SECTION OF MATHEMATICS AND PHYSICS

President :—K. R. Ramanathan, M.A., D.Sc., F.N.I.

Presidential Address

THE EARTH'S MAGNETISM AND THE UPPER ATMOSPHERE.

Introduction.

I have chosen as the subject of my address, 'The Earth's Magnetism and the Upper Atmosphere'. In the seventh session of the Indian Science Congress which was held at Nagpur in 1920, Dr. N. A. F. Moos presided over the section of Mathematics and Physics and spoke on 'Seismology and Earth's Magnetism'. Dr. Moos was the head of the Colaba and Alibag observatories for twenty-five years and his two volumes on 'Colaba Magnetic Data and their Discussion' contain many scholarly studies of an original character and still remain a vast storehouse of information for magnetic data. Dr. Moos is no more with us, but his work lives and inspires.

In recent years, considerable progress has been made in our knowledge of the upper atmosphere—from sounding balloons, investigation of the heights of appearance and disappearance of meteors, reflection of sound waves, atmospheric ozone, light from the night sky and auroræ, regular and irregular variations of the earth's magnetic field and, most fruitful of all, the experimental study of the ionosphere. It was, however, the study of the earth's magnetism that made the first definite contribution to our knowledge regarding the electrical properties of the earth's atmosphere. It still provides a healthy check on theories regarding the upper atmosphere and continues to be suggestive of fresh problems for experimental and theoretical investigation. On the other hand, knowledge derived from other sources is helping to unravel some of the complicated phenomena of the earth's magnetism. My task will be to make a survey of some of the problems, mainly of the earth's atmosphere which a study of its magnetic field has opened up or illuminated.

The Earth's permanent magnetic field and its harmonic analysis.

Exactly a century has elapsed since the foundations of a scientific study of the origin of the earth's magnetism were laid

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by C. F. Gauss in his famous 'Allgemeine Theorie des Erdmagnetismus'.[1] Let us recall what he had to say about the aims which have to be kept in view in the study of the earth's magnetism :

> 'Viewed from the higher grounds of science, even a complete knowledge of the phenomena after this manner (representation of the geomagnetic field by accurate and detailed maps) is not itself the final object sought. It is rather analogous to what the astronomer has accomplished, when for example, he has observed the apparent path of a comet in the heavens. Until the complicated phenomena have been brought in subjection to a common principle, we have only building-stones, not an edifice. The astronomer, after the comet has disappeared from his view, begins his chief employment, and resting on the laws of gravitation, calculates from the observations the elements of its true path, and is thus enabled to predict its future course. And in like manner, the magnetician proposes to himself as the object of his research, as far as the different and in some respects less favourable circumstances permit, the study of the fundamental causes which produce the phenomena, their magnitude and their mode of operation—and the anticipation with some approximation at least, of their effects in those regions where observation has not yet penetrated. It is at least well to keep in mind this higher object, and to endeavour to prepare the way for it, even though the great imperfection of the data may render its attainment impossible at present.'

Gauss in his great memoir applied the theory of potential to the earth's magnetic field and developed the method of spherical harmonic analysis to analyze the permanent field of the earth.

What we observe experimentally is the distribution of the intensity of the magnetic field on the surface of the earth and changes in its distribution with time. From these results of observation, the origin of earth's magnetism and its changes has to be deduced. Gauss worked out a method by which definite information can be obtained regarding the location of the sources. This depends on the analysis of the auxiliary quantity —namely, the potential—from which the several components of the intensity of the earth's field can be derived, not only at the surface of the earth, but also at different positions above and below the surface. The distribution of potential on the surface of the earth can be determined from observations of horizontal force alone. A knowledge of the vertical force is not necessary for this. Gauss showed how the potential can be expanded in a double series of spherical harmonics. One of these series is due to causes within the earth and the other to causes outside. The potential due to internal sources has terms proportional to

a^2/r^2, a^3/r^3, a^4/r^4, etc. while that due to external ones has terms proportional to r/a, r^2/a^2, r^3/a^3, etc. By making use of the additional knowledge of the distribution of the vertical force, it is possible to separate the internal from the external parts of the potential.

Assuming that the magnetic matter was situated within the body of the earth, and using the data of magnetic field at a few places, Gauss calculated the distribution of permanent field over the surface of the earth and obtained a fair agreement between the calculated and observed distributions. Discussing the assumptions, Gauss remarks: 'Another part of our theory on which there may exist a doubt is the supposition that the agents of the terrestrial magnetic force are situated exclusively in the interior of the earth. If we seek for their immediate causes, partly or wholly, without the earth, and confine ourselves to known scientific grounds, we can only think of galvanic currents. But the atmosphere is no conductor of such currents, neither is vacant space; thus in seeking in the upper regions for a vehicle of galvanic currents we go beyond our knowledge. But our ignorance gives us no right absolutely to deny the possibility of such currents; we are forbidden to do so by the enigmatical phenomenon of the Aurora Borealis, in which there is every appearance that electricity in motion performs a principal part. It will therefore still be interesting to examine what form magnetic action arising from such currents would assume on the surface of the earth.' While showing that the cause of the permanent field of the earth should be definitely located within the earth, Gauss did not overlook the possibility 'of a part, though comparatively very small part, of the terrestrial magnetic force, proceeding from the upper regions'.

He also pointed out that the variations of magnetic force taking place simultaneously at different places on the earth's surface can be subjected to a perfectly similar treatment.

Before we pass on to a consideration of the changing part of the earth's field, it is useful to summarize some of the salient features of the 'permanent' or quasi-permanent magnetic field of the earth as they are known at present. This consists of a homogeneous or 'regular' part and an 'irregular' part, the former being due to terms of the first order in the series development for the potential. The regular field is the same as that due to a uniformly magnetized sphere of the same size as the earth, the intensity of magnetization being ·074 (about 1/5500 of the remanent magnetism of cobalt steel) and the total magnetic moment $8{\cdot}4 \times 10^{25}$ C.G.S. units. The axis of magnetization cuts the earth's surface at 78½°N., 69°W. and 78½°S., 249°W. and is thus inclined 11½° to the earth's axis of rotation. The analysis of the irregular or 'residual' part of the field shows that the average equivalent intensity of magnetization is greater for those latitudes in which land predominates.

The earth's total field is made up of a part due to an internal potential system which accounts for 94 per cent. and an external and a non-potential system which accounts for the remainder.

From the analysis of the earth's field carried out at different epochs from 1842 to 1922, it is known that the magnetic moment of the earth has decreased from $0{\cdot}328/a^3$ in 1842 to $0{\cdot}324/a^3$ in 1885 and $0{\cdot}311/a^3$ in 1922, the average *annual* rate of decrease in the intensity of magnetization during 80 years being $\frac{1}{1500}$ of its value. Therefore, in addition to the well-known secular change in the direction of the earth's magnetic axis, a slow demagnetization of the earth is also going on. Whether this will continue or reverse its direction after some time is more than we can say at present. Regarding secular variation, Maxwell says: 'What cause, whether exterior to the earth or in its inner depths, produces such enormous changes in the earth's magnetism, that its magnetic poles move slowly from one part of the globe to another? When we consider that the intensity of the magnetization of the great globe of the earth is quite comparable with that which we produce with much difficulty in our steel magnets, these immense changes in so large a body force us to conclude that we are not yet acquainted with one of the most powerful agents in nature, the scene of whose activity lies in those inner depths of the earth, to the knowledge of which we have so few means of access.' Although seismology has given us new insight into the internal structure of the earth and the study of magnetic daily variations and variations associated with magnetic storms has definitely added to our knowledge of the conductivity of the earth's interior, the position as regards the fundamental problem of the origin of the earth's permanent magnetic field has not appreciably advanced since Maxwell wrote.

Besides the slow secular variation there are many other variations, some regular and others irregular, to which the earth's magnetic field is subject. The principal regular variations are the solar and lunar diurnal variations and their changes with season and solar activity, the annual variation and the eleven-year variation. The irregular variations or disturbances are of many classes, the most conspicuous of them being the world-wide 'magnetic storms'. The disturbances also have quasi-periodicities depending on (1) the rotation of the sun, (2) the inclination of the earth's magnetic axis to its axis of rotation, and (3) the sunspot cycle. The study of the geomagnetic *variations* and of associated phenomena such as the auroræ has given valuable knowledge about the electrical properties of the earth's atmosphere.

The Solar diurnal variations of the earth's magnetic field and their analysis.

The solar diurnal variation is the most obvious and the most important of the periodic variations of the earth's magnetic field. At places on the same latitude, the variation depends mainly on the local time (owing to the non-coincidence of the magnetic and rotational axes of the earth and local variations of the earth's magnetic field, there are, however, small differences in the diurnal variation from place to place in the same latitude). On magnetically quiet days, the daily variation is much greater when the sun is above the horizon than when it is below; it is greater in summer than in winter and increases with increase of sunspot frequency. The variation shows large changes as we go from the equator to the pole.

How the sun causes the daily variations in the magnetism of the earth was discussed by Balfour Stewart[2] in a famous article in the ninth edition of the Encyclopædia Britannica. He surmised that the upper regions of the atmosphere were most probably the seat of solar influence with electric currents circulating in them and did not consider as serious what was then considered as an objection, viz., that the conductivity of ordinary air was too small to sustain currents. He also pointed out that a system of currents in the upper atmosphere would exert an indirect effect on the magnetic needle by inducing currents in the body of the earth.

Schuster[3] was the first to investigate the subject in a quantitative manner. The first step in his analysis of variation data was to split up the curve of variation of each of the components into Fourier series. Gauss's method of spherical harmonic analysis was then applied to the Fourier coefficients of

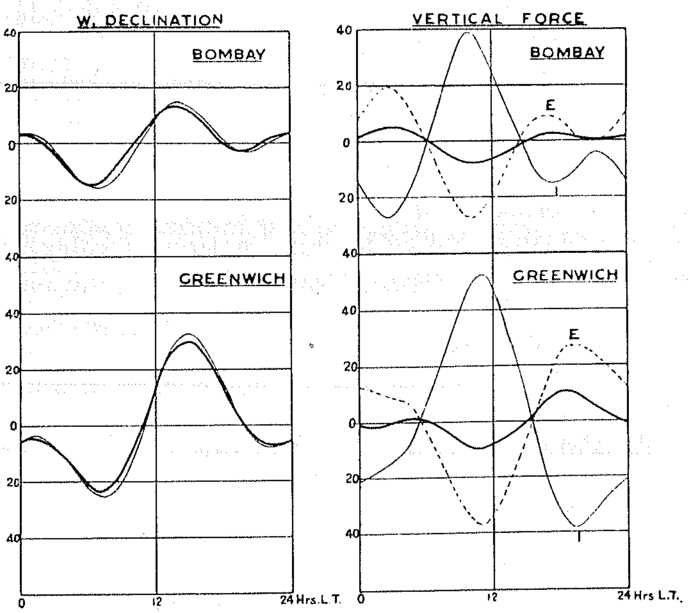


Fig. 1. Observed daily variation of declination and vertical force at Bombay and Greenwich (———) compared with values calculated on the assumption that the origin of the daily variations is (1) inside the earth (———) and (2) external to the earth (..........).

variation at four observatories—Bombay, Lisbon, Greenwich and St. Petersburg. He showed that the horizontal variation field could be represented by a surface harmonic but in order to explain the vertical variations as well, it was necessary to assume that the main source of disturbance lay outside the earth and that in addition to the external source, there was an internal source standing in fixed relationship to the external. In Fig. 1 are shown the observed variations of H at Bombay and Greenwich together with the variations calculated from the spherical harmonic expansion for the potential. On the right-hand side of the same figure are shown the observed variations of Z and the variations calculated from the potential distribution assuming that the source was (1) entirely outside the earth's surface and (2) entirely within the earth's surface. It is obvious that the main source has to be considered as lying outside the earth's surface.

A more complete analysis of the solar diurnal variation field using the data of 21 observatories was carried out by Chapman.[4] The results of the analysis are best expressed in the form of a diagram showing the system of electric currents in the upper atmosphere that could cause the observed field.

At the time of the equinoxes, the current system consists of four closed circuits, two lying on each side of the equator. Of the two circuits in each hemisphere, the one lying in the sunlit part of the earth is the more intense and the direction of the current is clockwise in the northern hemisphere with its focus at about 40°N. At the time of the solstices, the current system is more intense in the summer hemisphere and extends across the equator to the other hemisphere.

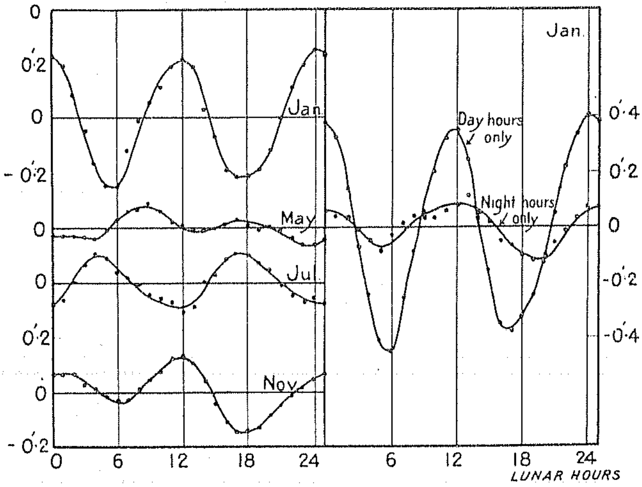
As the diurnal variation at the time of the equinoxes is symmetrical about the equator and as the vertical component of the variation field changes sign on crossing the equator, Schuster suggested that the electric currents are caused by horizontal oscillatory movements of the conducting upper atmosphere, rendered conducting by the ionizing action of solar ultra-violet radiation, across the vertical lines of force of the earth's field. The magnitude of the electromotive forces generated by such movements would depend on the velocity of movement and the vertical intensity. The current densities will of course depend also on the conductivity of the atmospheric layer which undergoes the oscillatory movement. The total flow of current in the day time circuit varies from 6×10^4 amperes at the time of the equinoxes to 9×10^4 in summer.

The Lunar diurnal variation field.

Before we go into the details of the oscillatory movement in the upper atmosphere, we shall consider an even simpler, though less obvious, variation field, namely that of lunar diurnal variation. Its mean magnitude at the equator is only about $\frac{1}{15}$ of that of the solar variation. When averaged over a large number of complete lunations, the curve of variation is a simple semi-diurnal sine wave. But in any particular phase of the moon, the amplitude is considerably enhanced during the daylight hours of the day. This was recognized as early as 1874 by Mr. Alan Broun[5] in his discussion of the observations of magnetic declination at Trivandrum (Fig. 2). It is very well brought out in Moos's analysis of the lunar diurnal variation at Bombay in different phases of the moon. The external current systems required to produce the lunar diurnal variation at the times of equinoctial and summer new moons have been shown in diagrams by Chapman.

FIG. 2.

MEAN LUNAR DIURNAL VARIATION OF DECLINATION AT TRIVANDRUM FROM A. BROUN'S ANALYSIS



There is little doubt that the lunar semi-diurnal wave is due to the tidal action of the moon on an atmosphere of varying conductivity.

In both solar and lunar diurnal variation fields, the external part is 2 to 2·5 times the internal and the phase of each of the first four harmonic components of the internal field is in advance of the corresponding components of the external field by about 20°. This is the evidence for believing that the internal field is an induction effect of the external primary field. The electromotive forces induced in a conducting sphere by currents circulating in an outer shell have been investigated by H. Lamb. In order to explain the relative phases and amplitudes of the external and internal fields, it is necessary to assume that the conductivity of the earth is non-uniform and that the crust of the earth down to a depth of about 240 km. has much smaller conductivity than the inside. We shall not, however, pursue this part of the subject further.

Cause of the upper atmospheric current system and its location in the atmosphere.

In explaining the upper atmospheric current system, there are two distinct questions to be answered. What is the cause of the atmospheric movement and how is the conductivity produced?

The answer to these questions has been attempted in the most comprehensive way in the 'dynomo' theory of diurnal variations. Schuster tried to connect the atmospheric movement with the well-known diurnal variation of atmospheric pressure. The most important term in the daily oscillation of pressure is the semi-diurnal term. This is a wandering pressure-wave moving from east to west with a free period of 12 hrs. together with a stationary wave from north to south with nodal lines at $\pm 35°$ latitude. The magnitude of the semi-diurnal wave, according to Simpson, is given by the equation

$$0{\cdot}937 \sin^3\theta \sin(2t+154°)+0{\cdot}137 (\cos^2\theta-\tfrac{1}{3}) \sin(2t-2\phi+105°)$$

where θ is the co-latitude, ϕ is the longitude east of Greenwich, and the unit of pressure is 1 mm. of mercury. The relation between wind and pressure variation, in which the deviating force of the earth's rotation is neglected, is

$$(\tfrac{1}{2}v^2)\,(d\psi/dt) = -\delta p/p,$$

where ψ is the velocity-potential, $d\psi/ds$ the velocity in the direction ds and v is the velocity of sound. The velocity-field corresponding to the moving pressure-wave shows maximum easterly winds at 9-10 hrs. and maximum westerly winds at 15-16 hrs. local time. The calculated and observed values of the semi-diurnal components of velocity at St. Helena are given below:

Semi-diurnal winds at St. Helena.

	Observed.	*Calculated from pressure variation.*
West to East ..	$-22 \sin(2nt+158°)$	$-21 \sin(2nt+154°)$
North to South ..	$35 \sin(2nt+237°)$	$9 \sin(2nt+244°)$

The unit of velocity is 1 cm./sec. While the phases of the wind and the amplitudes of the west to east component agree, the observed north to south component is much stronger than the calculated.

The amplitude of the lunar semi-diurnal pressure tide at the equator is only about $\frac{1}{16}$ of the solar tide.

If the oscillations in the upper atmosphere causing the magnetic variations are directly related to the barometric variations observed at ground level, there should be agreement as regards phase between the two variations. Let us now compare them:

Cause of variation.	Observed pressure variation at ground level	Observed magnetic variation.	Pressure variation calculated from magnetic variation.	Col. (4) corrected for phase change due to self-induction.
Solar ..	sin $(2t-206°)$	sin $(2t-65°)$	sin $(2t-155°)$	sin $(2t-115°)$
Lunar ..	sin $(2t-295°)$	sin $(2t-12°)$	sin $(2t-102°)$	sin $(2t-62°)$

There is thus a difference of phase between the observed pressure variation at the ground and the upper atmospheric pressure variation calculated from magnetic data. The calculated value exceeds the observed by 91° in the case of solar and by 233° in the case of lunar variation.

The probable solution of this difficulty as well as of a cognate difficulty regarding the conductivity of the upper atmosphere has been recently offered by C. L. Pekeris.[6] The question of the origin of the solar semi-diurnal wave of pressure itself has long been a puzzle. Analysis of the pressure curves of many stations leaves no doubt that the semi-diurnal wave is more fundamental than the diurnal. We know that there is an external periodic force acting on the atmosphere in the shape of daily insolation. But it is not the 24-hourly pressure-wave that has the largest amplitude in the barograms but the 12-hourly. The magnitude of the 12-hourly wave can be explained, as was suggested by Lord Kelvin, if the atmosphere had a free period in the close neighbourhood of 12 hrs. From the spreading of the air-waves from the volcanic eruption at Krakatau, it has long been known that the atmosphere has a free period of about 10½ hrs. and G. I. Taylor showed theoretically that the atmosphere has a free mode of oscillation of this period. An assumption in Taylor's calculation of the free period was that the stratosphere was isothermal. Now, various lines of evidence, such as the propagation of sound waves from explosions, the existence of ozone in the upper atmosphere, etc. have shown that there is an increase of temperature in the stratosphere above 35 km. Pekeris, assuming that this increase of temperature continues up to about 60 km. (temperature 370°K), beyond which it again decreases, reaching 220°K at 100 km., shows that there are two possible modes of oscillation, one with a period 10½ hrs. and another with a period 12 hrs. The 12-hourly oscillation has a nodal surface at 30 km. and the atmospheres above and below this level oscillate horizontally in opposite directions. The amplitude of the 12-hourly wave at 100 km. is nearly 200 times that at the ground. The work of Pekeris removes to some extent the difficulties of the dynomo theory of the diurnal variation of the earth's magnetic field.

While on the subject of pressure waves in the upper atmosphere, I may refer to the recent announcement of E. V. Appleton and K. Weekes in *Nature* on the discovery of a lunar semidiurnal wave in the height of the E layer over England. Making use of a series of quarter-hourly observations extending over a period of eight months, and suitably eliminating the effect of solar diurnal and seasonal variations of height, Appleton and Weekes have found evidence for the existence of a lunar semidiurnal wave with a pressure range $\delta p/p$ of ·068 at 110 km., which comes to nearly 6,000 times the lunar barometric range at ground level. The maximum height of the lunar tide is found to occur at about 20 mts. before the upper and lower culminations of moon respectively. The magnitude of the oscillation is 1·5 to 2 km. A large discrepancy appears in that the phase of the upper atmospheric tide is found to be nearly the same as that at ground level at Greenwich, a conclusion which is in *disagreement* with deductions made from the lunar magnetic variations assuming such currents to flow in region E. The amplitude of the tide is also much larger than that calculated by Pekeris.

The conductivity of the upper atmospheric layers responsible for the solar diurnal variation.

The currents in the upper atmosphere depend on the conductivity at the levels concerned. The fact that the range of magnetic variation is much larger during day than during night both for solar and lunar variations can be most simply explained on the assumption that the conductivity is not constant but varies during the day. Assuming that the electric currents responsible for the diurnal variations lie in a spherical shell concentric with the earth, Chapman showed that the relative proportion of the various harmonics can be satisfactorily explained if the conductivity is assumed to be of the form $1+3\cos Z+\frac{9}{4}\cos^2 Z$, where Z is the zenith distance of the sun. If the velocities of oscillatory movement in the upper atmosphere are the same as those calculated from the surface barometric variation, the total conductivity $\int \sigma dh$ of the conducting layer just beneath the sun comes to $1{\cdot}1\times 10^{16}$ e.s. units in minimum sunspot years and $1{\cdot}8\times 10^{16}$ in maximum sunspot years. If the effect of self-induction is taken into account, the maximum conductivity will be increased to $2{\cdot}3\times 10^{16}$ e.s. units. If this conductivity is uniformly distributed over a thickness of 50 km., the mean specific conductivity will be $4{\cdot}5\times 10^{8}$ e.s. units or 5×10^{-3} ohm^{-1} cm^{-1}. This may be compared with the specific conductivity of sea-water which is 4×10^{-2} ohm^{-1} cm^{-2}.

The level of the solar diurnal variation layer.

The question of the level of the atmospheric layer in which the magnetic diurnal variations arise is one of great interest.

We know that maxima of electron concentration occur at about 100 km. in the E layer and at about 270 km. in the F layer. Besides, there is a D layer with a variable and smaller electron concentration at 50–60 km. A lower F_1 layer separates out from the main F_2 layer during day and rejoins it at night.

A comparison of the curves of variation of the ionization of different regions with the time of day, season and sunspot frequency suggests that the diurnal variation currents flow in or near the E region of the atmosphere.

The conductivity of any region of the upper atmosphere can be estimated from ionospheric data. In doing this, a few complicating circumstances have to be kept in mind. In a magnetic field, the conductivity of an ionized gas is not isotropic but is smaller in a direction transverse to the field than in one parallel to it, in the ratio $\nu^2/(\nu^2+\rho^2{}_H)$, where ν is the collision frequency of the charged particles and $\rho_H=He/2mc$. In high magnetic latitudes where the vertical component of the field is large, and also in low magnetic latitudes for east to west direction, it is the transverse conductivity that will decide the magnitude of the currents. Moreover, both electrons and ions can contribute to the conductivity. To make a correct estimate of the total conductivity of a region, we have therefore to know the law of distribution of ions and electrons with height. The question has been recently discussed in a thorough manner by Appleton[7] in his Bakerian Lecture 'Regularities and Irregularities in the Ionosphere'. He finds that the total direct current conductivity $\int \sigma dh$ of the E region for horizontal electromotive forces is about $2{\cdot}3\times10^{11}$ e.s. units if we assume that the conductivity is due to electrons, the maximum density of electrons being $1{\cdot}5\times10^{5}$/c.c. and their collision frequency at that level 10^{5}/sec. If on the other hand, it is assumed that the conductivity is due to ions of mass, say 28, and the corresponding collision frequency is 10^{3}, the total conductivity for the same number of ions comes out to be 4×10^{12} e.s. units. At a low pressure and in a magnetic field, the ionic conductivity can thus be more important than the electronic conductivity.

As an ionized region absorbs the energy of high frequency waves passing through it and the absorption is related to the conductivity, the total direct-current conductivity of the atmospheric layers below the F region can also be estimated from the reflection coefficients of waves penetrating the E layer but reflected back to earth from F. The total conductivity calculated in this manner for summer noon over England comes to be of the order 10^{11} e.s.u., assuming the absorption to be due to electrons.

As we have already seen, the D.C. conductivity demanded by magnetic diurnal variations is of the order 10^{16} e.s.u., if we assume that the oscillatory movements in the upper air are the same as those calculated from the barometric variations at ground-level. With Pekeris' correction the conductivity required will become 200 times smaller. Even then, it would be larger than that calculated from ionospheric data. This difficulty has been to a large extent removed by Massey's[8] recent work on atomic processes in the upper atmosphere in which he has shown that the rate of recombination of electrons in the *E* layer is much slower than that of either attachment or detachment and that an equilibrium ratio of 100 : 1 will be set up in that region in a few minutes between the negative ions and electrons. With a density of ions of 10^{7}/c.c. at 100 km., the contribution to the conductivity will come mainly from the ions and will be sufficient to explain the high value required by magnetic data.

In spite of its drawbacks, the 'dynomo' theory of solar and lunar diurnal variation seems to explain observations best. When Chapman first worked it out in detail, there were two main difficulties: one was that the phase of the magnetic variations did not agree with that deduced from the barometric variations at ground level and the second was that the electric conductivity demanded was much larger than that deduced from radio data. The first objection was reduced in importance by Pekeris' work on tidal oscillations in a two-layered atmosphere in which he showed that the semi-diurnal wave at 100 km. is opposite in phase to that at the ground and the second objection was met partly by Pekeris' showing that the amplitude of the 12 hourly wave at 100 km. is nearly 200 times that at the ground and partly by Massey's work on processes of recombination and attachment in the upper atmosphere wherein he gave reasons for thinking that the density of negative ions in the *E* region may be about 100 times that of electrons in the same region.

It may also be mentioned that owing to the increase of molecular conductivity at higher levels, the damping of tidal oscillations by conduction and viscosity will be negligible at 100 km. and will be very large at 200 km.

Diamagnetic and drift-current theories of solar diurnal variation.

Two other theories of solar diurnal variation have been proposed, a diamagnetic theory of the upper atmosphere by Ross Gunn and a drift-current theory by Chapman. According to the former, in the upper levels of the atmosphere where the time between two collisions of a charged particle is long compared with the time for a rotation of the particle round the lines of magnetic force, the particle will rotate round the lines of force in such a direction as to render the layers diamagnetic, the susceptibility depending on the density of electrons and ions and on their speeds. Assuming a suitable variation of charge density with local time, qualitative agreement with the observed field variation can be obtained, but the calculated field is too small unless temperatures of the order of 1000°C are assumed for the long free path region. According to the drift-current theory, in the region of long free paths, the charged particles fall freely under gravity and their motion being inclined to the direction of the magnetic field, they are deflected in a horizontal direction, giving rise to an eastward current over the equatorial regions. Owing to the diurnal variation of ionization, the currents will not remain parallel to the latitudes throughout the day but will diverge and converge giving rise to the observed variation of field. The theory has not been worked out in a quantitative form.

Both these theories place the seat of solar diurnal variation in the long free path region.

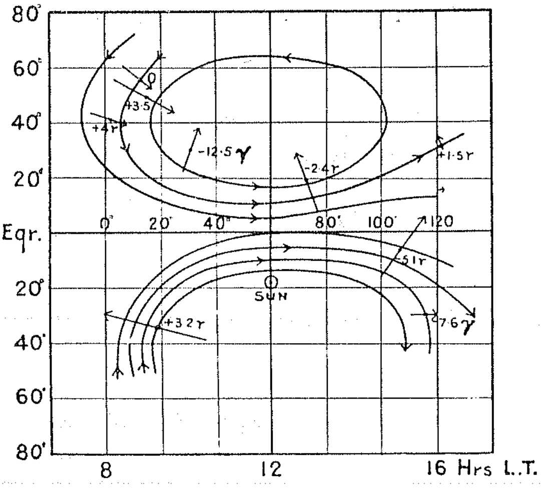
Evidence from magnetic disturbances associated with radio fade-outs.

Within the last four years, fresh evidence has appeared regarding the location of the currents responsible for the solar diurnal variations. This comes from an analysis of the magnetic disturbances accompanying radio fade-outs. In long distance short-wave radio transmission, it was noticed that occasionally the signals entirely disappeared quite suddenly and made their reappearance after a period ranging from 15 to 45 minutes. Detailed investigation by M. Jouaust of France showed that these fade-outs occurred simultaneously over different parts of the earth. J. H. Dellinger [9] of the American Bureau of Standards working in collaboration with the workers of the Mount Wilson Solar Observatory discovered that when the radio fade-outs occurred, there was a simultaneous appearance of a bright eruption on some small portion of the sun's surface (usually in the neighbourhood of a sunspot) and as the brightness of the solar eruption waned, the radio signals gradually regained their strength. It was also noticed that during the time of the solar eruptions, there appeared in the traces of self-recording magnetographs a characteristic sudden disturbance, a phenomenon which had been noticed as early as 1859 and remarked on by Balfour Stewart. To understand the character of the changes in the ionosphere responsible for these disturbances, it is necessary to study the distribution of the changes of the directions and magnitude of the magnetic field over the surface of the earth. This was done by A. G. McNish[10] for the western hemisphere. In 1936, the magnetograms of the Alibag Observatory showed 16 clear instances of such disturbances. On enquiry the Engineers of the Indian Radio and Cables Co., Ltd., supplied a list of the times of occurrence of the radio fade-outs which had been observed in India during the communication of signals between

India and England and India and Japan. On all such occasions, marked disturbances in the magnetic curves had occurred. In

FIG. 3.

ELECTRIC CURRENTS IN THE UPPER ATMOSPHERE ASSOCIATED WITH THE RADIO FADE-OUT OF 26TH JAN. 1937—BEGINNING 7h. 57m. G.M.T.



The arrows show the directions and magnitudes of the changes in the horizontal field and the figures the changes in the vertical field, positive sign indicating increase in downward component.

Fig. 3 are plotted the changes of magnetic field due to one such disturbance which occurred on January 26, 1937.* The important point to notice is that if we assume the disturbance to be due to a system of electric currents in the upper atmosphere, it is nearly of the same form and position as the system of currents required to explain the solar diurnal variations of the earth's field. This suggests that the effect of the solar outburst is to produce an increase in the ionization and hence the conductivity in and near the levels at which the ordinary quiet-day variations take place.

Progress in ionospheric technique has provided means of locating the approximate level at which a sudden burst of ionization is caused by the solar eruption. During a radio fade-out, the initial cut-off of reflected waves from the ionosphere is abrupt from all the layers E, F_1 and F_2, but the waves reflected from the lower layers disappear a little earlier. The reappearance of the signals is distinctly earlier from F_2 than from F_1, from F_1 than from E and so on. When the signals have reappeared the charge-densities of F_2 and F_1 show practically no change, while the charge-density of E shows a slight increase. These facts

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* I am indebted to the Directors of the respective observatories for kindly sending me their original magnetograms or their copies from which this and similar charts have been prepared.

and the rapidity with which normal conditions are restored make it certain that the ionization due to the solar flare takes place in and below the *E* layer. The current system due to the fade-out being similar to the solar diurnal variation makes us infer that the latter also is located in or near the *E* layer.

Magnetic storms.

Besides the periodic variations of the earth's magnetic field, there are irregular variations of different kinds. Some of them are of well-defined types. The most important of them is the 'magnetic storm'. In our latitudes, a 'world-wide' magnetic storm may cause changes of horizontal intensity amounting to 800 γ, or more than one-fifth the normal value of

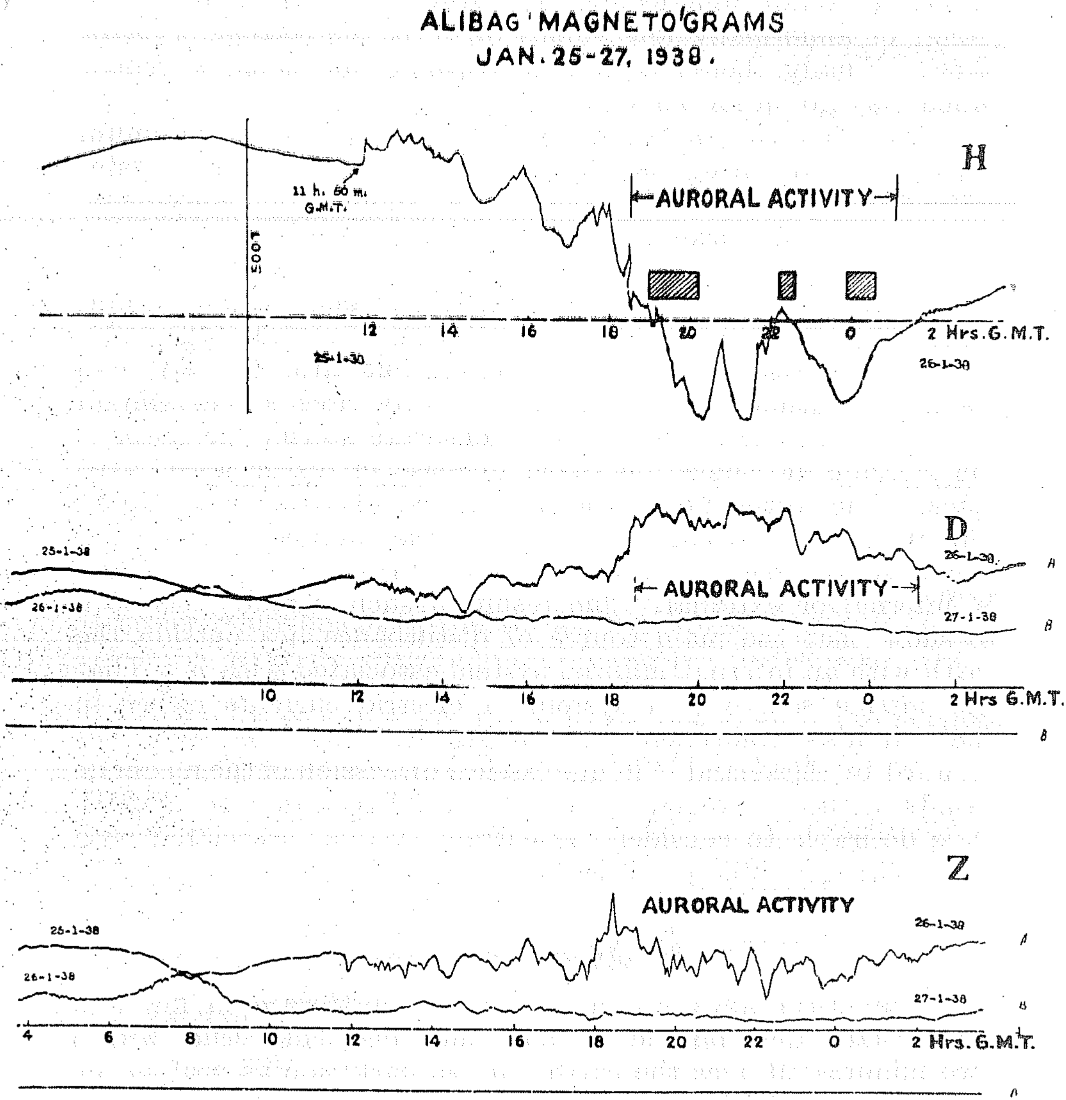

Fig. 4.

the field. The characteristic features of magnetic storms have been analyzed by Moos,[11] Chapman[12] and others. Moos made a detailed analysis of Bombay data and Chapman extended and amplified it including data from other parts of the earth. The time-variation of the magnetic elements after the onset of a storm depends to an appreciable extent on the time of the day. It can be analyzed into (1) a storm-time variation and (2) a local time variation. The local time variation consists of a diurnal oscillation, with maximum departures from normal in M and Z, the horizontal and vertical components of the field, at about 6 hrs. and 18 hrs.

Magnetic storms often begin with an impulsive change in H—generally an increase—followed by oscillations. Within an hour or two after this 'sudden commencement', follows a period of rapidly diminishing H, lasting for 6 to 12 hrs. The period of abnormally low values of H is the second or *main phase.* Finally, there is a gradual return of conditions to normal, which may go on for three or four days. (Fig. 4.)

Both the 'sudden commencement' as well as the maximum change of field during the main phase of the storm show systematic geographical distributions. The 'sudden commencement' —which is most marked in H—is generally a maximum near the equator and decreases towards the poles. Sometimes, there is an increase of intensity in the neighbourhood of the auroral zone. The maximum disturbance during the main phase also shows a decrease in the same direction, but after 60°– 65° geomagnetic latitude, the disturbance sharply rises to a maximum in all the elements. The more intense the storm, the lower is the latitude at which the sharp increase in disturbance takes place. The storm-time variations can be analyzed in a manner similar to the diurnal variations by the method of spherical harmonic analysis in order to ascertain whether the source is internal or external. The result of such a study has been to show that the main source of disturbance lies outside the earth with an internal induced system associated with it. That the outside source is a system of electric currents either in the earth's atmosphere or outside it, was the view put forward by Birkeland [13] in his classical discussion of the magnetic results of the Norwegian Aurora Polaris Expedition of 1902-03. It is desirable to consider the current systems associated with the preliminary phase and the main phase of the storm separately.

(*a*) *Preliminary phase.*

The disturbance vector is directed northward in low and middle latitudes and the sudden commencement occurs within two minutes all over the earth, on the dark side as well as the bright side. The impetus is a maximum over the equator, and there is sometimes, but not always, another maximum near the auroral zone. The current system required is an eastward flow all round the earth, and corresponds to the 'positive equatorial perturbation' of Birkeland.

Main phase.

The current system due to the main phase has been studied by Chapman[14] and his co-workers and by Goldie.[15] The system can be divided into two parts corresponding to the storm-time and the local time variations of the disturbance field. These consist of (1) a westward flow with a diffuse maximum of current density over the equator and a concentrated maximum over the auroral zone and (2) a system of four vortices, two in the northern and two in the southern hemisphere. The direction of the forenoon vortices is cyclonic and of the afternoon ones anticyclonic. The afternoon vortices are generally the more intense. The combined and component current systems (assuming them to lie in a thin spherical shell surrounding the earth) are shown in diagrams by Chapman. In the maximum storm-time phase of moderate storms, a total current of the order of 5×10^5 amperes, flows westward in extra-auroral regions and currents of the order of $3{\cdot}5 \times 10^5$ and 2×10^5 amperes flow westward and eastward respectively in the auroral zone. In very great storms, the current density may exceed ten times this amount. Chapman's scheme of electric current systems may be compared with those worked out for individual disturbances by Birkeland and for the average of 10 storms by Goldie.

Location of the currents.

There is little doubt that during the main phase of the storm, the currents *in the auroral zone* lie mainly in the earth's atmosphere. The connection between auroræ and magnetic storms is very close, great magnetic storms being associated with marked southerly movement of the auroral region (see Vestine's diagram showing average directions of magnetic disturbance vectors and of auroral arcs). The most frequent height of auroræ is in the neighbourhood of 110 km. Birkeland, from his calculations of the spatial variation of the field near the auroral region found that the heights of the currents lay between 150 and 600 km. Goldie estimated the mean heights of the currents to be 290 km. at 2 hrs. local time and 370 km. at 17 hrs. McNish[16] and Vestine in recent analysis of the heights of electric current systems due to 'polar elementary storms' and smaller disturbances have taken into account the effect of the induced field inside the earth and found that the hypothesis that fits the facts best is a current at 100–150 km., a region where the direct current conductivity of the upper atmosphere is a maximum. The probability therefore is that the concentration of magnetic field in the auroral zone during the main phase of magnetic storms is also due to a concentrated current system round the geomagnetic pole at a height of 100–150 km. above the earth flowing along auroral paths of large conductivity.

The location of the current system causing an 'equatorial perturbation' is more difficult. Various reasons make it necessary to place it well outside the earth's atmosphere. The magnetic changes are greatest in regions round the equator and the disturbing vector is directed similarly in both the northern and southern hemispheres. The facts of magnetism can be most simply explained by assuming, with Birkeland, that it is due to a ring-current round the earth with maximum intensity over the equator, the size of the ring being comparable with the diameter of the earth. The direction of the ring-current would be eastward at the time of 'the sudden commencement' and westward during the main phase of the storm. That the formation of such ring-currents is possible when a stream of charged particles flows towards a magnetized sphere was demonstrated by the laboratory experiments of Birkeland and the calculations of Störmer.[17]

An attempt at finding the position of the equatorial ring-currents has been recently made by S. E. Forbush[18] in the case of two magnetic storms, one of which began on August 21, 1936 and another on January 16, 1938. The storm-time variations of the earth's field were analyzed, assuming them to be due to (1) a westward ring-current over the geomagnetic equator and (2) two concentrated westward current systems over the north and south auroral zones, at a height of 150 km. above ground and (3) the associated induced fields. The result of the analysis as regards the position of the equatorial ring-current is shown in the following table:—

Estimated value R/a of equatorial ring-current.

Date of commencement of storm.	Time after commencement.	Estimated zonal current and polar distance.	R/a
Aug. 21, 1937	30–78 hrs.	4×10^4 amp. and 20°	4·0
	54 hrs. (adjusted by smoothing)	do.	2·5
Jan. 16, 1938	22–46 hrs. 54–78 hrs.	$6{\cdot}2\times 10^4$ and 28°	15·8
	54 hrs. (smoothed)	do.	2·1
Disturbed days minus quiet days.		2×10^4	2·3

In the case of storms, the radius of the ring-current is not less than two earth-radii, but may greatly exceed that figure. For a mean disturbed day, the radius is of the order of 2 to 3 earth-radii.

A line of study which in the near future is likely to yield valuable information regarding these ring-currents is the effect of magnetic storms on cosmic ray intensity. That there was a decrease in cosmic ray intensity throughout the earth from the equator to 50°N. during a magnetic storm was noticed by a number of cosmic ray investigators during the magnetic storm of April 26, 1937. Usually, a fall of horizontal intensity is associated with a decrease of cosmic ray intensity. It was pointed out by Chapman that this effect was probably due to the postulated ring currents and that the change in cosmic ray intensity might enable us to determine the height of the currents above the earth. While for the same storm, the changes in H and changes in cosmic ray intensity seem to be correlated, the mean ratio $\triangle J/\triangle H$ for different storms are different. For instance, in the storm commencing on August 21, 1937, there was hardly any effect on the cosmic ray intensity. This can be explained if the current systems for different storms flow at different distances. The calculated values of the radii of the equatorial current system calculated from the changes of cosmic ray intensity in three or four magnetic storms are 3 to 4 earth-radii.

A serious difficulty, however, remains. In the above calculations, it is assumed that the effect of the external current system is to increase the magnetic field outside the system and hence to decrease the number of cosmic ray particles reaching low and moderate latitudes. While this is of course true, there will be a corresponding decrease of field between the earth and the external current system and since the largest deflections of the charged particles will occur within this space, the net effect of the ring-current would, *a priori*, be expected to cause an increase in the allowed cone of cosmic rays and hence an *increase* in its intensity. Clay and Bruins[19] think that the only way to escape out of the difficulty is to assume that circular currents normally exist over the equator but that during magnetic storms, they decrease or oscillate. Detailed calculations of the effect of a ring-current on the paths of charged particles are necessary and will no doubt be forthcoming shortly.

Cause of magnetic storms.

The close correlation between magnetic and auroral activity makes it clear that the origins of the two are intimately connected. The corpuscular theory of Birkeland and Störmer explains many of the facts well and in spite of weighty objections to the theory, it appears probable that some modification of it will survive. A stream of charged particles directed from outside towards a magnetized sphere, such as the earth, will describe a series of orbits determined by the magnetic moment of the sphere and the momentum of the particles. Störmer showed that there exists, about the sphere, a toroidal space with its axis coinciding with that of the sphere, into which the particles will not enter. The equatorial radius of this space is given by $(2^{\frac{1}{2}}-1)\ C$, where $C=(Me/mv)^{\frac{1}{2}}$, M being the magnetic moment of the sphere, and e, m and v the charge, mass and velocity of the particles. C has this physical significance that it is the radius of the equatorial circle which is a possible orbit for the particle. There is thus only a limited region round the magnetic poles to which particles from outside can have entry. The maximum angular extent of this region depends on the momentum of the particles. A table showing the values of C and the maximum angular distance from the poles at which particles can enter the earth's atmosphere, is given below for various kinds of particles.

TABLE.

Nature of particles.	Velocity cm./sec.	$\frac{mv}{e} = H\rho$	C in earth radii.	Angular distance of entry (from magnetic axis).
Cathode rays	$1{\cdot}9\times 10^9$	108	1400	2°·3
	$9{\cdot}0\times 10^9$	540	660	3°·4
β rays	$2{\cdot}4\times 10^{10}$	1800	345	4°·6
	$2{\cdot}8\times 10^{10}$	4500	220	5°·8
α rays	$1{\cdot}4\times 10^9$	290,000	28	16°·6
	$2{\cdot}06\times 10^9$	398,000	23	18°·1
Ca^+	$1{\cdot}6\times 10^8$	$6{\cdot}6\times 10^5$	17	20°

Even fast β ray particles with a velocity of $2{\cdot}8\times 10^{10}$ cm./sec. cannot get beyond 5°·8 from the magnetic pole. As we know from auroral and magnetic observations that the maximum current densities occur at 20–23° from the poles, the particles, if electrons, must have even greater velocities, or they should be particles of atomic size with momenta exceeding those of the fastest α rays. Milne has calculated that Ca^+ atoms moving away from the sun, would get gradually accelerated owing to absorption of solar radiation from regions outside the centres of the Fraunhofer H and K lines and acquire a maximum velocity of $1{\cdot}6\times 10^8$ cm./sec. Such particles will reach the earth in about 28 hrs. and enter the earth at about 20° from the magnetic axis. But their momenta would be too small to penetrate to a depth in the atmosphere as low as 80–100 km.—which seems to be required by auroral phenomena. Ionospheric studies in the auroral region also point to the conclusion that the particles reach a height of 80–100 km. above ground. Leiv Harang,[20] of the Auroral Observatory at Tromsφ in Norway ($\phi=69°40'$N., $\lambda=18°57'$E.) summarizes the general results of radio-echo observations there during magnetic disturbances as follows:—

(1) Momentary formation of a new layer at the level of the *E* layer during storms.

(2) Formation of an absorbing layer below the usual *E* layer during the intense phase of the storm causing weakening and sometimes cessation of the echoes on all wave-lengths.

(3) Formation of high *F* layers during and after the storm with subsequent lowering of height.

(4) Decrease of the critical frequencies of F_1 and F_2.

(5) Rapid changes of *P′f* curves in periods of magnetic activity.

It has been suggested by Störmer and demonstrated experimentally by Brüche that if there is a ring-current round the earth, its effect would be to shift the position of entry to nearer the equator. If the observed position of the auroral zone is to be explained in this manner, we should expect that the position of maximum disturbance should depend on the strength of the ring-currents, that is, on the strength of the disturbance. It is true that during large disturbances, there is a tendency for the zone of maximum disturbance to shift equatorward, but during

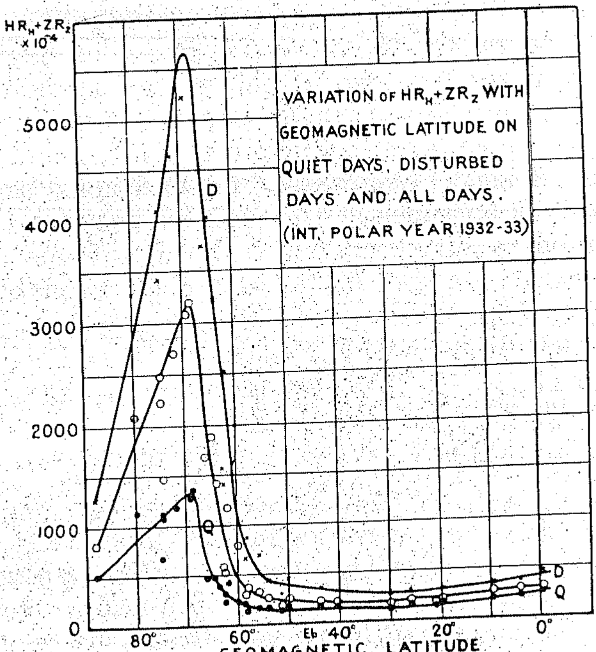

FIG. 5.

weak disturbances, no such tendency seems observable. This may be seen from Fig. 5 in which is shown the variation of disturbance with distance from the magnetic equator on all days, quiet days, and disturbed days prepared from the range data published by the International Commission for Terrestrial Magnetism.

Birkeland and Störmer considered the stream of corpuscles projected from the sun and moving towards the earth as having charges of the same sign. It is now generally agreed that such a stream would not hold together all the way from the sun to the earth without dissipation. Chapman and Ferraro have attempted to work out a detailed theory of magnetic storms and auroræ, assuming the particles to be neutral on the aggregate but composed of equal numbers of positive and negative charges and probably also accompanied by a good number of uncharged particles. Such a composite stream can approach the earth much nearer than a stream of particles all having the same sign; and if a moderate difference in speed between the positive and negative particles is permissible, it is possible for them to form a ring-current round the earth; but, as Chapman says, 'It must be confessed that we have no clear indication whether or how such a ring could be formed'. However, present-day evidence is tending more and more to the view that an equatorial ring-current is formed outside our atmosphere.

Such a ring-current, when varying, must produce induced currents in our atmosphere; and the question remains to be answered whether we can explain all the effects that we observe in low latitudes during magnetic storms by the effect of the induced currents in a non-uniformly conducting atmosphere. For example, there is the local time variation of magnetic storms. Again, ionospheric workers in moderate latitudes also have found that during magnetic storms, the waves reflected from the F_2 region become weaker, the height of this region increases and its electron density decreases. Observations are obviously needed from low latitudes of the changes that take place in the upper atmosphere during magnetic storms. Some observations perhaps do exist, but they have not become available.

Before leaving the subject, it is desirable to consider briefly a purely atmospheric theory of magnetic storms worked out by Hulburt and Maris.[21] They assume that in times of activity, the sun occasionally emits a sudden blast of ultra-violet radiation lasting for a short period, mainly in the region of wave-lengths below 1500Å. The radiation produces ionization both in the long and short path regions of the sunlit atmosphere. According to them, therefore, the particles do not come from outside; they are produced in our atmosphere mainly in low latitudes. The ionization in the long free path region produces an eastward current and gives rise to the initial phase of the storm with its increase in H. The ionization in the short free path region increases the conductivity of the atmosphere and causes its expansion; and upward velocity of 10 km./hr. can cause a decrease in H of 100 γ at the equator. The expansion is also supposed to engulf the long free path ions in the rising tide of molecules and convert them into short free path ions. The consequent reduction in the number of long free path ions is believed to be responsible for the observed after-effect of the storm in keeping down the horizontal component of the earth's field below normal for a few days. The most serious objection to the ultra-violet theory is, as pointed out by Chapman, that the ultra-violet theory can account for a velocity of only about 10^6 cm./sec. for the particles by ultra-violet ionization and impact with excited particles and that this velocity is far too small for the particles to penetrate down to 80 km. and explain the various observed features of auroræ.

Conclusion.

From what has been said, it will be clear that the subject of Terrestrial Magnetism presents many problems of great interest both to the experimental and the theoretical physicist. We are still far from the solution of the fundamental problem of the origin of the earth's permanent magnetic field. More information can undoubtedly be gathered about the electrical and magnetic properties of the earth's interior by a study of the magnetic variations on the lines of Chapman and his school. I have not even touched on the application of magnetic methods to the study of the structure of the top layers of the earth's crust—a method which has given results of economic value in other countries and has begun to yield results of great geophysical interest in the hands of the Survey of India. Our knowledge of the exact locations in the earth's interior and in the atmosphere, of the sources of regular and irregular variations of the earth's field is still very incomplete. The question of the existence, permanent or otherwise of a system of ring-currents round the earth is still a matter for discussion.

It has been said that the sun and stars provide us laboratories in which experiments on matter are carried on under conditions of temperatures and pressures which can never be realized in the laboratory. So too our mother Earth provides us a magnet of stupendous dimensions with which various experiments on matter are being continuously carried on and it is for us to observe and collate the results and reason on them so as to know a little more about her and about matter in general.

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