# Theories of Terrestrial Magnetism.*

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## EARTH'S MAGNETIC FIELD AND SECULAR VARIATION.

VERY valuable criteria have been given by Gauss and by Schuster, the former showing that the main origin of the earth's magnetic field is within the earth, and the latter that the cause of the daily variations is external to the earth's surface. Any predominant magnetic effect due to external causes need not, therefore, be looked for.

What do we know of the so-called permanent field ? Examination of the available data leads to the conclusion that the magnetic field may be regarded as moving westwards along a parallel of latitude at the rate of a few seconds of angle per day, the rate of movement being such that, if continued for some hundreds of years, the field would make a complete revolution round the earth, the motion being in the opposite direction to that of the earth's rotation. The secular variation may therefore be regarded as caused by change in direction of the axis of magnetisation. If outer space is a conducting medium, there will be relative motion between the magnetic field of the earth and it, and the moving field will induce currents in the outer conducting medium, and these currents in turn will react and induce other currents and associated magnetic phenomena. There will also be mechanical reactions, and Schuster showed how these reactions can be calculated. It is certain that the induced currents must tend to destroy the motion of the inducing field, and that one effect must be to reduce the period of rotation. Such a reduction in the period of rotation would result even if the magnetic axis coincided with the axis of rotation, but when the two axes do not coincide there is another retarding couple acting on the magnetic field.

A circular movement of the magnetic pole about the axis of rotation may be regarded as produced by two radial movements at right angles operating from that axis. Such motions of the magnetic field will induce currents in the conducting layer, and the reacting forces will tend to destroy the movements which produce them, that is, the tendency will be to make the two axes coincide. The total result is, therefore, to slow down and eventually destroy the rotation of the magnetic axis and to reduce the angle of separation of the two axes and eventually cause them to coincide. A bird's-eye view of the magnetic and geographical poles taken over a long period of time would reveal a spiral path for the magnetic pole, the latter drawing nearer and nearer to the geographical pole.

It is, of course, not necessary to assume a large volume of outer space to have uniform conductivity to produce such effects. An outer layer will suffice, and the conductivity may be uniform or patchy, but the reactions will be of the sign indicated. It is certain that the movements of the magnetic field are not simple as outlined above but are very complex, and that unexpected reversals occur, so that it is not possible to predict the conditions even twenty years ahead. The theory advanced is, however, still capable of explaining the variations, for any conducting layer may not only vary greatly over considerable areas, but there may be relative motion between the earth and portions of the layer which also varies.

## ELECTRIC CURRENTS CIRCULATING ROUND THE EARTH.

The next simplest theory to that of a magnetic core is that the magnetic field is due to electric currents circulating round the earth, and this naturally gives rise to the question of the seat of origin of the electromotive forces necessary to maintain such currents. If the currents are uniform in density throughout the volume of the earth, the magnitude of this density would be about $10^{-8}$ amp. to produce the necessary intensity of magnetisation. If we suppose that there was once a source of electromotive force but it has long ceased to operate, the currents produced would take a very long time to die down owing to self-induction. But it is much more profitable to look for a possible electromotive force not only to produce but also permanently to maintain a current system.

Such a possible source was indicated by Larmor at a meeting of the British Association in 1919. Larmor pointed out that in the case of the sun, surface phenomena indicate the existence of a residual internal circulation mainly in meridian planes. If this circulating conducting material cuts a magnetic field which in direction is the same as that of the earth, circulating currents will be set up in such a direction as to augment the magnetic field, and eventually a condition of equilibrium will be set up between the producing electromotive force and the attenuation effects. The system is, in fact, that of a self-exciting dynamo, and the energy of the system is obtained at the expense of the energy of the circulating conducting material.

While in the case of the earth any internal circulation of matter in meridian planes or near thereto is entirely conjectural, the theory does provide not only for the main field but also for the secular variation by changing the paths of the circulating currents.

Ross Gunn has recently put forward a theory attributing the magnetic field to electrical currents set up inside the earth in the high temperature regions where the thermal motions are considerable. Gunn suggests that the temperature of the inner earth is of the order of 10,000°, and as a consequence the material will be highly ionised and the conductivity correspondingly great. In the case of the upper atmosphere, Gunn has analysed the motions of ions and electrons of long free path spiralling about the magnetic lines of force, and in such a case a diamagnetic effect and drift currents are produced.

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An extension of the calculation to the inner earth where the free paths are short is made, and it is considered that the primary current system of the earth results from the motions imposed upon ions having a mean free path of the order $10^{-7}$ cm., the motion being imposed by the internal gravitational electric field at right angles to the magnetic field. The currents produced augment the original field in a regenerative manner.

### MAGNETIC EFFECTS ASSOCIATED WITH EARTH'S ROTATION.

Let us consider the possible ways in which a body may by virtue of its rotation act like a magnet. First consider the earth as a body carrying a positive or negative electric charge. If the surface density of the charge be $\rho$, the magnetic force at the equator parallel to the surface is

$$H_e = \frac{4}{3}\pi\rho r\omega$$

where $\omega$ is the angular velocity and $r$ the radius of the earth. If $Q$ is the total charge on the surface, the horizontal magnetic force may be written

$$H_e = Q\omega/3r = \frac{V\omega}{3}$$

where $V$ is the potential. In this case it is obvious that any small sphere charged at the same potential and rotating at the same angular velocity would produce the same surface field, since the radius of the sphere is not involved.

If, however, the charge be distributed uniformly throughout the earth—and this is necessary for uniform intensity of magnetisation—the value of the horizontal field at the equator is $Q\omega/5r$. If the charge on the earth be negative, the resultant field is such that there would be an upward vertical component at the north pole, and a south to north horizontal field at the equator. A field of this type does not exist in practice, the field of the earth being such that its direction is south to north at the equator and vertically downwards at the north pole. Moreover, it is not possible to produce by means of a single rotating charge, fields of the correct sign both at the pole and the equator, for if we change the sign of the charge the resultant fields at pole and equator are also changed in sign.

To overcome the difficulties of a surface charge, Sutherland suggested an equal but opposite charge concentrated at the centre of the earth, thus neutralising the electrostatic field due to the surface charge but not the magnetic effect of the charges in motion. Later he suggested that an inequality in the distribution of the earth's atomic charges might be a cause. There are a number of variants of this idea of separated charges. One is that the rotation of the earth brings about an electric polarisation in the atoms perpendicular to the axis of rotation, such polarisation producing a magnetic and also an electrostatic field. The direction of magnetisation of the field is not, however, that actually observed on the earth, the same difficulty presenting itself as that already considered with the charged sphere.

In 1891, and on several occasions since, Schuster has raised the question whether every large rotating mass is not a magnet, and so far back as 1891 he put forward the suggestion that the sun has a magnetic field associated with it.

The observed similarities between the magnetic fields of the earth and the sun, especially as the physical conditions are so different, naturally lend support to the theory that the magnetisation is brought about by rotation, and the fact that the axes of rotation and magnetisation do not coincide, while disturbing, may possibly be explained by reasonable assumptions.

If rotation of matter is necessary to produce the magnetic fields of the earth and the sun, the angular velocity, the radius, and the density must be important factors. If the magnetic effect is proportional to $D\omega r^2$, where $D$ is the density, the calculated intensity of the sun's field agrees with that observed, taking the earth's field as the standard. Unfortunately, owing to the square of the radius being involved in the expression for the field, an effect proportional to $D\omega r^2$ cannot be tested by experiments in the laboratory, as a value of $\omega$ necessary to produce a measurable effect could not be obtained. A magnetic effect proportional to $D\omega r$ can be and has been tested in the laboratory, but the effect is far too small to account for the earth's magnetism.

A theory which has been tested by laboratory experiments is one depending on gyroscopic action. If the magnetic condition of iron arises from the rotation of the electrons in the constituent atoms, the axes of rotation should tend to become parallel to the earth's axis of rotation. The net result so far as the magnetic effect is concerned is to cause each molecule to contribute a minute magnetic moment parallel to the earth's axis of rotation. The effect will be proportional to the angular velocity and not the radius, so that the effect can easily be tested in the laboratory. Barnett first succeeded by laboratory experiments in showing that magnetisation was produced in this way and that the intensity of the field observed was proportional to the angular velocity. The direction and general shape of the magnetic field of the earth could be accounted for by this gyromagnetic theory, but the intensity of magnetisation produced is far too small. The estimated value is about $10^{-11}$ times that of the earth.

### POSSIBLE MODIFICATION OF LAWS OF ELECTRODYNAMICS.

The difficulties confronting such theories as an electrically charged earth and the smallness of the gyromagnetic effect, have led to suggestions that the field may be due to some departure from the commonly accepted laws of electrodynamics.

In 1894 J. J. Thomson pointed out that if atoms exerted slightly different attractions on positive and negative electricity, then a large rotating body could produce a magnetic field. In such case the intensity would be proportional to $\omega r^2$, so that no laboratory experiments could confirm or refute the theory.

Swann, who has put forward a theory based on a slight modification of the laws of electrodynamics, points out that the ratio of the magnetic fields for the earth and sun would be obtained also for an expression of the form $D\omega^4r^4$, since the ratio of the values of $\omega^4r^4$ differs inappreciably from that of $\omega r^2$. According to this theory, spheres of such size that they may be used in laboratory experiments should give effects which are just measurable, and Swann and Longacre have made experiments with a copper sphere 10 centimetres in radius rotating at 200 revolutions per second, but the results obtained differ very appreciably from those calculated on the theory, that is, an effect proportional to $\omega^4r^4$.

### VERTICAL ELECTRIC CURRENTS.

There is, however, a possibility that a small portion of the earth's magnetic field may be due to vertical electric earth-air currents, which can easily be distinguished from currents circulating in the upper atmosphere or in regions beyond.

Rücker chose areas in Great Britain where the magnetic forces were well known, and failed to find any evidence of such vertical currents. Dyson and Furner made an examination of data available in 1922, and conclude that although there is some evidence, such currents are not indicated with any certainty. On the other hand, Bauer has made many calculations, and on all occasions has been forced to conclude that such vertical currents do exist.

The probable error, however, associated with the measurements is considerable; but sufficiently precise measurements could be made over a carefully chosen area which would enable a definite decision to be reached with respect to such vertical currents.

### DAILY VARIATIONS.

Schuster's analysis shows that the daily variation is probably due to electric currents in the upper atmosphere, but in addition to the magnetic effects of these currents there is an effect due to currents induced in the earth by them. These induced currents are naturally in the opposite direction to the inducing ones, and hence the magnetic effects for the horizontal intensity are additive, while those for the vertical force are opposed.

Chapman's analysis shows the system in the sunlit hemisphere to consist of two closed circuits which (at the equinoxes) may be taken as symmetrical with respect to the equator, their foci lying very nearly on the 11 A.M. meridian. As the electric currents are supposed to be induced by the movement of conducting layers of air in the magnetic field, such currents must also be produced near the ground, but the conductivity of the air near the ground is so low that their effect may be neglected. In the upper regions the movements, while larger, cannot be regarded as immeasurably greater than near the earth's surface, and the increase in current intensity can only be attributed to an increase in the conductivity, a view which Balfour Stewart was forced to adopt, although at the time there was little evidence to support it.

The magnitude of the dynamo effect is dependent on three factors—(1) the horizontal movement of the air, (2) the conductivity of the air, (3) the intensity of the vertical magnetic field. All these factors vary with latitude, and hence it is to be anticipated that the magnitude of the variations will also vary with latitude, which is the case. The intensity of the field can be calculated with considerable accuracy but the conductivity and movements of the upper air are not known, although such movements are attributed to thermal effects and hence will be a maximum in the daytime.

As a first and crude approximation we may imagine a spherical conducting layer to surround the earth, and in addition a conducting hemispherical cap over the hemisphere facing the sun, the height of this cap being a few hundred kilometres. Neither the complete spherical conducting shell nor the hemispherical cap are of uniform conductivity, and the matter constituting these layers moves with the earth, so that ionisation and recombination are always taking place.

While we have from wireless measurements fairly good evidence of the height of the lower conducting layers, our knowledge of the extent of the ionisation is not sufficiently good to enable us to do more than speculate on the merits of the theories advanced, for in addition to the dynamo theory there is one due to Ross Gunn known as the diamagnetic layer theory, and a third called the drift current theory. The differences between the theories are best brought out by considering the ionisation effects in the hemispherical conducting cap facing the sun. Pederson has calculated the number of electrons and ions per cubic centimetre at various heights, and he and Ross Gunn have considered the nature and magnitude of the conductivity of the upper ionised regions. They have shown that the conductivity varies with the direction of the magnetic field, the conductivity at right angles to the field being at times very small, and under certain conditions it approaches zero, while the conductivity in the direction of the field is unaffected by the field's intensity. Hence in layers where the conductivity transverse to the magnetic field is very small, such large circulating currents as are necessary for the dynamo effect cannot flow, and where there is an appreciable vertical magnetic field there can be but negligible horizontal electric currents. In the case considered by Gunn, where a charge in its spiral path can execute many revolutions between successive collisions, the spiral motion of the charge has the same effect as a small magnet opposed to the field, so that the whole hemispherical cap is equivalent to a diamagnetic layer, and to this diamagnetism Gunn attributes the diurnal variation. There appears to be no doubt that such a diamagnetic effect does exist, and that it contributes to the diurnal variations, but its magnitude is much too small to explain the whole of the diurnal variation.

Chapman has shown how the ionisation in the diamagnetic layer contributes far more effectively to the diurnal variation. He shows that the less the contribution made by a charged particle to the transverse conductivity (relative to the magnetic field) the greater is the mean drift velocity which it experiences, and in the case of the earth's magnetic field such drift currents are eastward in direction. There is, in fact, a steady drift of electrons and ions in a direction perpendicular to the lines of magnetic force and the gravitational field.

With regard to the relative merits of the three theories, an effect of the diamagnetic layer appears certain, but with it is associated the drift current effect which is much larger. The diamagnetic layer effect must therefore be regarded as secondary in importance. The dynamo theory involves motions of the air as well as ionisation,. and while on the whole the drift current theory appears to be superior, more information is needed of the number and distribution of ions and electrons in the upper atmosphere before coming to a final decision.

### SUNSPOTS AND MAGNETIC STORMS.

Any unevenness in the radiation from the sun as it rotates must also affect the conductivity and hence produce variations. Examination of magnetic records shows that many variations are related to the sun's period and also to sunspot periods, and it appears not improbable that there is overlapping of several periods probably intimately connected. The results obtained show that with rise and fall of sunspot frequency there are corresponding changes in the diurnal variation. Moreover, the amplitude of the daily changes rises and falls with the intensity of the magnetic disturbance. It follows, therefore, that change in amplitude of the diurnal variation in years of many sunspots is due to the same ultimate cause, namely, solar radiation, as that causing magnetic disturbance.

Magnetic storms are marked disturbances of solar origin, and to explain these many theories have been advanced, but the facts are not easy of explanation. One of the first theories put forward attributed magnetic storms to the magnetic fields produced by streams of charged particles from the sun acting like an electric current and producing a direct magnetic effect. Schuster showed that such a stream moving between the sun and the earth would move in a magnetic field of constantly increasing intensity, and would be subject to a retarding force also continually increasing. Lindemann has overcome this difficulty by suggesting solar streams which are ionised but on the whole neutral. The groups of particles are assumed to be projected from the solar prominences, and the gases in these are of such high velocity, $10^8$ cm. per sec., that the journey from the sun to the earth should be possible in less than two days, without serious recombination taking place. Moreover, owing to its neutrality such a stream will not tend to spread outwards by the mutual repulsion of its constituent particles.

Maris and Hulbert attribute the increase in ionisation to the action of ultra-violet light. They conclude that at heights of 300-400 kilometres temperatures of 1000° K. are reasonable, and at heights exceeding 400 kilometres the free paths of the particles are very long, the motions due to formal impact considerable, and the ionisation entirely due to the action of ultra-violet light. When the activity of the sun increases it is assumed that there is a tremendous increase of ultra-violet light; thus Maris and Hulbert estimate that if one ten-thousandth part of the solar surface (temperature 6000°) were removed and there were exposed regions of black body temperature 30,000°, the total ultra-violet energy would be increased $10^5$ times, whereas the solar constant would be increased by only 1 per cent.

Recently Chapman and Ferraro have suggested that magnetic storms are essentially connected with the approach of a neutral ionised stream towards the earth, the more important changes in the stream taking place in the direction of the sun at a distance equal to a few times the radius of the earth. Retardation of the stream results, and this retardation is naturally greatest at that part of the front of the stream in direct line with the centre of the earth. On either side the stream will advance and partly enclose the earth, and along the sides of the enclosure there will be charged layers due to the polarisation of the stream by the magnetic field. Across the space on the dark side of the earth it is assumed that a westerly current is set up due to charges passing over the space between the charged layers.

### NEED FOR MORE PRECISE DATA.

This very hasty sketch of some theories relating to terrestrial magnetism reminds me of Dr. Chree's remarks that the deductions from such theories are just as hypothetical as the theories themselves, and I am very sensible that this rapid survey is not only incomplete, but also that no theory considered is completely satisfactory. Moreover, while fully realising that they are vital links in any chain of evidence, I have avoided the companion subjects of auroræ, atmospheric electricity, and earth currents, because to have considered them would have taken far too long. I do, however, wish to emphasise that data of a precise kind are much needed to modify existing theories and to produce new ones, and I cannot do better than conclude with a remark of Rücker's in Bristol thirty-two years ago. Rücker said: "If there be any who are inclined to ask whether the careful study of terrestrial magnetism has led, or is leading, to any definite results, or whether we are not merely adding to the lumber of the world by piling up observations from which no deductions are drawn, we may answer that, though the fundamental secret of terrestrial magnetism is still undiscovered, the science is progressing. . . . But there are special and cogent reasons why the science of terrestrial magnetism should be cosmopolitan. For those who would unravel the causes of the magnetic movements of the compass needle concerted action is essential. They cannot, indeed, dispense with individual initiation or with the leadership of genius, but I think that all would agree that there is urgent need for more perfect organisation, for an authority which can decide not only what to do but what to leave undone."