MAGNETIC PROPERTIES OF THE EARTH'S INTERIOR

THE renewed interest in attempts to explain just why the earth has a magnetic field, and the feeling of optimism that at last this long-standing riddle of geophysics may soon be solved, were reflected in the contributions to the discussion on the magnetic properties of the earth's interior held on September 4 by Section A (Mathematics and Physics) of the British Association at its Liverpool meeting.

The discussion was opened by Sir Edward Bullard (National Physical Laboratory, Teddington), whose recent contributions to the dynamo theories of the main field and of its secular variation have been mainly responsible for the great revival of interest in this problem. In a most illuminating and entertaining introduction, Sir Edward reminded his audience of some of the important features of the field that call for explanation. The fact that the field resembles that of a uniformly magnetized sphere —that is, a dipole field—was established as early as 1600 by William Gilbert. During the past hundred and twenty years, however, the magnetic moment of this dipole field has decreased by as much as 4·5 per cent, a very remarkable rate of change for any planetary phenomenon. If this were to continue, there would soon be no field left to investigate! "However, I am happy to announce," continued Sir Edward, "that this contingency will probably be avoided, since there is now evidence that the moment reached a minimum about 1935, and appears now to be increasing again."

When the main dipole field is removed, the residual field is one of considerable complexity. A chart of this field is not unlike a meteorological chart in appearance. The resemblance is even closer when one remembers that both charts will change with time, the secular changes in the geomagnetic field during, say, a century being of the same order as those occurring on a weather map during a week. The comparison is perhaps not entirely fanciful and tends to suggest that the geomagnetic phenomena may originate, like the weather changes, from causes associated with fluid motions. Another specially significant feature of the geomagnetic field is the observed westward drift by about 0·2° longitude a year of the general pattern of the secular variation field, this drift being superposed on the general waxing and waning of the individual foci of change.

Sir Edward then reviewed the many and varied explanations, including some that he frankly labelled "magic", which have been put forward to account for the existence of the magnetic field. In view, however, of the features already mentioned and having regard to the reasonable assumptions we can make about the properties of the earth's interior, the only kind of explanation likely to be satisfactory is one which involves the production and maintenance of electric currents flowing mainly in the liquid core. The radius of this core is known with considerable exactness from seismological studies, and there are good reasons for believing that it has a metallic conductivity. The electric currents might be produced by chemical action, or by thermoelectric or dynamo effects. No precise mechanism involving chemical effects appears to have been considered, but mechanisms involving thermoelectric and dynamo effects have both been discussed in some detail.

The possible existence and effectiveness of thermoelectric couples at the interface between the metallic core and the silicate mantle have been considered by Dr. S. K. Runcorn at Cambridge, who has suggested that, if temperature differences caused by heat convection exist on the surface of the core, electric currents will be set up flowing partly in the core and partly in the mantle. Since the thermoelectric e.m.f.'s are radial, the resulting magnetic field would not be the dipole field actually observed, but further interactions with fluid motions in the conducting core could lead to this field. Sir Edward considered, however, that the temperature differences on the surface of the core which are required in this theory are so great that they would imply an unlikely large heat convection within the core.

In the dynamo theory, as developed mainly by Prof. W. M. Elsasser in the United States and by Sir Edward in Great Britain, the electric currents are generated through electromagnetic induction by the interaction of fluid motions in the core with the internal magnetic field of the currents themselves, the whole system forming a self-exciting dynamo which obtains its energy from the heat generated by radioactive material in the core. A heat generation of a few per cent of that occurring in surface rocks would suffice to maintain a convective motion with material rising at some places and sinking at others. The radial component of this convective motion will be affected by the earth's rotation and will lead to a radial gradient of angular velocity of the fluid, the outer part of the core rotating more slowly than the inner part. Since a highly conducting fluid will tend to carry any magnetic field along with it, this retardation of the outer part of the core may be the cause of the westerly drift of the secular variation field. The convective streaming in the fluid core together with the differential rotation might, in the presence of some small initial magnetic field, build up and maintain the field at some definite level; in other words, the core would behave as a self-exciting dynamo. To prove rigorously that this is possible, it is necessary to show that Maxwell's equations for a moving fluid possess solutions of the necessary type. This analytical problem has been studied by Sir Edward, and he believes that it will be feasible to establish the possible existence of such a dynamo. The analysis is, however, extremely complex, as the large gathering fully appreciated when some of the equations involved were shown on the screen.

Prof. A. T. Price (University College, Exeter) then described how the study of short-period fluctuations of the geomagnetic field can yield information about the distribution of electrical conductivity within the earth. Though this information is rather limited, due account must be taken of it when seeking to explain some of the features of the geomagnetic field, especially the secular variation. Several types of fluctuation have been studied; but most work has been done on the daily variations and the storm-time variations. Both these are primarily of external origin, being due to varying electric currents in the ionosphere; but these ionospheric currents induce other currents within the earth, and a comparison of the magnetic fields of the inducing and induced currents can tell us something about the electrical conductivity of the region where the induced currents flow.

The calculations which have so far been made indicate a considerable rise of conductivity with increasing depth within the earth, from about 10^{-16} e.m.u. or less for dry surface rocks to a value of at least 10^{-11} e.m.u. at about 900 km. depth. No direct information about greater depths can be obtained from the magnetic variations, because the corresponding induced currents do not penetrate appreciably farther than this. If, however, the observed rise of conductivity can be accounted for on some reasonable hypothesis based on known physical laws, it may be possible to extrapolate the results to greater depths with some degree of confidence, and this has in fact been done. A very reasonable supposition is that the increase of conductivity is associated with the increase of temperature as one goes downwards in the earth. The material of the earth's mantle is probably some form of olivine, and is in any event almost certainly a semi-conductor, in which the conductivity σ at high temperatures will be a function of the temperature T of the form $\sigma = \sigma_0 \exp(-A/kT)$. The coefficients σ_0 and A may depend somewhat on pressure and temperature ; but the important changes in σ will be due to the exponential factor.

Laboratory measurements of the conductivity of various olivines at temperatures up to 1,500° C. have recently been made by H. Hughes at Cambridge, following some earlier work done there by H. P. Coster. These experiments reveal a very great increase of σ with temperature, and it appears that most of the materials examined behave like ionic semi-conductors at sufficiently high temperatures. From his results Hughes has determined the relevant values of σ_0 and A. He has also obtained corresponding values of these coefficients for the earth's mantle by comparing the distribution of conductivity, as derived from the geomagnetic data, with recent estimates of the distribution of temperature within the earth. The values he obtains, $\sigma_0 = 2 \times 10^{-3}$ e.m.u. and $A = 3 \cdot 5$ eV., are of the same orders of magnitude as those derived from his laboratory studies. He has therefore used the above formula to extrapolate for σ throughout the mantle, and thus obtains an estimated value of about 3×10^{-8} e.m.u. near the base where it meets the liquid core. This is somewhat higher than earlier estimates. One consequence of a higher conductivity of the mantle would be a tighter electromagnetic coupling between the mantle and the core, and this seems likely to remove one of the difficulties which appeared hitherto in the explanation put forward by Vestine, and by Munk and Revelle, to account for certain sporadic variations in the length of the day, which appear to be associated with variations in the rate of westward drift of the secular variation field.

Another important aspect of the geomagnetic field was discussed by Mr. J. Hospers (University of Cambridge), who described geological evidence which indicates the occurrence of repeated reversals of the main field. He gave an account of work recently done on the natural permanent magnetization of lava flows and sediments found in Iceland. The historic flows of Mt. Hekla, 1766–1948, are magnetized approximately in the direction of the present local geomagnetic field, and their magnetism has undoubtedly been acquired through cooling in the existing field. For the post-glacial lava flows, about 2,000–6,000 years old, the angle of mean direction of magnetism with that of the present field is 7·5°, and with that of the dipole field is 2·5°. This suggests that over a period of some thousands of years the magnetic pole has been centred on the geographic pole. Early Quaternary flows show, however, a reverse magnetization, and Tertiary flows show alternating series of normal and reverse magnetizations. T. Nagata, in Japan, has shown that certain specimens of pumice from Mt. Haruna can acquire a reverse magnetization on cooling in a magnetic field ; but no similar effects have been found for any of the Icelandic lavas. The observations, therefore, indicate that repeated reversals of the local magnetic field have taken place ; moreover, since the changes have all corresponded to the field swinging right through 180° without intermediate directions being in evidence, it seems probable that the reversals of the field are in fact world-wide. This implies that the main geomagnetic field can reverse its direction every 2×10^5–5×10^5 years, and that this has been happening at least since Miocene times—that is, for the past 20×10^6 years.

The mean direction of magnetization of the Tertiary flows is very close to the direction of the present dipole field. This suggests that, unless the magnetic axis has departed appreciably from the rotation axis, which seems unlikely from the foregoing evidence, there have been no appreciable changes in latitude or orientation of Iceland during the past 20×10^6 years. Some further work on Eocene flows in Northern Ireland, which are about 50×10^6 years old, indicate that, if any polar wandering occurred during Tertiary times, it was much less than has sometimes been supposed.

In the final paper to the symposium, Dr. F. J. Lowes (University of Liverpool) discussed the possibility of attributing the earth's magnetic field to currents produced by thermoelectric effects at the interface between the core and mantle, and examined the implications of this hypothesis. The existence of a considerable voltage distribution is required on the surface of the core, and this in turn requires considerable temperature differences, which are assumed to be produced by the convective motions within the core. The resulting currents would, however, flow in the mantle as well as in the core, in contrast with the situation in the dynamo theory, where the most intense currents flow well within the core. There is, moreover, a difficulty in the dynamo theory in that the changing currents which give rise to the secular variation must flow, owing to the skin effect, within 10–100 km. of the surface of the core, whereas the liquid eddies required to produce these currents would have radii of about 500 km. In the thermoelectric theory this difficulty is avoided because changes in the voltage distribution would directly affect the currents flowing in the mantle, and lead to the observed changes in the magnetic field. The thermo-electric theory also seems to fit in better with recent explanations given for sporadic changes in the length of the day. These are thought to be due to transfers of momentum between mantle and core, the necessary torques being of electromagnetic origin. This requires magnetic fields of order 10–100 gauss in the lower part of the mantle, a condition which is probably more easily met in the thermoelectric than in the dynamo theory. It must, however, be admitted that the difficulty of providing sufficiently effective thermoelectric forces at the core–mantle boundary still remains.

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