THE SECULAR CHANGE IN THE EARTH'S MAGNETIC FIELD

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Summary

The hypothesis that the secular change in the magnetic field of the Earth is due to electric currents induced in the material of the core by its movement through the general magnetic field of the Earth is examined. Detailed calculations are made for the focus of rapid change in South Africa. It is shown that many of the observed facts can be accounted for by a circular motion with a diameter of a few hundred kilometres situated near the surface of the core. To get numerical agreement the field at the core has to be assumed larger than seems probable. The magnetic axis of the eddy is approximately horizontal and points N. 45° W.

1. *Introduction.*—If any element of the Earth's magnetic field is observed for a few years it is found that the fluctuations of short period are superposed on a gradual change which sometimes continues in one direction for a hundred years or more. A comparison of the spherical harmonic analysis of the horizontal and vertical fields shows that both the main field and its secular change have an origin within the Earth. The total change in the field can be large, for example the horizontal force at Cape Town has decreased by 48 per cent of its present value during the last hundred years. The secular change is distinguished from all other geophysical phenomena of internal origin by its time-scale. The processes of geology take time measured in millions rather than tens of years, and this difference is the central difficulty in the explanation of the secular change. The outer 3000 km. of the Earth is known from seismology, from the bodily tides and from the variation of latitude to be a rigid solid for forces with periods of a year or less. Thus whatever may be its properties for forces exerted for millions of years, it is quite impossible that the change in the magnetic field is due to a motion of matter in the outer parts of the Earth. It is equally impossible that it is due to changes in temperature, for the time-scale for such processes over a volume with a diameter of a few hundred kilometres is measured in hundreds of millions of years. Equally, chemical changes and changes of phase can be rejected, as they would involve changes in volume and movements of the surface that could not pass unnoticed. The complete lack of any relation between the secular change and any topographic or geological feature also speaks against a superficial origin.

We are thus driven to seek an origin for the change of field in the core of the Earth. The material of the core is known from seismology to be liquid, and from its density it may well be a molten metal. It has been plausibly suggested that it may be an alloy of nickel and iron of a composition similar to that of meteorites. If this is so, it may be subject to turbulent currents due to thermal convection or to the shearing forces associated with the secular deceleration of the Earth. Such motions would cause the conducting material of the core to move across the Earth's magnetic field and would produce electric currents. These electric currents would produce a further magnetic field, and it is the purpose of this paper to consider the hypothesis that the changes in this field constitute the secular change. We do not consider the origin of the main field itself, but merely use the observed fact of its existence as part of the mechanism required to produce the secular change.

Various writers from Halley * onwards have considered the possible connection between motions in the interior of the Earth and geomagnetism. Most of these have attempted explanations of the main field and have discussed the secular variation as an incidental complication. The object of the present paper is more modest; it is to determine whether the observed facts of the secular variation are consistent with an origin in the core and to examine a particular hypothesis in an elementary way.

2. *The Secular Change in South Africa.*—It has long been known that the secular change is a comparatively local phenomenon. That is to say, it does not proceed in a systematic way all over the Earth but changes from one area to another. There exist regions a few thousand kilometres in diameter in which the field changes more rapidly than elsewhere. The rate of change in these regions waxes and wanes, and the regions appear and disappear in a way that is at present imperfectly known. The relatively restricted area in which the changes take place is one of the principal difficulties in finding an explanation, and suggests a limit to the possible depth of the cause. If any theory which places the cause in the core is to succeed, it must be shown that a cause in the core can account for the scale of the phenomena in space.

One of the most striking changes in the field in recent years has occurred in South Africa, and we take this as an example. Fig. 1 shows the vectors representing the annual change in horizontal field at 1922.5. The change in vertical field is also indicated. It is constructed from data given in tables 25, 29 and 33 of the monumental report by Vestine and others †, in which all the information from magnetic measurements is reduced to give a coherent picture of the secular change. The values for 1922.5 have been chosen, as the secular variation is probably better known at that date than at an earlier or later period. It is at once apparent that in the area of most rapid change the horizontal vectors are roughly parallel and point to the south-east. The vertical component is directed upwards in the north-west part of the area and downwards in the south-east. This field suggests that it is due to a horizontal dipole with its north pole towards the north-west. We therefore try whether a dipole 400 km. below the surface of the core in lat. 25° S., long. 20° E. will give any resemblance to the vectors representing the observed annual change in field. In particular we wish to discover whether such a dipole is or is not too deep to explain the field, for if a dipole gives too wide a distribution at the surface of the Earth it is unlikely that any acceptable distribution can be found in the core. The relations are best shown by a section along the line from 5° S., 0° E. to 45° S., 40° E. This line is marked on Fig. 1. Fig. 2 gives the section. It is clear that the dipole gives a good representation of the field if its moment is chosen to give agreement at the point immediately above it.

The main difference between the observed and the calculated fields is that the latter is too steeply inclined at the more distant points. It may be shown that such a discrepancy can be removed by substituting a distribution extended in a horizontal direction for the point dipole. A small latitude of this kind is obviously desirable, as the actual currents are unlikely to be exactly equivalent to a point

* E. Halley, *Phil. Trans.*, No. 195, 563–578, 1692. W. M. Elsasser, *Phys. Rev.*, **69**, 106–116, 1946; and **70**, 202–212, 1946, the argument in these papers, which the author did not see till the present work was complete, is in many points similar to that of the present paper. S. Chapman, *Terr. Mag.*, **48**, 142, 1943. J. Frenkel, *C.R. Acad. Sci.*, *U.R.S.S.*, **49**, 98, 1945.

† E. H. Vestine, L. Laporte, C. Cooper, I. Lange and W. C. Hendrin, *Description of the Earth's Main Magnetic Field and its Secular Change*, 1905–1945, Carnegie Institution, Washington, 1947.

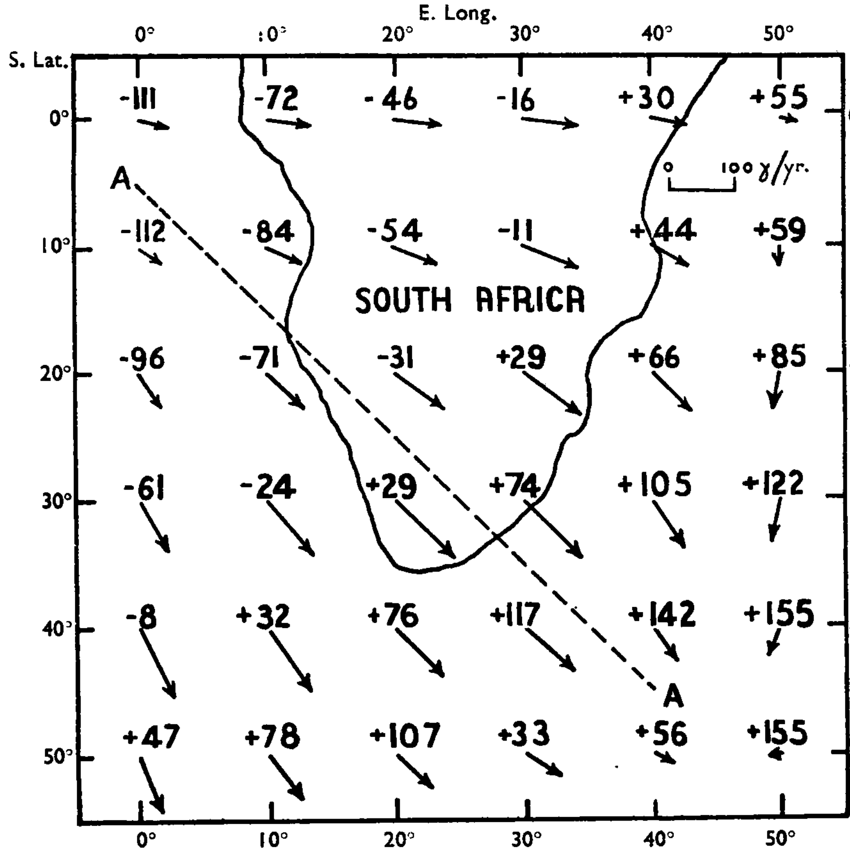

FIG. 1.—*Arrows show change in horizontal field, figures give change in vertical field in γ/year (+downwards). AA is the line of section for Fig. 2.*

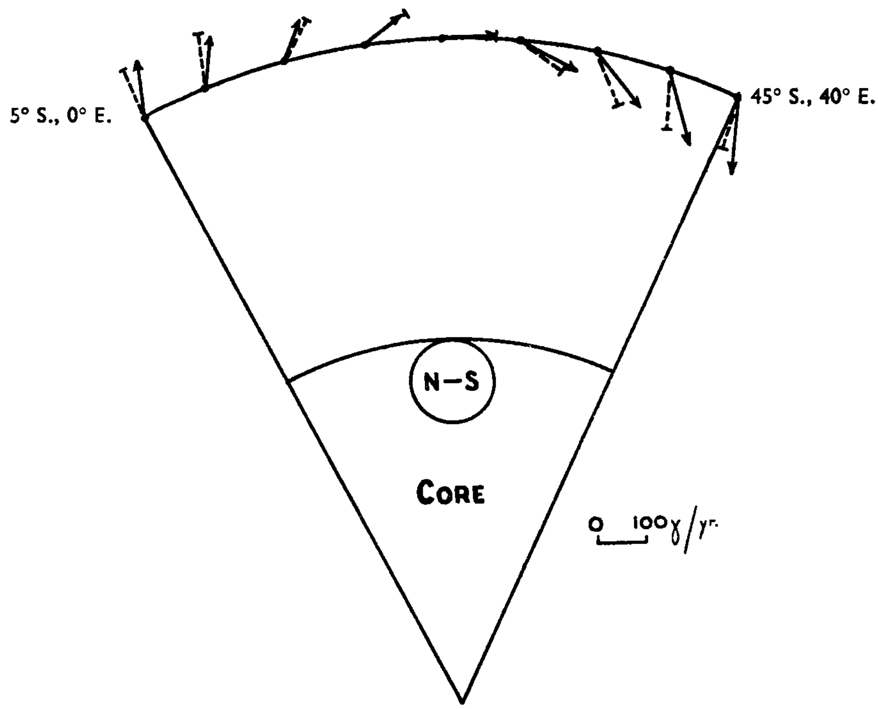

FIG. 2.—*Section along AA of Fig. 1. Small circle has a radius of 400 km.*
⟶ *observed.* - - - -| *dipole.*

dipole. The field is relatively insensitive to the depth of the dipole over a range of a few hundred kilometres and that calculated for a dipole at the surface of the core cannot be shown separately on Fig. 2.

A line of dipoles stretching from north-east to south-west, and all with their north poles to the north-west, gives a very similar result. If we consider the disturbance over a wider area, we find that it is part of a larger feature stretching towards Cape Horn (Vestine, fig. 121 (A)), the line of dipoles is thus perhaps the more reasonable arrangement.

The result that it is possible to find a simple distribution of magnets at the surface of the core that will account for the secular change is of critical importance as showing that a theory assuming an origin in the core is capable of giving the right general dimensions for the phenomena. It is a prediction of such a theory that the areas of rapid change cannot be substantially smaller than the South African focus.

The moment found for the dipole needed to account for the change occurring each year in the field in South Africa is $4\cdot4 \times 10^{22}$ gauss cm.^{3} if a point dipole is assumed. A line dipole would require a moment of 6×10^{13} per cm. of its length.

The present change has been in progress for many years, the longest series of measurements being that at Cape Town. When the first measurements of field strength were made there in 1843, the field was decreasing by about 35γ/yr. In about 1895 the rate increased suddenly to about 100γ/yr. In the last ten years this decrease has shown some sign of slackening. The earliest and latest available observations of force are:

	Horizontal	North	West	Vertical	Total
1843	0·2089	0·1825	0·1016	0·2802	0·3495
1945	0·1412	0·1290	0·0577	0·2876	0·3202
Change	−0·0677	−0·0535	−0·0439	0·0074	−0·0293

The total vector difference between the force in 1843 and 1945 is 0·0696 gauss or 21 per cent of the mean of the total field at the two dates. It is, of course, not known how long the changes will continue in the same direction, nor how long they had been in progress before 1843. As the observed change is already one of the largest known, it may well be that it will not continue for much longer. For the present discussion, we shall take 0·08 gauss to be the maximum disturbing field that has to be explained. This would require a dipole of moment $2\cdot0 \times 10^{24}$ gauss cm.^{3} (2·5 per cent of that of the whole Earth) or a line of dipoles of moment $3\cdot4 \times 10^{15}$ gauss cm.^{3}/cm. to be produced or removed near the surface of the core in a period of about 100 years.

The dipole could not be assumed to be more than a few hundred kilometres below the surface of the core without giving too widespread a field at the surface. The radius of the moving mass associated with an area of rapid secular change is thus limited to a few hundred kilometres.

The growth and decay of such a dipole can be considered as due to

(*a*) changes in the radius of the eddy,
(*b*) changes in its angular velocity (but see Section 6 below),
(*c*) rotations of the eddy,
(*d*) the eddy sinking or rising.

We have at present no means of distinguishing between these processes, though a more thorough analysis of the secular change may do so. A further possibility is that the eddy might move in a horizontal direction; from Vestine's maps there seems little evidence of this. In particular the remarkable centre of change off the south-east coast of the U.S.A. seems to have stayed roughly in the same place till it faded away.

3. *Field of a rotating sphere and cylinder.*—The actual motion of the material of the core is doubtless complicated. As a very crude approximation we consider a portion of it to move like a rigid sphere rotating about a diameter or a rigid cylinder rotating about its axis. The screening by the surrounding stationary material is considered in Section 8 but the spreading of the currents outside the rotating body is neglected.

If a sphere of radius a and conductivity κ rotates sufficiently slowly in a magnetic field F directed at right angles to its axis, a system of currents is set up which describe circles in planes parallel to the field and to the axis of rotation. The external magnetic field produced by these currents is the same as that produced by a dipole at the centre of the rotating sphere. The magnetic moment of this dipole is at right angles to the angular velocity ω and to F. It is given by

$$M = \sigma F a^3/15 = 2\pi\kappa\omega a^5 F/15, \qquad (1)$$

where

$$\sigma = 2\pi\kappa\omega a^2.$$

This system of currents can only exist so long as σ is much less than one. The field produced at the surface of the sphere is then small compared to F. At higher speeds M/Fa^3 is a function of σ only, but increases more slowly than σ, At high speeds it becomes independent of σ and tends to the constant value of $\frac{1}{2}$, giving

$$M = \tfrac{1}{2} F a^3. \qquad (2)$$

The direction of the moment swings through a right angle as σ increases, and for large σ it becomes anti-parallel to F.* There is then no field in the interior of the sphere and the currents are almost entirely confined to a surface layer of thickness $a/\sqrt{\sigma}$.

The results for the moment per unit length, M_1, of a cylinder rotating about its axis which is at right angles to the field are similar. For slow rotation

$$M_1 = \tfrac{1}{8}\sigma F a^2 \text{ per unit length,} \qquad (3)$$

and for fast rotation

$$M_1 = \tfrac{1}{2} F a^2 \text{ per unit length.} \qquad (4)$$

A field along the axis of rotation produces no currents either in the sphere or the cylinder.

4. *Field required inside the Earth.*—We require a disturbance of about 20 per cent of the total field to be produced at the surface of the Earth by the magnetization of a sphere or cylinder with a radius of not more than a few hundred kilometres at a depth of about 3000 km. So great a disturbance will require the field produced by the currents at the surface of the sphere to be several times the surface field of the Earth. The field at great depths is not known, but is unlikely to be more than a moderate multiple of the surface field. Thus the field produced by the currents at the surface of the rotating body must be comparable with the whole field there. In fact, as is shown below, it is difficult to account for the fields

* The *Handb. der Phys.*, **15**, p. 360 and others state that the moment does not get nearer than 45° to F. This appears to be incorrect. I am indebted to Professor Blackett for pointing this out and also that my own views on this subject were erroneous.

required, and it is necessary to assume that the rotation is fast enough for the moment to be given by (2) or (4) rather than by (1) or (3).

To produce a moment in the required direction, that is with the north pole directed towards the north-west, the axis of rotation must lie in the vertical plane normal to this direction. The field F inducing the currents must be in the plane containing the axis of rotation and the direction of the moment. Its component resolved to the south-east must be positive. The components in directions at right angles to this are of no importance. If a cylindrical eddy is assumed, its axis must be roughly horizontal and the vertical field must then be small. The magnitude required for the south-east component depends on the radius and on the depth, d, assumed for the sphere or cylinder. If the maximum disturbance of the horizontal field at the surface of the Earth is to be H_0, then

$$F > 2H_0 d^3/a^3 \text{ for a sphere,}$$

$$F > H_0 d^2/a^2 \text{ for a cylinder.}$$

If the rotating body just touches the top of the core, then

$$d = 2900 + a \text{ km.}$$

If H_0 is taken as 0·08 gauss, F has the following minimum values:

a	100	200	400	600 km.
F	4000	600	90	30 gauss for sphere
F	70	20	5	3 gauss for cylinder

These values may be compared with those predicted by two extreme theories of the main field. If the cause of the field lies deep in the interior of the core, all its components will increase inwards as the inverse cube of the radius. It would not be correct to take the measured field at the surface as the starting-point for such a calculation, as this includes the disturbance we are discussing, and also local and regional anomalies. Instead, we take the contribution of the dipole at the centre of the Earth that most accurately represents the field of the Earth as a whole. The point 25° S., 20° E. has a geomagnetic latitude of $-24°·3$. The fields in 1922.5 taken from smoothed isogams and from the dipole field are:

	Horizontal	Declination	Vertical	Total
Observed (smoothed)	0·182	21·6° W.	0·287	0·340 gauss
,, dipole	0·282	12·7° W.	0·254	0·379 gauss

The latter of these gives a field of 3·3 gauss at a point 400 km. below the surface of the core if the field is assumed to be proportional to the inverse cube of the distance from the centre of the Earth. This is of the required order of magnitude for a rotating cylinder. The component to the south-east is $-2·1$ gauss and is thus in the wrong direction.

It might be suggested that the observed change is due not to the development of an eddy but to its disappearance. That is to say the eddy might have existed in full strength 100 years ago and produced a field to the N.W. at the surface. Its subsequent decay or movement might then have caused the observed reduction in horizontal field. The field at the core required for this would agree in direction with the calculated field, but the hypothesis is not attractive, as the present horizontal field in South Africa is much below that which is normal for its geomagnetic latitude. It thus seems more probable that the field is depressed below its usual value than that it is recovering from a previous excess.

Runcorn's version of Blackett's theory of the main field * gives a horizontal field in the correct direction, but can only provide a total field of 1·1 gauss and a component of 0·8 gauss to the south-east. This is in the right direction but about six times too small. The vertical field is 0·6 gauss upwards, and the dip 32°.

It is difficult to see a way out of this difficulty, but in view of the crudity of our model and the lack of information about the field at great depths, it cannot be taken as conclusive evidence against the theory. The long cylindrical eddy appears considerably more promising than the spherical one, as it requires a much smaller field at the core to produce a given effect.

5. *Electrical conductivity of the core.*—To estimate the velocities necessary in the circulation to whose interaction with the field the currents are ascribed, it is necessary to estimate the electrical conductivity of the material of the core.† We tentatively assume that the core has a composition similar to that of iron meteorites which usually consist of iron with 5 to 10 per cent of nickel. At room temperature and zero pressure such an alloy has a specific resistance of about 30×10^{-6} ohm cm. Pure iron gives about 10×10^{-6}. When the temperature is raised, the extra resistance due to alloying (20×10^{-6}) will not increase, but the resistance of the pure iron will. At 900 deg. C. the latter has reached 126×10^{-6}. This temperature is high compared to the Debye temperature of the lattice, and at higher temperatures the resistance may be expected to increase proportionally to the absolute temperature. The resistance of most metals about doubles on melting. We thus have for the specific resistance at zero pressure and temperature T in degrees absolute,

$$\rho = 2(20 + 126T/1173)10^{-6} = (40 + 0{\cdot}22T)10^{-6} \text{ ohm cm.}$$

The temperature in the core is not known, but is not likely to be much below the melting-point of basic rocks which may be estimated ‡ at $(1400 + 3d)$ deg. C., where d is the depth in km. At the surface of the core this gives 10,000 deg. C. The gradient may have been overestimated but the result cannot be grossly in error. The resistance at zero pressure and 10,000 deg. C. is about 2200×10^{-6}.

Increase of pressure reduces the resistance. The change of resistance is connected with the change of density by compression, the resistance ρ_p at pressure p being given by

$$\rho_p/\rho_0 = (D_0/D_p)^s,$$

where ρ_0 is the resistance at zero pressure and D_0 and D_p are the corresponding densities. For iron s is experimentally found to be 4·1, for nickel it is 3·35. Theory gives 3·20 and 3·76 for the two metals. We adopt 3·6. The density at the surface of the core is about 9·4 g./cm.³ § (the pressure is $1{\cdot}4 \times 10^{12}$ dynes/cm.²), which gives $\rho_p/\rho_0 = 0{\cdot}47$. Thus the specific resistance of the material near the surface of the core may be taken as

$$\rho = 1 \times 10^{-3} \text{ ohm cm.} = 1 \times 10^{6} \text{ e.m.u.}$$

and the conductivity as

$$\kappa = 1000 \text{ ohm}^{-1} \text{ cm.}^{-1} = 1 \times 10^{-6} \text{ e.m.u.}$$

* K. Runcorn, unpublished.

† The discussion is based on information given by N. F. Mott and H. Jones, *The Theory of the Properties of Metals and Alloys*, Oxford, 1936.

‡ H. Jeffreys, *The Earth*, Chap. 7, 1929.

§ K. E. Bullen, *An Introduction to the Theory of Seismology*, p. 222, Cambridge, 1947.

The above argument allows for the change in the mean free path of the conduction electrons with temperature and pressure, but not for a change in their number. Further theoretical and experimental work is desirable.

6. *Velocities required.*—The magnetic moment of a sphere or cylinder rotating in a magnetic field exceeds 80 per cent of its maximum possible value if $\sigma > 50$, that is if

$$\omega a^2 > 50/2\pi\kappa.$$

If $\kappa = 1 \times 10^{-6}$ e.m.u. this gives $\omega a^2 = 8 \times 10^6$ and the following values for ω, for the time of rotation T, and for the maximum velocity v,

a	100	200	400	600 km.
ω	8×10^{-8}	2×10^{-8}	5×10^{-9}	2×10^{-9} sec.$^{-1}$
T	2·5	10	40	90 yrs.
v	0·8	0·4	0·2	0·12 cm./sec.

These velocities are minimum values, there is no reason why they should not be exceeded, but the field produced by the induced currents will not be increased if they are. Without a detailed theory of the origin of the motions it is difficult to say what velocities are to be expected, but these do not seem large enough to raise any difficulty.

7. *Currents required.*—The currents will be almost confined to a layer near the surface of the rotating body of thickness $a/\sqrt{\sigma}$. If this is small compared to a, the currents may be thought of as circulating in a thin spherical or cylindrical shell of this thickness. The current density required to produce a moment M in a sphere, or M_1 per unit length in a cylinder, is then,

$$I = 2M\sqrt{\sigma}/\pi^2 a^4 \text{ for a sphere,}$$
$$I_1 = M_1\sqrt{\sigma}/4a^3 \text{ for a cylinder.}$$

If M is taken as 2×10^{24}, M_1 as $3{\cdot}4 \times 10^{15}$ and σ as its minimum value of 50, then these expressions give the following results for the minimum current densities:

a	100	200	400	600 km.
I	3000	180	11	2×10^{-6} amp./cm.^{2}
I_1	60	8	0·9	$0{\cdot}3 \times 10^{-6}$ amp./cm.^{2}

These are very small and raise no difficulty by heating. For example, for a 400 km. sphere the heat generated is about 6×10^{-16} cal./g. sec. or only 10^{-3} of that produced by radioactivity in surface rocks.

The electrodynamic forces are of order IH per cm.^{3}, where H is the magnetic field. For a field of 5 gauss they would be about 5×10^{-7} dynes/cm.^{3} for a cylinder of 400 km. radius. The centrifugal force at the periphery of this cylinder when it is moving with a velocity of 0·2 cm./sec. is 9×10^{-9} dynes/cm.^{3}. The electrodynamic forces would therefore need to be considered in a detailed theory of the motion of the fluid.

8. *Decay of currents.*—If the motion stops, the system of currents will not at once cease. *If the secular change is due to changes in the radius or velocity of the eddy*, it is necessary that the time of decay of the current system when the exciting cause is removed should not be more than about a hundred years. Otherwise the currents cannot change quickly enough. The largest time constant τ for the currents in a sphere is $4a^2\kappa/\pi$. With $\kappa = 1 \times 10^{-6}$ this gives

a	100	200	400	600
τ	4	16	60	140 yrs.

Using the same conductivity the time constant for the whole core is 3400 years.

If the conductivity of the core were higher than we have assumed, the time of decay of the currents would be longer than is assumed above and they and their field might be considered to move with the material of the core when the eddy turned or shifted its position. I have not investigated this in detail but it seems possible that a long time of decay for the currents is not necessarily inconsistent with a rapid change in field at the surface of the Earth.

A related question is the reduction of the field at the surface of the Earth by the screening of the conducting material around and above the rotating body. For changes with period τ the thickness of material s to reduce the field to $1/e$ is $\sqrt{(\tau/4\pi^2\kappa)}$. With the value of κ used above, this gives

τ	1	10	100	200	1000 yrs.
s	8	30	80	130	280 km.

The distances corresponding to the observed period of 150 to 200 years (double the time taken for the field to go from maximum to minimum) are rather smaller than could be wished, but not seriously so.

The screening by the material of the core would prevent motions more than a few hundred kilometres from the surface of the core from producing any perceptible effect. It will also limit the possible rate of secular change, but not its time differential. It is a conspicuous feature of the observed changes that while the change in a year is limited to about 100γ the rate sometimes changes suddenly as much as 50 γ/yr. in three or four years. This remarkable behaviour is consistent with the present picture.

The conductivity of the part of the Earth outside the core has been considered by Coster *, who concludes that it at first increases with depth, reaches a maximum of about 1 ohm^{-1} cm.$^{-1}$ (10^{-9} e.m.u.) at 300 km. and thereafter decreases slowly. The calculated penetration depths s_1 for a conductivity of 10^{-9} are :

τ	1	10	100	200	1000 yrs.
s_1	300	800	3000	4000	9000 km.

As the conductivity chosen is the maximum, these results are satisfactory. The actual value of the conductivity is, however, very uncertain and further laboratory work is desirable. The study of short-period magnetic fluctuations merely shows that the conductivity for some distance below 600 km. must be at least 10^{-11} e.m.u., which is a factor of 100 less than we have taken. Such a reduction of the conductivity would decrease the screening.

9. *Effect of Viscosity.*—It is not intended in this paper to discuss the hydrodynamics of the assumed motions, but some idea of the quantities involved is desirable. The effect of pressure and temperature on the viscosity of molten iron is not known, but Professor Born and Mr Yang inform me that their combined effect is likely to be a small decrease. The viscosity of the core may thus reasonably be taken as about 0·01 g. cm.$^{-1}$ sec.$^{-1}$. The kinematic viscosity ν would then be about 10^{-3}. The greatest time for the motion of a fluid in a rigid envelope to decay to $1/e$ of its initial value is $0{\cdot}05a^2/\nu$. This gives periods of hundreds of millions of years. If this result could be taken as an estimate of the time for which the eddies will last, it would mean that they would be practically permanent and that the secular change would be due to their moving from place to place or diving into the core, but not to changes in their speed or size.

It seems doubtful if this result is correct, as the Reynold's number of the motion (av/ν) is very large. From the argument of paragraph 6 its value cannot

* *M.N., Geophys. Suppl.*, **5**, 199, 1948.

be less than 4×10^9, and is independent of a. Such a large value suggests that the eddies will destroy themselves by turbulence rather than by the viscous forces associated with stream-line flow.

For stream-line flow the viscous forces would be of order $\eta v/a^2$ per cm.^{3}. This is 10^{-17} to 10^{-19} dynes/cm.^{3}, and is negligible compared either to the centrifugal or the electrodynamic forces. If the flow were turbulent the viscous forces might of course be much larger.

10. *Causes of the Motion.*—It is not profitable to speculate about the causes of the motion till a more thorough knowledge of it has been obtained from the analysis of the secular change over a wider area, and until its hydrodynamics have been further explored theoretically.

One possibility is that the radioactive generation of heat in the core might produce thermal convection currents. Any asymmetry in the Earth's cooling would have a similar effect. Another possibility is that the slipping of the outer part of the Earth over the core as the Earth slows down by tidal friction may play a part.

11. *Conclusions.*—The rapidity of the changes that constitute the secular variation seems to defy any explanation that does not invoke motions in the liquid core of the Earth. We have shown that the observed size of the areas of rapid change are also consistent with an origin in the core. The fact that the secular change never exceeds about 20 per cent of the whole field, is an argument for a causal connection between the main field and the secular change. If they had quite separate origins it would be odd, in view of the great variability of the phenomena, if such a relation always held. The suggestion here made is that motions in the core interact with the main field to produce electric currents. As has been shown above, there is some difficulty in getting a sufficient field by these means, and in this respect the theory is unsatisfactory. It is possible that some of this difficulty can be removed by a more thorough analysis of the secular change. It seems from a cursory inspection of the maps that there is a world-wide as well as a regional part of the secular change. This world-wide part could be ascribed to motions some thousands of kilometres in diameter and only the residue to the smaller eddies. In particular it is possible that the comparatively slow change at Cape Town from 1843 to 1900 (0·02 gauss in all) was not due to a local eddy.

The best course seems to be to find a current system that will fit the observed change over the whole world and then to try to find a likely distribution of velocity and field in the core that will give this current system. The fact that the fields required are rather larger than at present seems likely, is unfortunate but cannot easily be discussed in the present state of the theory of the origin of the main field.*

The proper investigation of the theory sketched in this paper will be a lengthy matter, and it is given in its present incomplete state in the hope that it may stimulate modifications that will agree more exactly with the very complicated facts.

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**Note added in proof.*—Professor L. Slichter has pointed out that the difficulty about the direction of the field near the surface of the core would be removed if the main field were due to currents circulating in the outer part of the core.