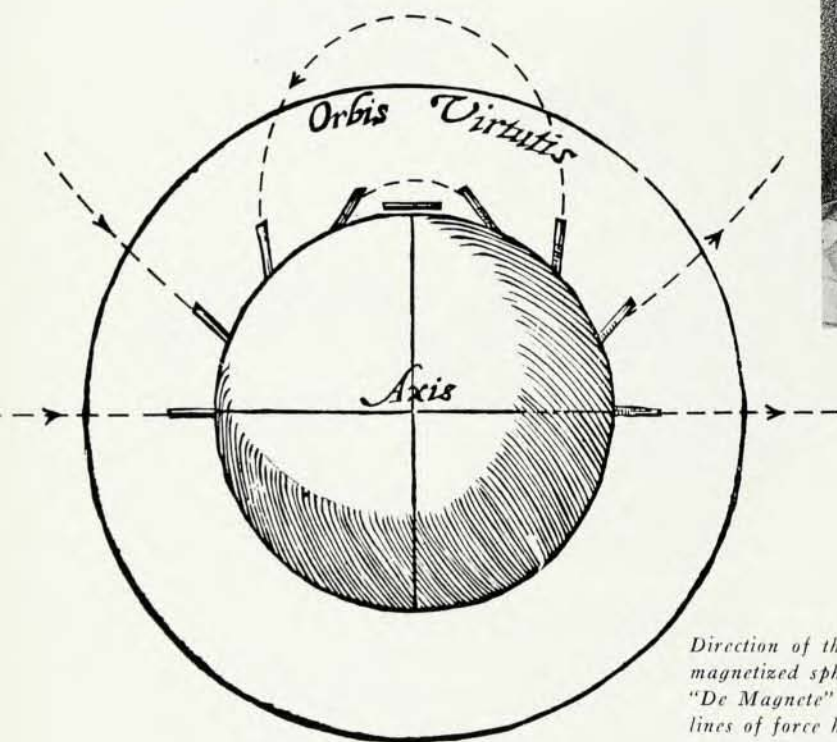


A controversial discussion of the origin of the earth's magnetic field by an English geophysicist.

TERRESTRIAL MAGNETISM

by E. C. Bullard



William Gilbert, 1544-1603
The Bettmann Archive

Direction of the magnetic field of a uniformly magnetized sphere from William Gilbert's "De Magnete" (published 1600). The lines of force have been added.

It has been known for many hundreds of years that a suitably suspended bar magnet will turn itself so that its axis lies roughly in a north-south direction. This unexpected and useful property early attracted the attention of navigators and was among the first subjects to be studied after the rebirth of science in Europe in the fifteenth and sixteenth centuries. These studies culminated in the work of William Gilbert, Queen Elizabeth's physician, who

wrote in 1600, "Magnus magnes ipse est globus terrestris," the earth itself is a great magnet.

Gilbert found that the forces on a compass needle

E. C. Bullard, British geophysicist who has recently been named to succeed Sir Charles Darwin as director of the National Physical Laboratory, is at present professor of physics and head of the physics department at the University of Toronto. Until 1948 he was head of the department of geodesy and geophysics at Cambridge. During the war he was associated with the Admiralty, being occupied first with the degaussing of ships against the magnetic mine, and later with anti-submarine problems.

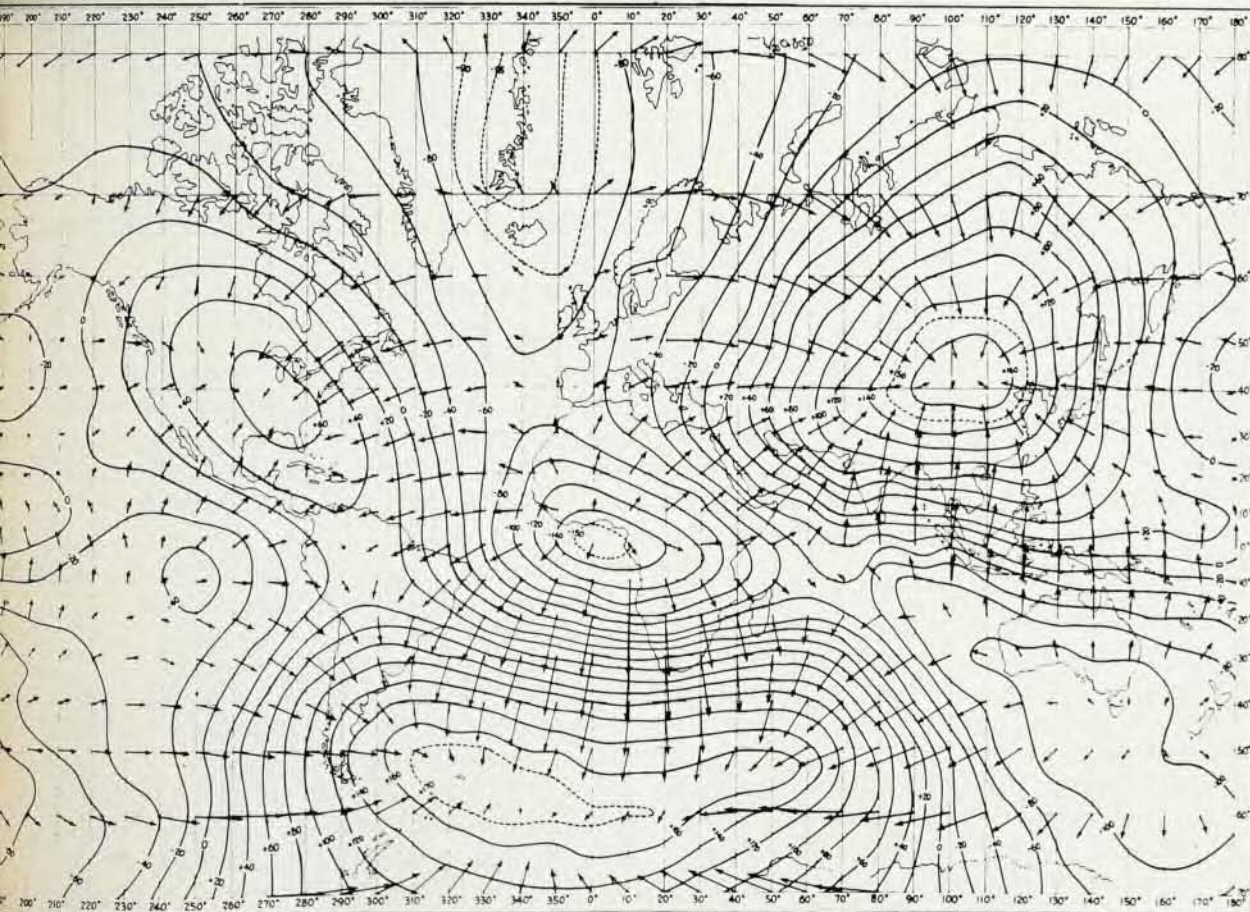
or a dip needle are the same as would be experienced if the earth were a great magnet. This suggests that the explanation for the earth's magnetic field is to be sought within the body of the earth rather than in the air or in the stars. All later work has confirmed Gilbert's conclusion. Apart from small fluctuations such as the daily variation and magnetic storms, the whole magnetic field of the earth is of internal origin. This was proved formally by Gauss in 1839.

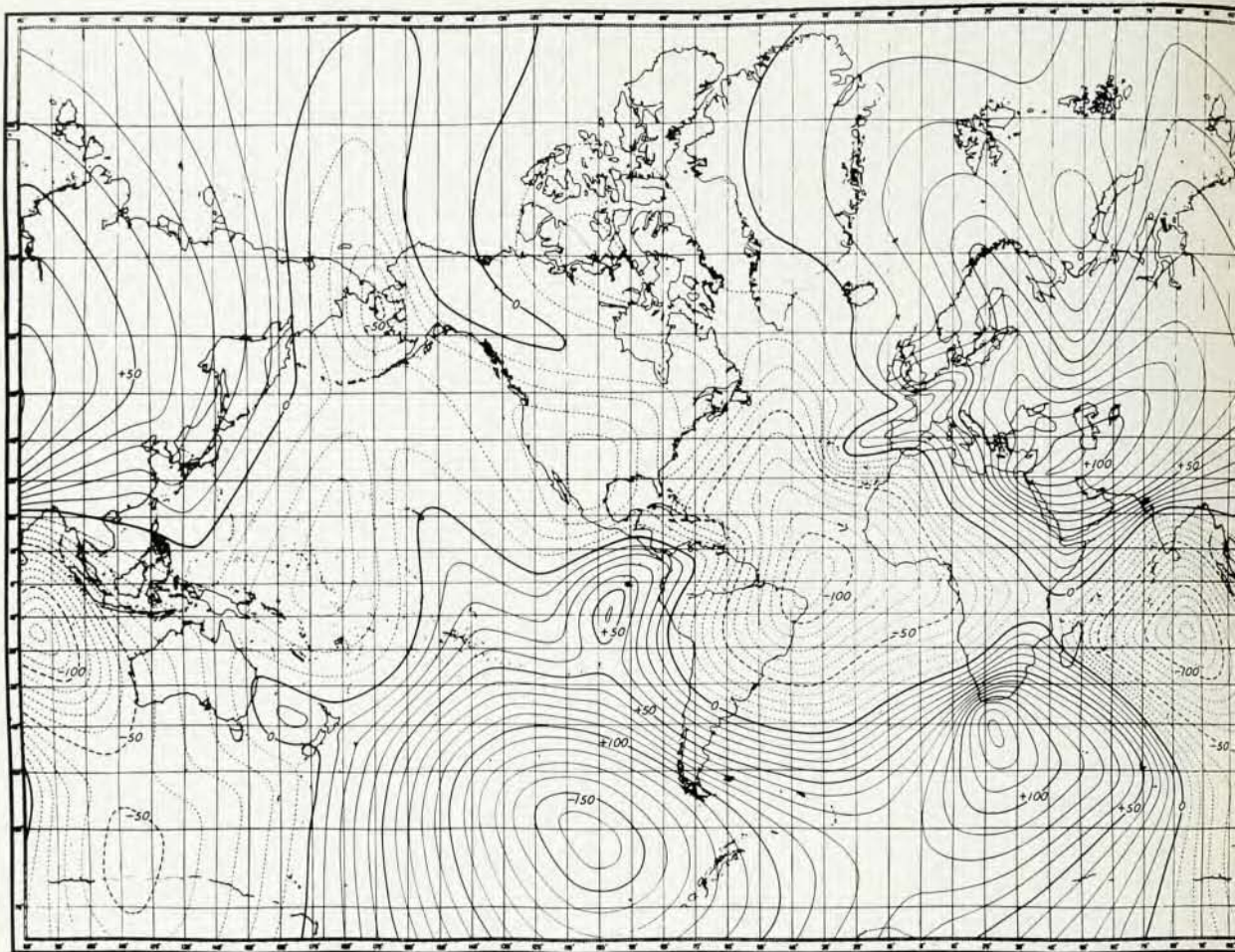
The magnet to which Gilbert compared the earth was a sphere cut from a lodestone, a naturally occurring magnet composed of the mineral, magnetite. His lodestone was a close approximation to a uniformly magnetized sphere, and its field did in fact represent the earth's field within about twenty percent. It is remarkable that Gilbert obtained his results two hundred years before the development of a formal theory of magnetism, and without knowledge of the inverse-square law, or of field

strength, dipole moment, magnetic potential, or the other abstractions that now flow so easily from the pens of examination candidates. His methods were simple: he made a sphere of lodestone and placed upon it little pieces of iron each "about the size of a barleycorn." He found that these lay in the same way as did a freely suspended magnet placed at the corresponding point on the earth. To the figure from his book, reproduced here, are added the lines of force of the field of a uniformly magnetized sphere; the agreement with the directions shown by Gilbert is remarkable.

The earth's field is roughly that of a uniformly magnetized sphere, a very simple result. When, however, we look more closely and inquire how the earth's field differs from this ideal field all simplicity is lost. There is a bewildering and apparently aimless complexity, rather comparable to that of a meteorological chart. I shall attempt to show later that the resemblance may not be merely fanciful.

Departure of earth's magnetic field in 1945 from that of uniformly magnetized sphere. Arrows show horizontal component and contours the vertical component. The fields are in units of a milligauss.





Rate of change of the vertical component of the earth's magnetic field in 1942 in one-hundredth of a milligauss per year.

Early in the seventeenth century it was noticed that the compass does not always point in the same direction, but shows a slow drift continuing for many years before reversing. This change, called the secular variation, is a complex phenomenon. The magnitude of the field at a given place may rise and fall by as much as thirty percent and the direction may swing as much as twenty degrees on either side of the mean direction. The rate of change varies from place to place and the changes at a given place are often irregular; it is therefore not possible to specify a precise period. The change however normally proceeds in one direction for about a hundred years.

The illustrations showing how the magnetic field of the earth differs from the field of a uniformly magnetized sphere, and the rate at which the field is changing, must be thought of as stills from a mov-

ing picture. As time goes on the lines of both figures move like the isobars on a weather map, only much more slowly, the change in one hundred years being comparable to those occurring in a week on the weather map. All these changes can be shown, by the methods of Gauss, to have their origin within the earth.

Possible Causes

Let us leave the complexities and seek an explanation for the main part of the field, the part resembling that of a uniformly magnetized sphere. If we can find this the rest is not difficult.

The field outside the earth is *like* that of a uniformly magnetized sphere, but it does not follow that the earth *is* a uniformly magnetized sphere. In fact, there are many ways of arranging magnets

inside a sphere to give a specified field outside it. In particular, a dipole placed at the center of the sphere will give an external field like that due to uniform magnetization, which is therefore often called a dipole field. The various arrangements can only be distinguished if we have measurements of the field inside the sphere, which we do not have for the earth.

In the absence of measurements of the field within the earth, the evidence for any theory of the origin of terrestrial magnetism is indirect. To be acceptable a theory must be consistent with the laws of physics and with the structure of the earth deduced from seismology and other branches of geophysics. But even if a theory does not formally conflict with what is known about the earth it is unlikely to be accepted, and is indeed unlikely to be correct, if it makes improbable assumptions about the state of affairs deep in the earth. It may, for example, be impractical to prove that the earth does not contain coils of copper wire; but even so it is unprofitable to assume that it does. One must refrain from outlandish assumptions even though they are not directly rejected by experience. Further, a satisfactory theory must be flexible enough to account for the departures from an exact dipole field and for the secular variation. It is also desirable, though perhaps not essential, that a theory of the earth's field should apply to the sun and stars. It should also explain why the magnetic poles of the earth lie as near as they do to the geographical poles.

Origin of Magnetic Fields

A magnetic field may be produced by permanent magnetization, by the motion of charges, by rotation, or by electric currents, and theories of the origin of the earth's field have been based on each of these.

The earth consists of a central liquid core with a radius of about three thousand four hundred kilometers surrounded by an outer solid shell of silicates. It is usually supposed that the core is composed of molten iron. It seems impossible that this core can be permanently magnetized, for only ferromagnetic bodies can be magnetized permanently, and no ferromagnetic liquids are known. If a ferromagnetic liquid existed, relative motion of its parts would introduce a disorder which would progressively reduce the magnetization of the whole. It is difficult to believe that a liquid could remain sufficiently im-

mobile throughout geological time for a magnetic field of the extent of the earth's to have persisted; in fact, as will be shown later, there are strong reasons for supposing motion to occur.

The silicate shell is probably composed of basic rocks and is usually supposed to consist largely of olivine. Such materials owe what small magnetization they have to the presence of magnetite, which loses its ferromagnetic properties at temperatures above five hundred and eighty degrees centigrade.

Thus if an explanation of the earth's magnetic field is to be based on ferromagnetism either the temperature of a large part of the earth must be below five hundred and eighty degrees or the temperature at which magnetite becomes nonmagnetic must be raised by pressure, or some other material must become ferromagnetic at high pressures.

None of these assumptions has any justification in theory or observation, and even if one of them were correct the theory could not be used to explain the magnetization of the sun or stars and could not account for the earth's magnetic poles being near its geographical poles.

The idea that the earth's field is due to permanent magnetization is thus not attractive, and there is no evidence to support it. It can not, however, be said to have been definitely disproved.

As to the second possibility, magnetization by the motion of charges, if the earth contained a distribution of negative charge in its outer parts and an equal positive charge deep in its interior a magnetic field would be produced by the motion of the charges as the earth turns in its daily motion. Charges sufficient to produce the observed magnetic field would give electric fields of about one hundred million volts per centimeter in the interior of the earth. Such electric fields are far beyond what can be sustained by any known substance, and are fatal to any theory of this type.

Appreciable magnetization by rotation also seems improbable. It is known from theory and from experiment that any body will become magnetized if it is rotated. This magnetization is due to an orientation of the elementary atomic magnets analogous to the orientation of a gyro compass caused by the rotation of the earth. For the earth this effect gives a field in the right direction but ten thousand million times less than that observed.

While this known magnetization by rotation can play no appreciable part in the production of the

earth's field, it has been suggested that there may be another connection between rotation and magnetization. This relates magnetic moment to angular momentum, the constant of proportionality containing the Newtonian constant of gravitation. This expression can be made to give approximately the right magnetic moment for the earth. P. M. S. Blackett has recently pointed out that it also gives correctly the magnetic field of the sun and of certain stars and has urged that this may be more than a numerical coincidence, and may represent a new relation between mechanics, gravitation, and magnetism.

It is essential to such a theory that matter in rotation should be magnetized, but that matter moving in a straight line should not. No self-consistent way of describing this has yet been devised. The theory seems also to violate the principles of the special theory of relativity, but this is perhaps to be expected of a connection between gravity and magnetism, which must rest on some unified field theory lying deeper than the special theory of relativity.

On the whole the theory appears to lack experimental support and to raise very serious theoretical difficulties. The numerical agreement obtained with the fields of the earth, sun, and stars is suggestive, but hardly conclusive. Such a theory could only be established by compelling experimental evidence. The most convincing proof would be experimental verification in the laboratory of magnetization by rotation. An experiment to test this is on the border line of practicability. Secondly, the predictions of the theory as to the field within the earth might be verified. If the cause of the field lies deep within the earth, all its components will depend on the inverse cube of the distance from the center, and all will increase with depth near the surface. Blackett's theory suggests that the cause of the field is distributed through the whole bulk of the earth so that on descending a mine part of the cause will lie above us. This is easily shown to lead to a decrease of the horizontal field with depth. A distinction between distributed and core theories can therefore be obtained by measuring the horizontal component of the magnetic field underground in mines or bores. The results so far obtained are inconclusive because the field increases in some places and decreases in others. These differences are presumably due to local disturbances caused by magnetic rocks beneath the mines in which the measurements were made.

The Earth as a Dynamo

The most likely origin of the earth's field appears to be electric currents which circulate within the earth. The easiest path for such currents lies in the core, which is probably metallic, and our problem would be solved if we could find a way of maintaining them.

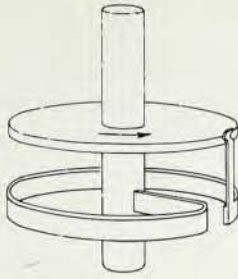
The currents in the core required to maintain the earth's field are of the order of five thousand million amperes, which gives a current density of about a fiftieth of a microampere per square centimeter and would imply an electric field of 5×10^{-12} volts per centimeter assuming a reasonable value for the electrical resistance of molten iron. The electric field integrated around the periphery of the core would give about one hundredth of a volt. There is, therefore, no obvious absurdity of the kind encountered in discussing the possible production of the magnetic field by moving charges.

Electric currents may be produced by chemical action (as in a battery), by the thermo-electric effect, or by electromagnetic induction in a conductor moving in a magnetic field.

No one has succeeded in basing a plausible theory of the earth's field on either of the first two of these, and they will not be further considered here. The third, however, appears to provide a most promising approach to the problem.

In essence the theory suggests that the earth contains a dynamo which produces the currents that maintain the field. This dynamo must be self-exciting, that is it must itself generate the magnetic field required to produce the currents. Motions are supposed to take place in the earth's core which cause the conducting material of the core to cross the lines of force of the magnetic field and thus to produce an electromotive force and a system of electric currents. These currents are supposed to maintain the field.

Such systems are occasionally used in electrical engineering where they are called homopolar dynamos. The simplest is shown in the illustration. It consists of a disc of copper driven by an axle. A coil, drawn as a single turn, runs from the rim to the axle and makes rubbing contact with the edge of the disc and with the axle. If the disc is rotated in a region where there is no magnetic field, no current is produced. This state is, however, magnetically unstable. If a small field is present, and its lines

Homopolar dynamo

of force cross the disc, an electromotive force is produced between the axle and the rim and a current flows in the coil which completes the electrical circuit. If the direction of rotation is correct, the field produced by this current will re-enforce the initial field. If the rotation is sufficiently rapid, the current and the field will then grow till the energy dissipated as heat equals that supplied to the shaft driving the disc. This process continues even if the original exciting field is removed. All that is required is a small initial field to start the process in the same way that a small, transitory, mechanical impulse will start a large movement in an unstable mechanical system such as a pin balanced on its point.

It would be absurd to suppose the mechanism of the illustration to exist inside the earth, but it is not absurd to inquire whether a process of the same kind may not occur if the material of the earth's core or of a star is in motion. Sir Joseph Larmor suggested in 1917 that it is possible to have a motion in a sphere of conducting fluid that causes it to act as a dynamo. Larmor never pursued his suggestion, but in recent years Elsasser in the United States, Frenkel in Russia, and the present writer have argued that it is possible. The arguments are not conclusive and it is of great importance that, apart from all special models, the possibility or impossibility of dynamos of this kind should be put beyond doubt.

Motions in the Core

There has been some speculation on the causes of the hypothetical motions in the core of the earth required by the dynamo. Only four causes have been seriously suggested, the gradual slowing of the earth, tidal forces due to the sun and moon, precession, and thermal convection. The writer believes that the first two are inadequate, though Professor

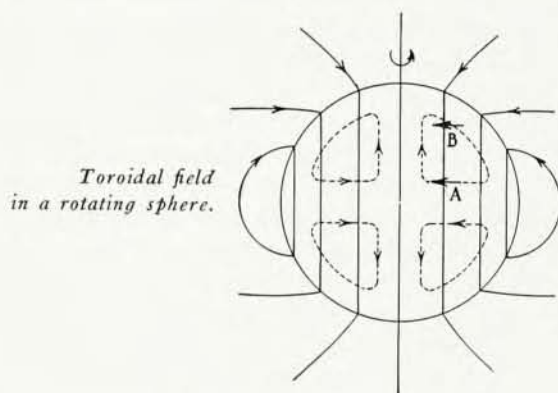
Elsasser does not agree and has argued for a dynamo driven by tides in the core.

A theorem due to Poincaré is usually supposed to show that as the earth precesses the core moves with it like a rigid body. If this is so, precession will produce no relative motion of parts of the core and can drive no dynamo. There is however some doubt if the theorem is applicable to the earth, and it is possible that the interior of the core may not partake in the full precessional motion of the outer parts of the earth. Until the theory has been further elaborated it is useless to discuss the consequences, but it is not impossible that we have here the elements of a dynamo.

Thermal convection, the movement within a liquid arising from temperature differences, appears another possible source of motion in the core. If it is to occur heat must be generated in the core and this heat must escape outwards. Our knowledge of the thermal state of the core is extremely vague, its temperature, its thermal conductivity, and the differences in temperature necessary to start convection being all uncertain by a factor of at least three. In addition we have no idea of the amount of radioactive material that it contains, and thus no idea how much heat is generated. The orders of magnitude do not, however, seem unreasonable. It is likely that a heat generation of a few percent of that occurring in rocks near the surface of the earth would suffice to maintain a convective motion.

The nature of this motion has not been investigated but, by analogy with convection in a flat dish of liquid, it may be expected that the motion on a nonrotating globe would consist of a moderate number of rising and falling currents arranged in a regular way over the surface. If the sphere rotates, a falling current will carry angular momentum towards the center and accelerate the rotation there. Such an acceleration is well seen when the slowly rotating water in a wash basin runs down a central drain. Near the outside of the core there will be a corresponding deceleration. Thermal instability therefore causes two kinds of motion, one with upward and downward streaming, and the other a differential rotation, faster near the center and slower near the outside. A motion of this kind with two upward and two downward currents spaced round the equator has been investigated in some detail and seems likely, though not certain, to be able to act as a dynamo.

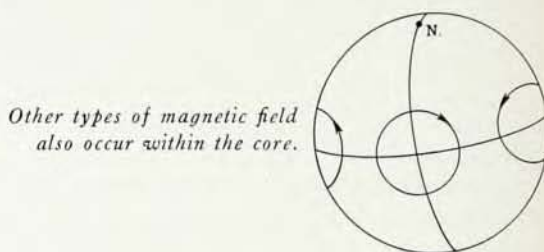
This dynamo produces a field outside the earth that closely resembles a dipole field. Inside the core the field is more complicated. These complications are largely due to the differential rotation discussed above. The effect of this can be seen from the illustration which shows a dipole field outside the core continued through the interior as if it were uniformly magnetized. As the sphere rotates, an electromotive force will be produced as shown at A and B. If the core rotates like a rigid body the electromotive forces at A and B will be equal and no current will flow. If, however, the interior of the core rotates more rapidly than the outside, the electromotive force at A will be greater than that at B and electric currents will flow around the paths shown by dotted lines. These currents will produce a magnetic field running inside the core along circles of latitude from west to east in the northern hemisphere and from east to west in the southern.



This field is at right angles to the inducing field and in no way interferes with it; the induced field is therefore proportional to the relative velocity of the parts of the core and may greatly exceed the dipole field. Calculation shows that a relative velocity of a millimeter a second can produce a field exceeding thirty gauss. This field, which is called the toroidal field, is an essential feature of any dynamo theory. It is entirely confined to the interior of the core and can not be detected by observations at the surface of the earth. So strong a field produces mechanical forces on the material of the core which greatly exceed those due to viscosity, and there is little doubt that it must play a major part in the dynamics of the core and of the outer parts of the sun and stars.

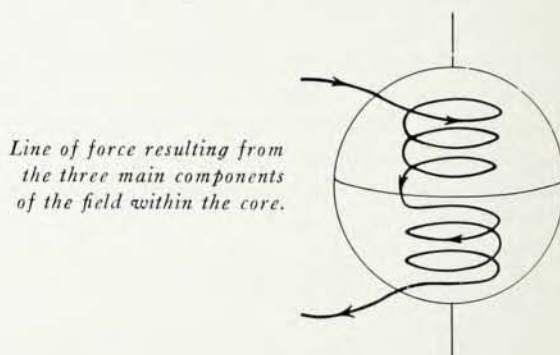
A discussion of particular motions shows that

other types of magnetic field also occur within the core. For the simplest model the most important of these is a field having closed lines of force running in circles symmetrical about the equator. Thus the



field in the core has three main components, one roughly like that of a uniformly magnetized sphere, the east-west toroidal field, and the field last mentioned. When these are put together a line of force will appear somewhat as illustrated. Outside the core we have a dipole field, inside the core each line of force circles the axis a few times from west to east; it then crosses the equator, circles the axis a few times from east to west, and emerges as a part of the dipole field in the southern hemisphere.

Much remains to be done on the thermo-, hydro-, and electrodynamics of these processes, and it is possible that the whole structure is illusory and can not maintain a field. Even if this were so and the field were really maintained by some other mechanism, it is likely that many parts of the scheme would survive, and that the toroidal field at any rate will form a permanent feature of geo- and astrophysics.



Departures from a Dipole Field

If we can find a theory of the dipole field it is not difficult to explain the departures from that field and the secular variation. All that is necessary

is to assume small eddies near the surface of the core which wax and wane in about a hundred years. These will interact with the magnetic field to produce electric currents which will themselves produce a further magnetic field at the surface of the earth. Such a process produces a field that varies only slowly from place to place, retains the same sign over some thousands of miles, and is thus very suitable for the explanation of fields like those shown earlier which illustrated how the earth's field differs from that of a uniformly magnetized sphere and how it changes with time. Anomalies of a more local nature are due to magnetic material in the crust.

If the facts are to be explained in this way it is necessary that the field within the core should be large enough to induce sufficient current in the eddies to give the observed irregularities of field at the surface. It is an advantage of the dynamo theory of the origin of the main field that it does provide a strong field in the core. A theory which did not provide something resembling our toroidal field would have difficulty in using this simple and natural explanation of the secular variation.

The fields produced by a number of simple convection systems should be investigated to see if they are capable of inducing the required currents in reasonably placed eddies. This has not been done, but it seems that the dynamo theory possesses the right sort of complexity. The illustrations which show the variations in the earth's field resemble weather charts and it is thus natural that their explanation should depend on motions of a fluid. They demand a cause of the same order of complexity as does the

weather, but with a more leisurely tempo. This the dynamo theory provides.

The Sun and Stars

The material of the sun is believed to have an electrical conductivity about the same as that assumed above for the core of the earth; it is known to be in violent motion and to have a rate of rotation that varies radially and with latitude. All the ingredients of our dynamo are therefore present on a grander scale than on earth. A field larger than the terrestrial one would therefore be expected. In fact the sun is believed to have a general magnetic field about a hundred times as strong as that at the surface of the earth, though this is not certain. Sunspots have a field a hundred times stronger still. The field of a sunspot may perhaps be a part of the toroidal field brought to the surface by material rising along the axis of the spot.

There is a wide and almost untitled field in the explanation of the complex magnetic changes seen on the sun in the light of the theory outlined above. We cannot see the core of the earth, but we can see the sun; we can measure the magnetic field on the earth with an accuracy of one hundredth of a milli-gauss, but that on the sun is uncertain by a million times as much. Thus the students of terrestrial and solar magnetism have each their own difficulties. At last it seems possible that their subjects may be unified in a synthesis in which each will supply part of the picture of a process common to the earth, the sun, and the stars.



Magnetizing iron by forging it in a position parallel to the magnetic meridian. From Gilbert's "De Magnete."