THE ORIGIN OF THE EARTH'S MAGNETIC FIELD

By E. C. BULLARD, Sc.D., F.R.S.
Director, National Physical Laboratory.

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Mr. Vice-Chancellor, Ladies and Gentlemen:

There is nothing you could have asked me to do that fits better with my interests and inclinations than to give your lecture founded in memory of Edmond Halley. Halley was a great man in a great age and is one of the founders of the modern world. From my point of view he has an additional advantage, he is not Newton. Newton's greatness depends on an insight, originality and power of abstraction that are beyond ordinary experience. I have no idea what it would feel like to be Newton, but I do, I think, know what it might feel like to be Halley.

As I see it, we remember Halley because of the width of his interests and the vigour with which he pursued them. He was interested in everything. He was a mathematician and an astronomer; he was Assistant Secretary to the Royal Society; he operated the mint at Chester; he translated Arabic mathematical works and investigated the relics of Roman Britain; he was a sea captain and a hydrographer, and he invented one of the first practicable methods of diving. To all these subjects he contributed something.

As a young man he was an undergraduate at Queen's College in the University of Oxford. In his third year he decided that he had had enough of formal education and went to St. Helena to observe the southern stars and to prepare a catalogue of them. On his return, King Charles II instructed the University to allow him to count this work as part of his qualifications for a degree. This voyage to St. Helena had a lasting effect on Halley's interests, and drew his attention to many things on which he afterwards worked. In particular, he became interested in the ship's compass and in the variations of the Earth's magnetic field. In 1683 and 1692, he published two papers in the Philosophical Transactions of the Royal Society in which he discussed the origin and nature of that field. Later, from 1698 to 1700, the Board of Admiralty lent him a ship with which he made a voyage in the Atlantic to study the matter further. This was, I believe, the first of the great voyages sponsored by the Admiralty for scientific purposes. Unfortunately, when he set sail in 1698, Halley was troubled by a mutinous first-lieutenant and was obliged to return. In the next year, however, he went as far south as the antarctic ice would allow, and measured the declination of the compass at numerous points in the north and south Atlantic oceans. A map showing the results of this voyage was published in 1701. After this Halley's interests seem to have shifted elsewhere; he says, "The nice Determination of this and of several other particulars in the Magnetic System is reserved for remote Posterity; all that we can hope to do is to leave behind us Observations that may be confided in, and to propose Hypotheses which after Ages may examine, amend or refute." This "after age" has now, I think, arrived and the time has come to look again at the magnetic field of the Earth and to see how far the ordinary laws of physics are able to explain it.

A hundred years before Halley's time, William Gilbert had demonstrated that the magnetic field of the Earth is similar to that surrounding a uniformly magnetised sphere. Halley showed that this is only a rough approximation and that the field is, in fact, considerably more complex. If we remove the part that resembles that of a uniformly magnetised sphere, the dipole field as it is called, we are left with a pattern of considerable complexity showing a number of centres towards which the lines of force converge. These may be regarded as subsidiary magnetic poles; their existence was first pointed out by Halley.

The pattern of the non-dipole field is not only complicated, but changes with the passage of time. The field at any place often varies fairly uniformly in one direction for 50 or 100 years and then starts to drift in the reverse direction. The general appearance of the maps showing the non-dipole field and its changes are not unlike those of a weather map. This, I think, suggests that a satisfactory theory of the origin of the field must possess a certain flexibility and a certain complexity. We need, in fact, something of the same sort of variability as the causes of the weather.

It is surprising how little is known of the cause of the field. Two hundred and fifty years ago Halley complained, "Now although the great utility that a perfect knowledge of the Theory of the Magnetical direction would afford to mankind in general, and especially to those concerned in Sea affairs, seem a sufficient incitement to all Philosophical and Mathematical heads, to take under serious consideration the several phaenomena, and to endeavour to reconcile them by some general rule; yet so it is; that almost all the Authors, from whom a discourse of this kind ought to have been expected, pass by in silence the difficulties they here encounter." Since his time, a great amount of information has been secured about the rapid changes in the field and very satisfactory explanations have been given for these, depending on phenomena occurring in the Sun and in the upper atmosphere. The main part of the field and its slow variations have, however, nothing to do with things outside the Earth. It was shown conclusively by Gauss over a hundred years ago that their causes lie entirely within the Earth. Here is the central difficulty of the problem: what is there within the Earth that can change in a hundred years? The time scale of terrestrial magnetism is entirely different from that of geology. In geology, large changes take millions or tens of millions of years, but at Cape Town the horizontal component of the Earth's field has changed by 30 per cent in a hundred years. Further, the magnetic field shows no relation to the major features of geology. The pattern of continents and oceans or of mountains and plains is not reflected in the maps of the field or of its changes. These difficulties are insuperable so long as we suppose the origin of the field to lie in the outer solid part of the Earth, but both can be met if we consider causes in the central fluid core. The existence of this core is beyond doubt. Its radius has been measured by seismology with an accuracy of a few kilometres, and its density and compressibility are known with some accuracy. Its radius is about half that of the Earth and its density is so high as to suggest strongly that it is composed of a liquid metal. There has been some controversy as to whether this metal is molten iron or whether silicate is converted to metal by the high pressure prevailing within the Earth. For our present purpose it is not necessary to decide this question; all we need is a fluid conductor. If we can suppose the fluid material of the core to be in motion, it is possible to give a very simple and natural explanation of the secular variation. Suppose the core to move in the presence of a magnetic field; this motion will induce a system of electric currents which will give a magnetic field at the surface. Thus, if there are irregular whirls and eddies near the surface of the core, variations will occur in the field observed at the Earth's surface. Detailed investigation shows that the orders of magnitude required are not unreasonable. All that is necessary is a motion with a velocity of a few tenths of a millimetre per second.

If the secular variation is to be accounted for in this way, some mechanism must be provided for causing motion within the core. This is a far from trivial problem, as the core is well shielded from external influences by the solid part of the Earth. A natural suggestion is that as the rotation of the Earth is slowed by the friction of the tides in its shallow seas, the inner part of the core runs on ahead of the outer part and relative motions are thus produced. It may be shown that this attractive mechanism is impossible. Such a relative rotation in the presence of a magnetic field produces electromagnetic forces that are so large as to stop the motion in a few months or a few years. It is essential that the motion be maintained by forces; it cannot merely be allowed to run on by inertia. The only available force seems to be gravitation. If the gravitational field inside the Earth is to produce a motion, there must be density differences, and the only plausible suggestion that has been made is that these are due to temperature differences. In brief, the suggestion is that the motion of the material of the core is a motion of thermal convection. We know so little of the core that it is difficult to say whether such a mechanism is possible or not. The temperature and the electrical and thermal conductivities of the core are all uncertain by a factor of three, and the rate of generation of heat within it by radioactivity is entirely unknown. The orders of magnitude are not unreasonable. A heat generation of 1 per cent of that in surface rocks would provide a flow of heat sufficient to cause instability. The main difficulty is to remove the heat from the surface of the core, and this difficulty does not appear insuperable. I believe the most fruitful attitude to this question is to assume the existence of the motions and to see what can be deduced about the core, rather than to assume properties of the core and then to enquire whether the motion will take place. The argument in favour of the motion drawn from the secular variation is so strong that its existence is one of the most definite pieces of information that we have about the core, and is much less hypothetical than some of the other quantities involved. Such arguments suggest a rather low temperature for the core (say a few thousand degrees).

The theory described above is imperfect in that it assumes the existence of the main field of the Earth and uses it to account for the irregularities and for the secular variation. This in itself does not take us far in our main problem, which is to account for the origin of the field. There are only four ways in which a field can be produced. They are:

(*a*) permanent magnetism;
(*b*) the motion of electrostatic charges;
(*c*) electric currents;
(*d*) some unknown process.

No substance is known which is capable of permanent magnetisation at temperatures above about 1000°C., and there is no reason to suppose that the high pressure within the Earth will affect this rule. Although almost nothing is known about the temperature deep within the Earth, there is little doubt that it is above 1000°C. Even if the Earth was cold when it was formed, a uranium content that was a minute fraction of that of surface rocks would be sufficient to raise it above 1000°C. in the time that has elapsed since then. In any case the core must be hot enough to keep it liquid. Even if it were possible to imagine an Earth with an inside cold enough to be ferromagnetic, we should still have to arrange for the core to be liquid and for motions to occur in it in order to account for the secular variation. In addition, if we suppose the Earth to be ferromagnetic we should have to find a separate mechanism for the magnetic field of the Sun and stars, which are certainly not ferromagnetic. The most that can be said is that our ignorance of the inside of the Earth is such that we have no direct and conclusive proof that the interior of the Earth is not ferromagnetic. I do not believe, however, that anyone seriously supposes that it is.

The possibility of the magnetic field of the Earth being produced by the motion of electric charges carried round in its daily rotation can, I think, be excluded. It is easy to show that an electric field of over 10^8 volt/cm. would be associated with the charges, and this is far above the dielectric strength of any rock.

Professor Blackett has recently revived the suggestion that the Earth might be spontaneously magnetised by its rotation. The only known effect of this kind is many millions of times too small, and his suggestion involves a new fundamental relation between magnetism, rotation and gravitation. There is no experimental evidence in favour of such a relation and no compelling theoretical reason for expecting it. It can only be proved or disproved by experiment. Even if the experiments were favourable we should still need a specialised mechanism, such as motions in the core, to account for the secular variation and for the details of the field.

Finally, we come to the possibility that the field is due to electric currents. This is the natural cause to suggest for a changing and complicated field, since in a fluid currents can change and their lines of flow can move. For a satisfactory theory of the Earth's field, two conditions must be met, the currents must be started and they must be maintained. For the Sun, the natural rate of decay of the currents would be so slow that it is only necessary to start them; there has not been sufficient time since the creation for them to die out.

It has occasionally been suggested that currents could be started and maintained by chemical or thermoelectric action. Such theories are well worth pursuing, but are difficult to make quantitative and no very convincing arguments have been produced in favour of them. I shall not consider them further here.

The only remaining alternative is the production of the currents by a dynamo. The mechanism I have described for the production of the non-dipole field and the secular variation is essentially a dynamo; that is, the motion of a conductor in a magnetic field produces electric currents. If this dynamo were self-exciting, the main field might also be explained.

A self-exciting dynamo is one in which a conductor moves in a magnetic field and produces currents which themselves give the necessary magnetic field. Such dynamos are well known in electrical engineering, but of course it is not possible to suppose that the interior of the Earth contains the pole pieces, coils and commutators from which such industrial dynamos are built. It is far from obvious whether a system of motions in a conducting sphere can itself constitute a self-exciting dynamo. My own belief is that it can, though no satisfactory proof has been provided. The question is a purely analytical one. Do Maxwell's equations possess solutions of the necessary kind ? Professor Cowling has proved that the process is impossible if the motion is symmetrical about an axis, and many people believe that this theorem is a foretaste of stronger theorems that will prove the process impossible in general. It is essential that this matter be put beyond doubt; uncertainty on such a point is intolerable.

A little progress can be made by considering the kind of motion to be expected from thermal convection. The essence of convection in a sphere is that the motion has a radial component. In a rotating sphere a radial motion will imply also a radial gradient of angular velocity, the rotation being faster near the centre than near the outside. This inhomogeneity in the rotation is necessary if angular momentum is to be conserved, and is analogous to the swirl often seen when water in a wash basin flows down a central waste pipe. The detailed theory of such a motion in the presence of a magnetic field has not been given, but there is reason to suppose that a series of rising and falling currents will be spaced around the equator. Such a motion, consisting of rising and falling currents not symmetrical about the axis of rotation, combined with an inhomogeneous rotation, is just of the type that would be expected to act as a dynamo, and I have good hopes of proving that it will in fact do so. The absence of such a proof is the main flaw in the theory.

If we assume that the dynamo will work, it is not difficult to find the kind of field that it will produce. It turns out that the field inside the core is unexpectedly complicated. The inhomogeneous rotation interacts with the dipole field to produce a field that spirals round and round the axis of rotation. This field is substantially stronger than the dipole field. The possible existence of such a field within the Earth, and also presumably within the Sun and stars, is one of the most important consequences of the dynamo theory. It is a new factor in astronomy and geophysics whose consequences have not yet been fully worked out. As it is confined within the conducting sphere it cannot ordinarily be directly observed. It is possible, however, that the magnetic field of a pair of sunspots is a part of this field brought temporarily to the surface by the convective motion of the material of the Sun. It may be that the Sun can give more direct evidence for the mechanism by which fields are produced than can the Earth, since the motions at the surface of the Sun can be observed whilst those in the core of the Earth can not.

The real difficulty in studying the origin of terrestrial and solar magnetism is the impossibility of direct observation and experiment within the Earth and the Sun. The only approach is to examine all theories in numerical detail and to hope that those that are incorrect will break down at some point and that one will be found that satisfactorily unifies the very complex facts.