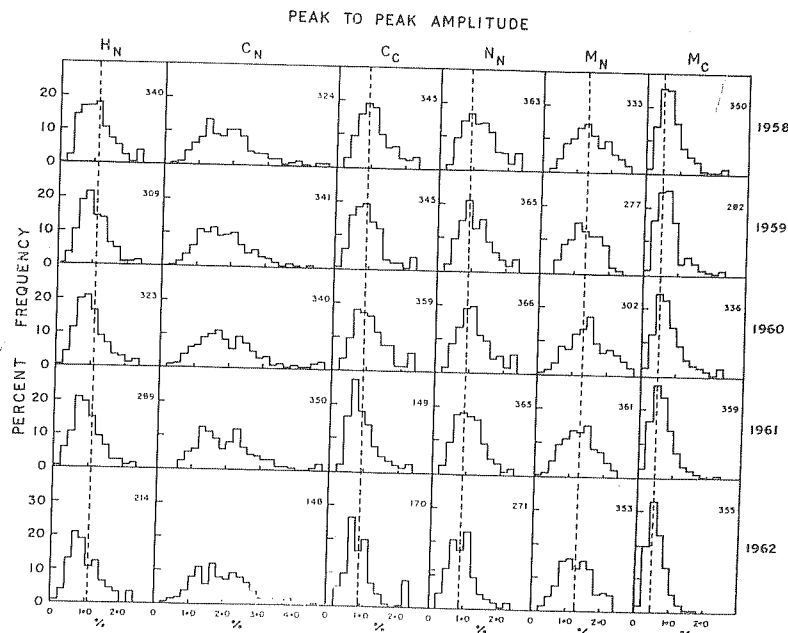


Fig. 3C.9. Peak to peak amplitudes.

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for the years 1958 to 1962. The weighted means of the distributions, after normalising for the change in the mean level of cosmic ray intensity with sunspot activity and correcting for the finite counting rate of the detector by an approximate method (Gottlieb)⁴⁷, are presented in table 3C.8.

Table 3C.8

Mean values of peak to peak amplitude (%)

Year	H_N	M_N	C_N	M_N	C_C	M_C	K_N	K_C
1958	.96	1.05	1.55	1.32	.96	.73	2.06	1.00
1959	.93	1.05	1.56	1.29	.84	.71	2.10	1.21
1960	.87	1.08	1.80	1.27	.99	.71	1.95	1.25
1961	.85	1.00	1.67	1.15	.80	.61	1.78	--
1962	.87	.91	1.60	1.07	.85	.53	--	--

It is seen that the mean value of peak to peak amplitude decreases in the majority of stations H_N , M_N , M_N , C_C , M_C and K_N in 1961-62 as compared to 1958-60. C_C and K_C show an increase. K_C has less number of days in each year and as shown in table 3C.1 both K_C and C_C have high statistical errors. Therefore much significance cannot be attached to this increase.

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3C.5.2. The change in the strength of anisotropy beyond the geomagnetic field

In Fig. 3C.10 are shown the frequency distributions of peak to peak amplitude in space (A^*) for days with positive exponent and for days with zero exponent. The mean values of A^* are given in table 3C.9.

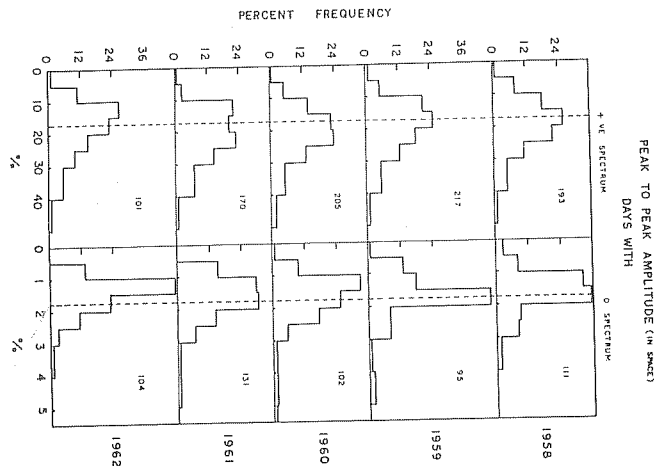


Fig. 3C.10. Peak to peak amplitude in space.

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Table 3C.9

A^{*}

Year	Mean A [*] on days with (in %)	
	+ve spectrum	0 spectrum
1958	1.12	1.62
1959	1.13	1.67
1960	1.21	1.71
1961	1.19	1.63
1962	1.05	1.46

It is seen that the mean value of peak to peak amplitude is less during 1961-62 as compared to 1958-61 for days with both positive and zero exponents. The reduction of A^{*} is about 10% and is significant (chi square test for the histograms at 5% level). The number of days with negative spectrum is too small in each year to be presented as frequency distributions.

As discussed in section 3A.4, the time of maximum of daily variation measured by a high latitude detector is independent of E_{min} to a large extent. In the case of low latitude detector, T_{max} is independent of E_{min} upto the geomagnetic cut-off, but is a function of the exponent.

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It is found from frequency distributions of both $H_N - C_N$ and $H_N - H_N$ using data of 2600 days that the most probable value is 3 hours. An exponent α of the variation spectrum of value $-.4 \sim -.6$ is required to explain these results. This value corresponds to the average conditions during the period 1958-62 and cannot be applied to individual days because conditions from day to day are quite variable.

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CHAPTER - IV

SUMMARY AND CONCLUSIONS

4.1. Study of cosmic ray anisotropy on individual days

1) The form of the daily variation on individual days is, in general, not compatible with a single modulating mechanism. This is deduced from the histogram of the difference between the time of maximum and the time of minimum of cosmic ray intensity on each day. The most probable frequency of the histogram, which for a single modulating mechanism should be close to 12 hours, occurs at 8 - 10 hours instead.

2) The additional modulating mechanism probably affects the direction of minimum intensity preferentially. Such a picture could explain, depending upon the nature of additional modulation, the larger variance in the frequency distribution of $T_{\min}$ than in the frequency distribution of $T_{\max}$.

4.2. Study of the change of anisotropy from day to day

1) The characteristics of the anisotropy vary significantly from day to day.

The cosmic ray anisotropy does not have the same energy dependence on all days. The days could be broadly classified as (i) days with positive exponent for the

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variation spectrum (i.e. the lowest energy particles are modulated proportionately less than medium energy particles), (ii) days with zero exponent for the variation spectrum (i.e. energy spectrum of the modulated intensity is the same as the spectrum of the background isotropic intensity) and (iii) days with negative exponent for the variation spectrum (i.e. the low energy particles are proportionately more modulated than the high energy particles). The percent number of days in each category is given in table 3B.2.

2) The strength is more and the variability in the directions of maximum and minimum of the anisotropy is less on days when the anisotropy has '0' exponent, than on days when the anisotropy has positive or negative exponents for the variation spectrum.

3) On 3 - 8% days, the daily variation cannot be explained by an external anisotropy.

4.3. Study of the change of anisotropy from year to year

1) It is seen in the annual histograms of I_{max} , I_{min} and A on individual days measured by each detector that with decreasing solar activity from 1958 to 1962, the most probable directions of maximum and minimum of the anisotropy remain unchanged. They correspond to 1600 hours and 0000 hours local time, respectively (Section 3C.2 and 3C.3). The peak

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to peak strength of the anisotropy decreases during this period. There is a reduction of 10% in source strength in the years 1961-62 compared to the years 1958-60. This conclusion is made from histograms of peak to peak strength of the anisotropy on days with positive exponent and also for days with zero exponent (Fig. 3C.1).

2) The change in the energy dependence of the anisotropy from years of high sun-spot activity in 1958-60 to years of low sun-spot activity in 1961-62 is such as to increase the number of days with zero and negative exponents of the variation spectrum and as to decrease the number of days with positive exponent (Table 3C.5).

4.4. Conclusions

It is shown that the form of anisotropy is not purely sinusoidal. Also, the directions of maximum and minimum of the anisotropy undergo large variations from day to day, while the peak to peak strength of the anisotropy lies anywhere between .4% and 3%. Further, all days do not have the same energy dependence of the anisotropy. Any theory of daily variation should explain these results satisfactorily.

The annual distributions of the characteristics of the solar anisotropy from 1958 to 1962 indicate that:

- (1) the mean direction of the maximum of intensity remains unchanged with declining solar activity in the present cycle. This would imply, if we accept the recent interpretation of the anisotropy by Parker¹, that in addition to the azimuthal drift there is a radially outward drift imparted to galactic cosmic rays. Both these remain on the average approximately unchanged during 1958 to 62. It would be interesting to continue this study upto the minimum of solar activity in 1963 and 64 when probably the conditions might alter.
- (2) the mean magnitude of the anisotropy and the spectrum of variation nevertheless change over the years that are studied. These indicate firstly a net decrease of the average strength of the local magnetic field stretched out by the plasma wind and secondly, less disturbed conditions of interplanetary plasma with decreasing solar activity. This should, of course, be expected with the change in distribution and number of active regions around the sun's equator which contribute to the non-uniformity of solar wind velocity.

Further extension of the study through the next solar cycle would be most valuable to see the effect of the 22 year cycle. The present results provide theoretical workers with a fresh basis for quantitative interpretations, and pose the question of explaining the physical significance of the modulation process which gives rise to a spectrum of variation of the anisotropy with a positive exponent.

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