# 3. Geomagnetism and the Earth's Core

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## Abstract

That the Earth has a magnetic field is one of the basic physical facts concerning the planet, and the history of geomagnetic observation forms a substantial part of the early history of science. Palaeomagnetism has contributed much information to the knowledge of the geomagnetic field over past geological time, especially in demonstrating geomagnetic reversals.

The most satisfactory process to invoke in explanation of the geomagnetic field is dynamo action in the liquid core of the Earth. The crucial flow pattern required and many other details of the process remain unknown, though various feasible models have been constructed for them. It appears possible to resolve the physical and chemical circumstances deduced for the core with a convection dynamo, driven at least partially by a power source of order $5 \times 10^{12}$ W arising from cooling.

Current research aimed at increasing the precision of knowledge about the core is centred on increasing the resolution of seismic interpretation techniques, and on exploring the possibilities of detecting the "gravitational undertones" and inertial modes of core oscillation.

## 1. Introduction

### 1.1. History

The study of the magnetic field of the Earth has ancient origins, lost at some time in antiquity when man first discovered that certain rocks tended to align themselves geographically if they were free to rotate. Such were the beginnings of the magnetic compass, which as a basic instrument of navigation for exploration and trade has played a fundamental part in the progress of civilization over the last millenium and possibly for much longer.

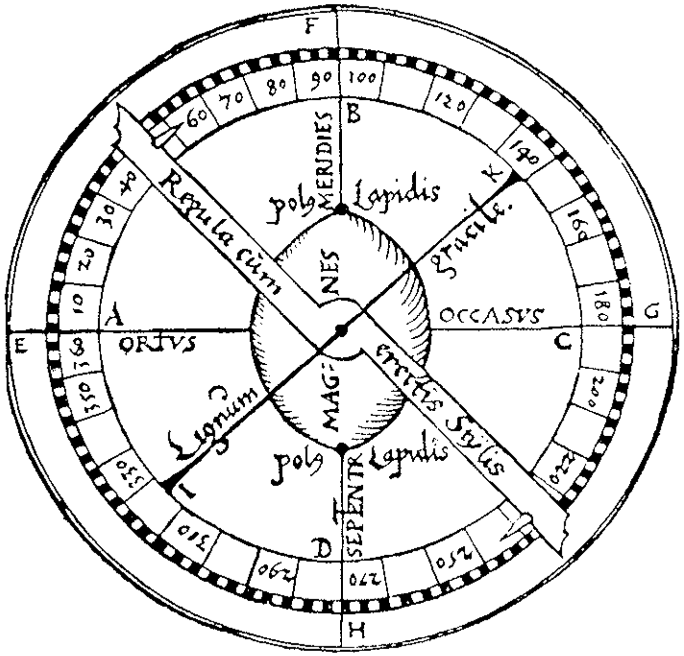


Fig. 1. Petrus Peregrinus' diagram for a compass which uses a naturally magnetized stone (*magnes*), supported to float in water. (From Harradon, 1943.)

Figure 1 shows the design of the first known documented compass to originate in Europe. The figure is taken from the article on thirteenth century Petrus Peregrinus by Harradon (1943). Smith (1970) points out that Peregrinus' work was significant not only for magnetism, but indeed for the development of the whole philosophy of experimental science.

The practical application of the compass in navigation caused the magnetic field of the Earth to be a subject of continued research. It is now measured all over the globe by ships, aircraft and satellites, and its fluctuations with time are monitored simultaneously by observatories throughout the world.

## 1.2. Deceptive Simplicity of the Dipole Field

The common picture of the magnetic field of the Earth as being dipolar, with poles effectively coincident with the geographic poles of the Earth, has a simplicity which is perhaps deceptive in view of the complexities of the subject which become evident upon closer examination: for analysis of the geomagnetic field in all its detail involves the application of physics ranging



from the properties of a highly rarified plasma leaving the Sun to the properties of ultra-compressed material in the core of the Earth. This article will be restricted to the basic problem of solid Earth geomagnetism: the physical processes in the Earth's core giving rise to what is known as the "main magnetic field" of the Earth.

## 1.3. Gauss' Theorem

The nineteenth century mathematician C. F. Gauss used the mathematical method of spherical harmonics to analyse the existing measurements of the global magnetic field. Several centuries earlier, Gilbert had concluded that the Earth's magnetic field arose from within the planet (as part of his theory that the Earth itself was like a great magnet), at a time when it had been common to attribute the directional properties of compasses to causes external to the Earth: one popular theory (since most observations were made in the northern hemisphere) was that the pole star exercised some attractive effect. Gauss showed in 1839 that the main magnetic field did indeed originate inside the planet, and this demonstration was perhaps the founding step of modern geomagnetism.

The essence of Gauss' method lies in the theoretical result that the magnetic potential of the observations may be expressed in terms with radial dependence $r^n$, where $r$ is the distance from the centre of the Earth and $n$ is some integer. Terms with negative $n$ then necessarily indicate an internal origin, for which the potential must go to zero at large radial distances. Similarly, terms with positive $n$ necessarily indicate an external origin, for which the radial derivative of the potential must be finite at small radial distances. In his analysis, Gauss showed that the terms corresponding to internal origin were overwhelmingly dominant.

## 1.4. The Magnetization of Crustal Rocks

Rocks can support magnetic fields through the induced and permanent magnetization of certain of their constituent minerals, and the phenomenon of rock magnetization is the basis of all magnetic techniques of geologic mapping over both land and sea. Crustal magnetization is responsible for the magnetic stripes on the ocean floors, which demonstrate sea-floor spreading. The principles of palaeomagnetism, central to the articles in this volume by M. W. McElhinny and E. Irving (Chapters 4 and 17), depend upon magnetization in crustal rocks.

However, rock magnetization is limited to crustal depths, as the phenomenon disappears when the temperature of a mineral reaches its "Curie temperature". This temperature is 580 °C for magnetite, so with typical thermal gradients at the Earth's surface being of order 25 °C $km^{-1}$, it can be seen that the base of the magnetized layer must be at depths of order 20 km. This is a very thin layer on the scale of the radius of the Earth, and magnetization of such a layer is not strong enough to account for the Earth's main magnetic field. Thus the dynamo theory has arisen, which places the origin of the main magnetic field in the earth's core, and attributes it to the flow of macroscopic electric currents, supported by a process of electromagnetic induction.

### 1.5. Electromagnetic Induction in the Earth

Electromagnetic induction takes place in two different regions of the Earth, in two different processes. Near the Earth's surface, primary fields originating external to the Earth induce secondary fields to arise within the Earth. These fluctuating fields combined are the "natural magnetic variations", which, measured at the Earth's surface, appear as small perturbations of the main magnetic field. The physics of such surface induction is relatively well understood, though the mathematics of applying it to general geological situations is involved. The study of natural magnetic variations is currently yielding much information on the electrical conductivity structure of the crust and upper mantle of the Earth.

Much deeper in the Earth, motional electromagnetic induction in the core is thought to generate the main magnetic field of the Earth in a dynamo process. Here the physics and mathematics are complex and the "geology" of necessity simple, in attempting to explain an induction process with the fascinating property that the primary and secondary fields are the same. Of all the contributions to the geomagnetic field, this core originating dynamo process is by far the most important.

### 1.6. Plan of this Article

The second part of this article introduces the physical elements of dynamo theory. A third part discusses miscellaneous aspects of the core and the geomagnetic field, chosen largely on the basis of their fascination for the present author. It should be emphasized in advance that much of the relevant knowledge concerning the core is very indefinite, and with its many degrees of freedom core science has been a fertile ground for creative ideas. As far as he can in these matters the author has adopted the philosophy of seeking to represent a consensus where he judges that one exists, or, if not, the majority view. It should of course be borne in mind that the majority view need not be the correct one.



## 2. Main Field Production by Dynamo Action in the Core

Thirty years ago discussion centred on whether a dynamo process in the core of the Earth was physically possible (cf. Elsasser, 1946, and a series of succeeding papers; Bullard and Gellman, 1954). By ten years ago it had essentially been established that this was so, but there was some fascination in investigating whether reasonably simple flow patterns could act as dynamos from a mathematical point of view (e.g. Lilley, 1970; Roberts, 1970; Gubbins, 1972). This demonstration has now been achieved for a number of cases, and the term "geodynamo" has come into the literature (Busse, 1975; Jacobs, 1975). Attention now concentrates particularly on the physics of the process in the Earth: what is the energy source, what is the flow pattern, how do reversals occur? A topical discussion also centres on the possibility that the core might be stably stratified, at least in part.

In leading up to one possible description for the dynamo, pertinent facts about the core shall be grouped according to whether they are (i) well established, (ii) under debate or (iii) hardly known at all. More informally, it will be seen that this grouping corresponds to the evidence for the facts being (i) beyond reasonable doubt, (ii) debatable, and (iii) so scant that it is hardly possible even to argue about them.

### 2.1. Well-established Facts about the Core

*Liquid Nature*

That the Earth has a liquid core is one of the great historic discoveries of seismology, and followed from the observation by Oldham in 1906 that the inner part of the Earth does not transmit seismic shear waves, as liquids do not.

*Size*

From seismology also comes evidence that the outer boundary of the core is clearly defined. Jeffreys (1939) determined the core radius to be 3473 ± 4.2 km, and Dziewonski and Haddon (1974) recently obtained 3485 ± 3 km. That such values are quoted to four significant figures is evidence of the precise nature of this branch of seismology, and, in the context of the uncertainties of dynamo theory, the core radius is known exactly. The possibility remains, however, of relatively very small undulations existing on the core–mantle interface; the subject of these is discussed in the contributions to this volume by M. W. McElhinny, J. R. Cleary and R. S. Anderssen (Chapters 4 and 5).

*Solid Inner Core*

Though the outer core does not transmit shear waves, certain seismic observations are best accounted for by an inner core which does transmit shear waves and so is "solid". This inner core is of radius 1220–1230 km (Bullen, 1975).

*Composition Mainly Iron*
The main constituent of the core is held to be iron, which has approximately the correct density and elastic properties to match seismic information and information on the Earth's total mass and moment of inertia, and which needs to form most of the core if the chemical abundances of the whole Earth are to be consistent with those of chondritic meteorites. There is considerable debate over the minor constituents of the core, which will be discussed below in Section 2.2, "Impurities in the iron" and "The potassium question".

*A Dynamo Exists in the Earth's Core*
The author has little hesitation in grouping the existence of a dynamo in the core as a well-established fact. While historically there have been other theories for the origin of the main geomagnetic field, the wealth of recently accumulated evidence especially on the time-dependent behaviour of the Earth's magnetic field leaves a core dynamo as really the only feasible source for it.

*Rotation Influences Dipole Field Generation*
The present circumstance of near coincidence of the geomagnetic and geographic poles is taken as evidence that the daily rotation of the core (as part of the Earth) in some way strongly influences the geodynamo, through the effect of Coriolis forces on the fluid flow in the core. While this is not understood in detail (as in fact the core flow itself is not known, see "Fluid flow pattern in the core" in Section 2.3), there is little doubt that some process of this nature occurs. That it has always been so over geologic time is a basic principle of palaeomagnetism, in which determinations of time-averaged magnetic pole position are taken to be determinations of geographic pole position, following early work on this fundamental problem by Irving (1956) and Blackett (1961) (see also Briden 1968).

This work showed, for the cases examined, that the geographic latitudes in which the rocks had formed (as deduced from palaeoclimatic data) agreed with the geomagnetic latitudes in which they had formed (as deduced from palaeomagnetic data).

A clear example of such a coincidence is given in Fig. 2 for the palaeomagnetic poles of reconstructed Gondwanaland (from McElhinny, 1977). The Ordovician–Silurian (O–S) palaeomagnetic pole falls in the present Sahara Desert of North Africa, where there is also geological evidence of Silurian glaciation, implying that at that time the present North Africa was near a geographic pole. Similarly the Permo-Carboniferous (PC)



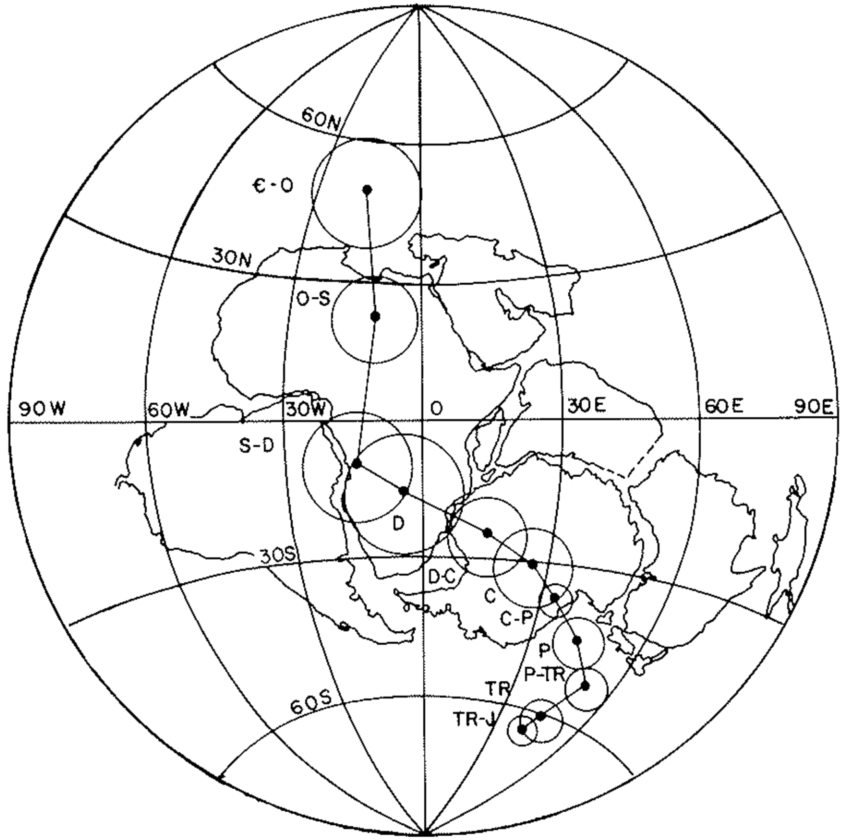


Fig. 2. Palaeomagnetic pole positions for Gondwanaland. (From McElhinny, 1977.)

palaeomagnetic pole falls near Tasmania, where independent geological evidence is also found of Permian glaciation.

Most palaeomagnetic pole determinations are a statistical average for many different rock samples, spread out in time so that their mean result will smooth out small excursions of the magnetic pole from the geographic pole such as occurs for the Earth at present.

## 2.2. Facts in Debate about the Core

The previous section listed facts which have been convincingly demonstrated. This section now approaches upon the more delicate ground of facts at present under debate, in some instances under heated debate. There is no significance to the order in which they are discussed.

*Impurities in the Iron*

The inner core may indeed be nearly pure iron, but the outer core must hold a component which is less dense and which increases the compressional seismic velocity. Upon the basis of geochemical abundance arguments (cosmic, solar and meteoritic) the most likely companion of iron in the core is nickel. However, adding nickel to iron in a model core does not improve the match of expected model properties with seismic Earth observations, and the further addition of a lighter element (or elements) must be made to the model. The main present contenders are oxygen, potassium, silicon and sulphur (Brett, 1976), with hydrogen also being reconsidered (Stevenson, 1977).

These impurities are important because their presence could affect the electrical conductivity of the iron, and also its melting characteristics. The question of potassium is particularly important for dynamo theory, because potassium in the core would form a radioactive heat source, crucial in discussing the energetics of dynamos (see "Energy sources for the geodynamo" in Section 2.4). Potassium is therefore now discussed separately.

*The Potassium Question*

Recently the question of potassium in the core has been revived. The argument has been basically that if the Earth is presently to have the appropriate chondritic abundance of potassium, then this potassium must be in the lower mantle or core as it is not found in the upper mantle or crust. Further, it could be incorporated in the core if it has a tendency to combine with sulphur which might be there (see Goettel, 1976).

The point has been discussed widely. Ringwood (1977) has recently reasserted rejection of this hypothesis on the grounds that there is no reason to expect the Earth to not be depleted in potassium: as are the Moon and the class of meteorites known as eucrites. Indeed, in this recent paper, Ringwood re-examines whether oxygen, not sulphur, might be the main "light" element in the Earth's core.

*Electrical Conductivity*

Early estimates of the electrical conductivity of a molten iron core by Elsasser (1946) and Bullard (1949) gave a mean value of $3\times10^5$ S m$^{-1}$, and this value was used by Bullard and Gellman (1954) in discussing core energetics, with the reservation that it was uncertain by a factor of three.

A number of investigations have been carried out on the problem since, from different points of view. Gardiner and Stacey (1971) and Stacey (1972) also arrive at the value of $3\times10^5$ S m$^{-1}$, in a range $(2\rightarrow10)\times10^5$ S m$^{-1}$. There is uncertainty due to the unknown effect of the impurities in the core (Johnston and Strens, 1973), especially as the composition of these impurities is itself unknown.



*Temperatures within the Core*

The basic structure from seismology of a liquid outer core and solid inner core was explained by Jacobs (1953) as being due to a relationship between melting point and actual temperature, as shown in Fig. 3. This has remained the most straightforward explanation. Thus determining the melting point of iron (with its possible impurities) at the known pressure of the inner core–outer core boundary gives a temperature estimate for that part of the interior of the Earth.

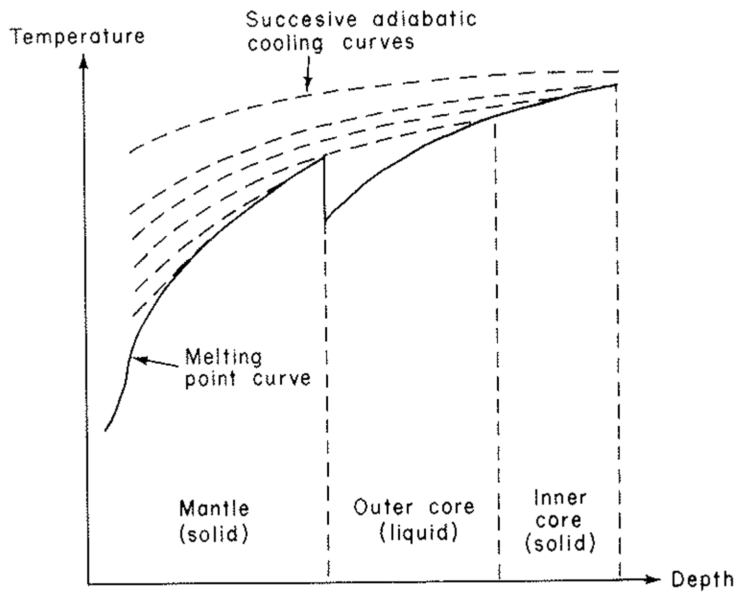


Fig. 3. Formation of a liquid outer core between a solid mantle and a solid inner core. The outer core becomes "trapped" as the inner core solidifies from its centre outwards, and the mantle subsequently solidifies from its base outwards. (From Jacobs, 1953.)

One of the first such estimates was 3900 K by Simon (1953) and one of the most recent is 4160 K (Stacey and Irvine, 1977), and indeed a figure of about 4000 K has not recently been much questioned.

Determination of the temperature at the mantle–core boundary is a more subtle matter. Traditionally the whole outer core is taken to be completely in convection, so that the actual temperature gradient should be the appropriate adiabatic temperature gradient for the material of the molten outer core. Then, given a temperature at the inner core–outer core boundary, it is possible to move radially outwards along the adiabatic gradient until the core–mantle boundary is reached, and thus to obtain a temperature there. An early such estimate was given by Jacobs (1954) as 3600 K, and Stacey and Irving (1977) recently obtained 2940 K, with several hundred degrees uncertainty.

A major difficulty lies in estimating the adiabatic gradient for the material of the outer core. Higgins and Kennedy (1971) in a controversial determination found that the adiabatic gradient was less than the melting point gradient, which if so would mean that the core was stable against convection (except for the innermost outer core; Kennedy and Higgins, 1973). Stronger evidence for this state of affairs appears to be needed, however, before the other estimates of adiabatic gradient (which allow convection) have to be abandoned, and with them a convection process driving the geodynamo. Liu (1975) has pointed out that considering the full phase diagram for iron at core pressures appears to avoid the difficulty.

Increased awareness of the possibility of stability in the core has, nevertheless, led to ideas which, depending on the distribution of heat sources, allow either the inner or the outer part of the fluid core to be stable against convection. In such parts heat flow must then take place by conduction, and the thermal conductivity of the core material becomes a key parameter. This is usually estimated using the Wiedemann–Franz relationship between electrical and thermal conductivities. Stacey (1972) thus obtains a core thermal conductivity estimate of 28 $\mathrm{W\,m^{-1}\,K^{-1}}$.

With such a value for thermal conductivity, the heat flow out from the core by conduction only along the adiabatic gradient is of order $3\times10^{12}$ W (Stacey, 1977). This must be a minimum estimate of heat flow from a convecting core since the convection would transport heat in excess of that transported by conduction alone.

## 2.3. Hardly-known Facts about the Core

The following questions arise in considering the core. Their nature is such, however, that it is not possible to predict at present how they might ever be clarified or resolved.

*Change with Time of Core Conditions*

Theories on core science depend crucially on the extent to which the core is developing with time. Information on whether the present inner core is cooling or growing, or both, would be invaluable as means of testing a whole range of possibilities. The search for such information rightly falls in the domain of palaeogeophysics, but there seems little hope of a direct answer regarding core evolution. There is a most significant body of data in palaeomagnetism (see "Palaeomagnetic evidence for the geodynamo", Section 2.4), and this can be expected to increasingly constrain theories for the geodynamo, but the data apply to the end results of a very complicated process, and it is not clear that they will be able to clarify the origins of the process.



*The Toroidal Magnetic Field within the Earth*

One property of a toroidal magnetic field in an electrically conducting sphere is that the field lines close on themselves entirely within the sphere, and never emerge outside. Toroidal fields play a most important role in most dynamo theories, but virtually by definition any toroidal magnetic field in the Earth's core can not be detected by surface observations. A number of investigations regarding the possible detection of toroidal fields in the Earth by their physical effects have been carried out, such as the following:

(i) the possibility that the observed secular variation of the geomagnetic field represents waves in a core toroidal field (Hide and Stewartson, 1972);
(ii) the possibility that seismic wave propagation through the core would suffer magnetoelastic effects (see Section 3.1);
(iii) the possibility that the electric currents supporting a core field would leak to the Earth's surface (Runcorn, 1954).

The results of such investigations have on the whole, however, so far proved inconclusive, and some independent estimate of the Earth's toroidal core magnetic field would be a great advance for dynamo theory.

*Stability of the Fluid Core against Convection*

The density distribution of a homogeneous material under an adiabatic temperature gradient follows the Williamson–Adams (or Adams–Williamson) equation:

$$\frac{\mathrm{d}\rho}{\mathrm{d}z}=\frac{g\rho}{\phi}$$

(Bullen, 1975), where $\rho$ denotes density, $g$ local gravitational acceleration, $z$ depth into the material, and $\phi = k/\rho$, where $k$ is the adiabatic incompressibility. Such a material, if a fluid, is neutrally stable as a particle displaced within it will stay put, neither seeking to travel further nor to return to its original position.

Generally, seismic observations have been consistent with material in the outer core of the Earth obeying this equation (Dziewonski *et al.*, 1975), indicating that the outer core is neutrally stable or else convecting: sufficiently rapid convection will maintain a temperature gradient which is nearly adiabatic. However, the increasing resolution of seismic data has given rise to the possibility of checking the consistency of the core material with the Williamson–Adams condition more closely (Jacobs and Masters, 1976). If, following Bullen, one writes

$$\frac{d\rho}{dz} = \eta \frac{g\rho}{\phi}$$

for the core, then the departure of $\eta$ from unity is a measure of the departure of core conditions from those of chemical homogeneity and temperature adiabaticity. In particular $\eta > 1$ will indicate stability against convection, and $\eta < 1$ instability.

The parameter $\eta$ has the practical advantage that it can be estimated inside much of the Earth by applying values obtained from the interpretation of seismic data to the above equation or to

$$\eta = \frac{dk}{dp} - g^{-1}\frac{d\phi}{dz},$$

where $p$ denotes pressure. There is also a close connection between $\eta$ and the squared "Brunt–Väisälä" frequency $N^2(z)$, given by

$$N^2(z) = (\eta - 1)\frac{g^2}{\phi},$$

where $N(z)$ is the angular frequency at which a slightly displaced fluid particle will oscillate adiabatically about its rest position, due to buoyancy forces. Thus departures of $N^2$ from zero correspond to departures of $\eta$ from unity and indicate departures from Williamson–Adams conditions in the core: $N^2 > 0$ ($\eta > 1$) indicates stability against convection, and $N^2 < 0$ ($\eta < 1$) instability.

An estimate of the distribution of $N^2$ for a recent model of the Earth's outer core is shown in Fig. 4 from Smith (1976). The validity of such results depends upon the resolution of the seismically-determined parameters and the density distribution used. The indications of core stability or instability from such diagrams must be notional until the resolution question is clarified, but are given in the figure to illustrate the principle involved. There may in fact be physical grounds for disallowing negative values of $N^2$, so that the problem would become the converse one of using marginal core instability as an extra constraint on the interpretation of seismic data.

*Fluid Flow Pattern in the Core*

The fluid flow pattern in the core is the key basis for the geodynamo, and the author is not a little melancholy about grouping it here as a "hardly-known fact". But while postulated flows range from oscillations of a stably stratified fluid through smooth global circulation to small-scale turbulence, the question seems completely open. Analysis of the secular variation of the



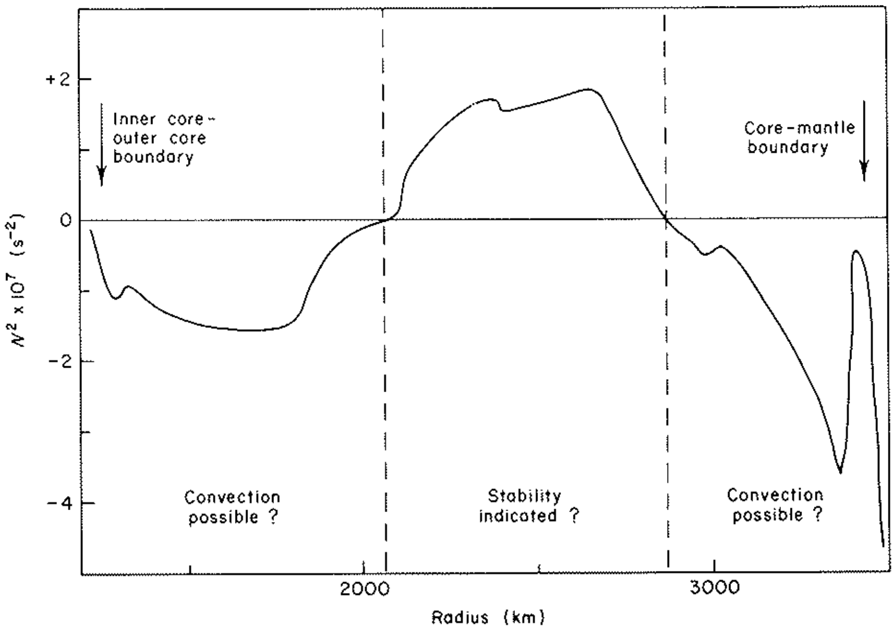


Fig. 4. The quantity $N^2$ estimated using the outer-core parameters of a particular Earth model (DG579). (After Smith, 1976.) The erratic behaviour of the curve reflects the dependence of $N^2$ on the first radial derivative of density: see text for discussion.

geomagnetic field observed on the Earth's surface over recent historic time has given rise to some estimates of fluid flow at the core–mantle boundary, and these are smooth, but the method would not be expected to resolve turbulence in the core fluid.

## 2.4. The Dynamo Equation

The description given here of dynamo theory will be physical rather than mathematical. Dynamo theory seeks to find a fluid motion which will perpetuate, by motional electromagnetic induction, an existing magnetic field. For reasons of simplicity, and because there is little justification in doing otherwise, dynamo regions are taken to be of homogeneous and isotropic electrical conductivity: profoundly different from the common dynamos of electrical engineering.

The basic equation for dynamo action is then quite straightforward to derive from electromagnetic induction theory. It is

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{v} \times \mathbf{B}) + \frac{1}{\sigma\mu}\nabla^2 \mathbf{B}, \tag{1}$$

where **B** denotes magnetic induction, **v** velocity, and $t$, $\sigma$ and $\mu$ denote time, electrical conductivity and magnetic permeability, respectively. In models for the Earth's core, **v** and $\sigma$ are considered to be non-zero only within a sphere, though the **B** field exists over all space (vanishing at great distances). A number of important aspects to be expected in dynamo behaviour may be seen simply by examining this equation.

(i) *Variation with time.* Since time enters the equation, there should be no surprise at the observations, over the last several hundred years, of secular change in the magnetic field of the Earth; nor at the much greater time fluctuations demonstrated by palaeomagnetism. Indeed, a dynamo which produces a steady magnetic field requires a rather special balance between the two terms of the right-hand side of equation (1), so that the left-hand side can be zero. Because equation (1) is a vector equation, this balance must occur in each of its three constituent scalar equations, at all points within the sphere.

(ii) *No preferred sign for* **B**. Because the dynamo equation is homogeneous in **B**, if it is satisfied by a particular **B** field it will also be satisfied by the negative of that **B** field. Thus a dynamo which supports a magnetic field in one direction can equally easily, by the same process, support a field which is everywhere reversed. This feature of dynamo action agrees in a satisfying manner with the palaeomagnetic evidence for no preferred polarity (either normal or reversed) of the geomagnetic field over geologic time.

(iii) *Balance of creation against diffusion.* The term $\nabla\times(\mathbf{v}\times\mathbf{B})$ in the dynamo equation is the source term, and represents the physical process by which magnetic induction is "created" through the flow of fluid across lines of force. By contrast, the term $(1/\sigma\mu)\nabla^2\mathbf{B}$ represents the tendency for field to decay away through ohmic energy loss by the electric currents supporting the field. The balance of these two terms, at a particular point, determines how the magnetic field changes with time at that point.

(iv) *Magnetohydrodynamic effect.* A magnetohydrodynamic effect enters the dynamo process as **v** may itself be affected by **B**: the general equation of motion for the fluid will contain an electromagnetic term for the Lorentz force on the fluid, of form $\mathbf{J}\times\mathbf{B}$, where **J** is electric current density. Since this term may alternatively be written $(1/\mu)(\nabla\times\mathbf{B})\times\mathbf{B}$, it will have the same value regardless of the sign of **B**, so that the indifference of the dynamo equation to magnetic field polarity carries through also into the equation of motion.

However including this non-linear effect of **B** in the process, though necessary physically, makes mathematical analysis of the dynamo problem very much more complicated, especially as the general equation of motion for the fluid (the "Navier–Stokes" equation), will also contain a non-linear term in the velocity **v**.



The simplest level of attack on the dynamo problem is to see whether a steady or growing **B** field can be found satisfying equation (1) for a given (steady) **v** field. This is called the kinematic dynamo problem, and may be attempted for unbounded or bounded regions. Attempts for unbounded regions have generally met with more success, although of course attempts for bounded regions come closer to geophysical application. Physical effects of boundaries in the dynamo problem have been discussed recently by Bullard and Gubbins (1977), who point out that strong electric current sheets tend to form near insulating boundaries. Because equation (1) is linear in **B**, it does not give any information on the magnitude of the **B** field to be expected in a kinematic dynamo.

The next level of complication is to solve the equation of motion simultaneously for **v**, putting in some appropriate body force. This is very difficult, but a number of attempts at the problem have been made on the basis of a time-stepping numerical method. Starting from some set of initial conditions, instantaneous values are calculated for the rates of change of **v** and **B** with time at all points. Increments to the **v** and **B** fields are made according to these rates of change operating for a short time interval, and the whole process is then repeated using the new **v** and **B** fields. In this way, time fluctuations of **v** and **B** have been clearly demonstrated numerically.

Dynamo theory is a subject of advanced mathematics and the interested reader is referred to reviews by Roberts (1967, 1971), Gubbins (1974), Levy (1976) and Krause (1977) for more details. There is, however, one important development appropriate to describe here: it has the name of "mean field electrodynamics" and is useful for treating problems involving turbulence. The concept is that the flow shall have two length scales: a small length scale for the turbulence and a large length scale for the regional flow in which the turbulence occurs. The viscosity must be sufficiently low that turbulence is not inhibited. The dynamo process can then be examined on these two different scales with valuable simplifying approximations, and the interactions between the scales analysed. The interesting physical effect to emerge is that small-scale motions can sustain a large-scale magnetic field.

*Palaeomagnetic Evidence for the Geodynamo*

Palaeomagnetic studies have yielded invaluable evidence regarding the history of the earth's magnetic field. In particular:

(i) The geomagnetic field has existed from the earliest geological times. Even the oldest pre-Cambrian rocks examined give evidence that they acquired their magnetization in field strengths of a similar order of magnitude to the present geomagnetic field strength (McElhinny and Evans, 1968).

(ii) The Earth's magnetic field has fluctuated with time, reversing irregularly. Its general behaviour is known for the past 500 million years, with better accuracy for more recent periods. In this volume, the paper by I. McDougall (Chapter 16) describes the history of reversals since the Tertiary Period, and the contribution from M. W. McElhinny (Chapter 4) deals with reversal rates. Palaeomagnetic resolution has been sufficient to trace some reversals through in detail (Dagley and Lawley, 1974). It has been pointed out by Jones (1977) that the long-term behaviour of the geomagnetic field may be influenced by convection in the lower mantle.

(iii) The evidence for long-term average coincidence of the magnetic poles and the rotation poles of the Earth was discussed in "Rotation influences dipole field generation" in Section 2.1. A new way of demonstrating that the field at Earth's surface has been predominantly dipolar was given recently by Evans (1976). Evans' demonstration is repeated in Fig. 5.

*Energy Needs for the Geodynamo*

The dynamo theory requires that the magnetic field of the Earth be supported by a flow of electric currents in the Earth's core (in association with a fluid flow of the material there). These electric currents, even for a steady magnetic field, will be continuously dissipating energy into heat by ohmic loss, due to the finite electrical conductivity of the core material. It is relevant to estimate what this ohmic power loss might be. The electrical conductivity of the core enters the calculations, and its uncertainty is carried through. To support the present field of the Earth as measured on the surface, Lowes (1970) estimated the minimum ohmic dissipation in the core to be of order $10^8$ W. Gubbins (1976) estimated $7.6\times10^{13}/\sigma$W, which, taking $\sigma$ as $5\times10^5$ S m$^{-1}$ (see "Electrical conductivity" in Section 2.2), also gives order $10^8$ W. If there is a strong hidden toroidal field in the core, then the ohmic power dissipation must be much higher, of order $10^{10}\rightarrow10^{11}$ W for a toroidal field of say 10 mT.

These are estimates of the power dissipated by the ohmic currents of the geodynamo. However, the power the dynamo will need to be supplied with will be greater, depending on the efficiency of the dynamo process. Various possible energy supplies for the dynamo process and their efficiencies will be discussed in the next section, but for one of the most obvious, heat, the efficiency is necessarily rather low. A heat engine operating between two temperatures $T_1$ and $T_2$ ($T_1>T_2$) has a maximum possible efficiency of



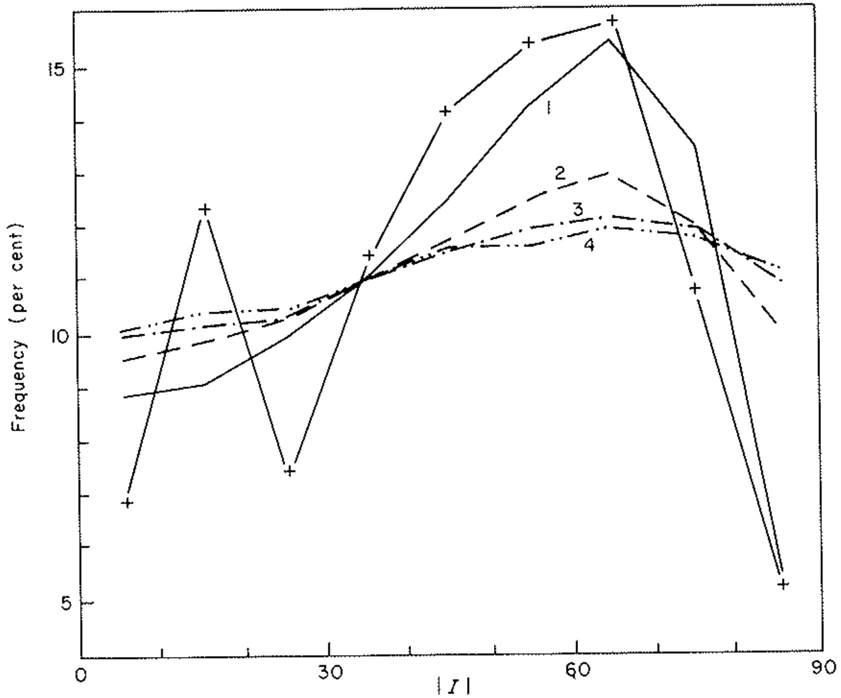


Fig. 5. Distribution of measured inclinations ($I$) of world-wide palaeomagnetic data. (From Evans, 1976.) Crosses show actual data. Curve 1 shows theoretical distribution for a dipole geomagnetic field; curve 2 for a quadrupole field, and curves 3 and 4 for corresponding higher orders. The data demonstrate that the geomagnetic field has been predominantly dipolar.

order $(T_1-T_2)/T_1$ (Bullard and Gellman, 1954; Metchnik *et al.*, 1974), and estimates of the efficiency of a convection dynamo in the core are of order 10 per cent maximum. Thus, to sustain a dynamo with ohmic dissipation in the range $10^8\rightarrow10^{11}$ W, the total energy flow through the process must be of order $10^9\rightarrow10^{12}$ W. The total heat flow out of the surface of the Earth, about $2\times10^{13}$ W, itself places a restriction on the heat flux out of the core and thus leads to a restriction in the maximum size of a toroidal field in the core (see Gubbins, 1976).

An interesting aspect of a thermally-driven core dynamo model is that the energy dissipated through ohmic loss by electric current flow is not lost to the system but reappears as a heat source in the fluid. Thus, viewed from outside, it is not possible to tell what fraction of the total power flowing out of the system has been "side-tracked" through the dynamo process.

*Energy Sources for the Geodynamo*

(i) *Cooling of core.* A general cooling of the core produces (a) a heat source uniformly distributed through the outer core, plus (b) heat emerging at the inner core–outer core boundary from the cooling inner core, plus (c) latent heat released at the inner core–outer core boundary by the inner core freezing there.

Verhoogen (1961) estimated the amount of heat produced by a cooling core and there seems little reason to modify his estimates. He found the simple cooling source and the freezing source to be of the same order of magnitude; and for them together to produce an energy flow of $10^{12}$ W out of the core, the Earth's interior should be cooling at the rate of some tens of degrees over $10^9$ years.

For an Earth with a history of cooling this is a modest change; so that cooling easily provides power flow for the geodynamo.

(ii) *Radioactivity in the core.* As mentioned in Section 2.2), the case for potassium in the core may need some special geochemical pleading: otherwise radioactive heating of the geodynamo would be a physically reasonable possibility. As a thermal process it too would suffer the general inefficiency of such processes discussed above in "Energy needs for the geodynamo".

(iii) *Precession of the Earth.* This was proposed particularly by Malkus (1968) as a power source for the geodynamo, but its adequacy as a power supply if flow in the core is laminar has recently been questioned by Rochester *et al.* (1975) and Loper (1975).

(iv) *Sedimentation.* There are several different ways in which the core fluid could be kept in motion by heavier material sinking and lighter material rising. Pondering the formation of the core itself, Urey (1952) suggested core motions could be set up by iron continuously falling into the core from the mantle. Later, Braginskii (1964) found that due to the inefficiency of thermal convection his dynamo models required too great a flow of heat out of the core, and he developed a theory in which silicon is released at the inner core–outer core boundary as the inner core (of effectively pure iron) is continuously formed by freezing the impure outer core material. The silicon, being lighter than the outer core fluid, floats upwards and may thus drive core motions.

The energy released by such a chemical differentiation process depends crucially upon the existence of a density increase at the inner core–outer core boundary. Modern seismological techniques are approaching the point of establishing whether or not a significant density increase occurs, and, on the basis of evidence that it indeed may, Gubbins (1976) has also favoured gravitational settling as a major contribution to the dynamo process. Gubbins (1977) points out that such a process does not have a fundamental inefficiency like thermal convection, but can in fact be very efficient.



(v) *Seismic energy.* The possibility that sufficient of the energy given off by earthquakes might be converted in the core to drive the dynamo was suggested by Mullan (1973), on the basis of an earthquake energy supply rate of $3\times10^{11}$–$3\times10^{12}$ W. Comparison of this power figure with the requirements of the geodynamo discussed above indicates that an unreasonably efficient seismic to dynamo energy transfer process would be required, though it is possible that the seismic energy figure may be an underestimate with regard to long period disturbances. Crossley and Smylie (1975) found that core oscillations suffered little damping and so might couple with a dynamo process, though Gubbins (1975) calculated that they would have insufficient amplitude. The case for seismic energy driving the dynamo seems at best to be marginal on present evidence.

*An Outline of the Geodynamo*

Repeating the caveat that core theories are generally indefinite, the author will here synthesize the foregoing ideas into a description of one way in which a dynamo process could be taking place in the core of the Earth. For the newcomer to dynamo theory the description may illustrate concepts and provide a model to think in terms of. The description which follows is not profoundly different from that of Bullard and Gellman (1954), whose dynamo model has been a working basis of earth scientists for more than twenty years, including the crucial period when development and acceptance of the sea-floor spreading hypothesis depended upon understanding the behaviour of the geomagnetic field.

First, the Earth is taken to be cooling from a hot origin (see A. E. Ringwood's contribution to this volume, Chapter 1), so that the power flow out of the cooling core is comfortably adequate to drive the dynamo process and has been so since early pre-Cambrian times. This power flow is of order $5\times10^{12}$ W: a modest fraction of the surface terrestrial heat flow, but sufficient to include the heat conducted along an adiabatic gradient in the outer core; a lesser flow would mean that the core was stable against convection (at least in part). This power flow comes both from general cooling and also from latent heat and possibly buoyancy forces at the inner core boundary, and so is enough to support an ohmic dissipation of perhaps $10^{11}$ W, thus allowing moderate toroidal fields within the Earth. The cooling rate is of order some tens of degrees per $10^9$ years, and the whole mantle also cooling at about this rate provides for another $5\times10^{12}$ W of the terrestrial heat flow. In the mantle, it is necessary for the heat given off by cooling to be transported by convection. The other $10^{13}$ W of surface heat flow comes from radioactive elements, mostly concentrated in the crust.

The actual flow patterns in the core, aligned by Earth's rotation and thus in some unspecified way producing an axial field, may be like those determined experimentally by Hide (1953) (see also Runcorn 1954) and Busse (1975), from where Fig. 6 is taken. They will be modified by the radial

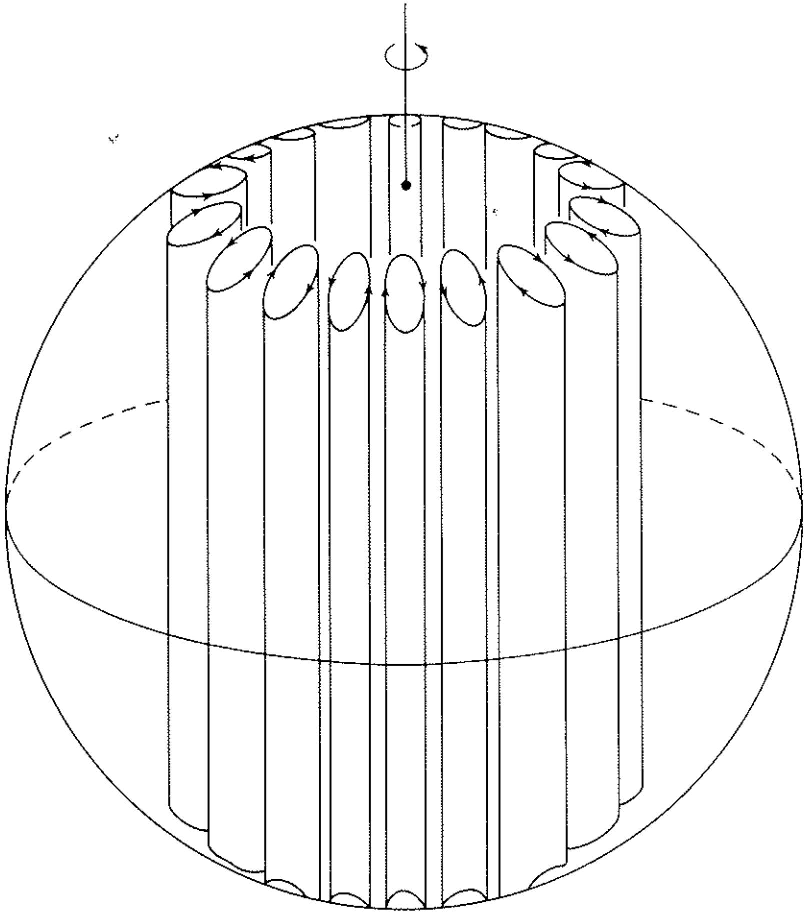

Fig. 6. A sketch for the onset of convection in a rotating sphere. (From Busse, 1975.)

buoyancy occurring in the central gravitational force field of the Earth's core and also (possibly extensively) by magnetohydrodynamic forces. Time fluctuations of the magnetic field will occur even when the flow pattern is



relatively steady, due to the very stringent requirement for stability that the right-hand side of equation (1) must balance in all three components at all points in the core. The magnetic time fluctuations will be exacerbated when the fluid flow changes with time due to magnetohydrodynamic forces, and even due to the simple developments which occur in convective flows when the area above an uprising column is heated in excess of its surroundings, and an area below a sinking column is cooled in excess of its surroundings. The delicate state of core thermal conditions may well cause by themselves a quite natural migration of convection patterns with time.

The determination and observation of new core-dependent parameters may enable such a model to be modified and refined. But the exact nature of the geodynamo may remain one of the Earth's best kept secrets.

## 3. Miscellaneous Processes

The core may demonstrate a whole range of processes which could not be modelled under laboratory conditions and which, if not unique to the Earth, could nevertheless only at present be reasonably expected to be studied in any detail on this planet: foremost amongst these is, of course, the dynamo process itself, just described. The final part of this article now briefly discusses three others.

### 3.1. Interaction of Magnetic Fields and Seismic Waves

As noted in Section 2.3, any evidence on the toroidal magnetic field strength within the core would be most valuable. A number of authors have therefore examined the possibility (first suggested it seems by Cagniard, 1952), that the magnetic field in the core would interact with seismic waves passing through it, to an extent detectable in surface seismic observations. Such phenomena in which magnetic and elastic forces interact have been called "magnetoelastic" (a term also used to describe the somewhat different phenomena of the elastic properties of actual magnetic material).

Elastic waves can be strongly damped by non-uniform magnetic fields in laboratory experiments (Lilley and Carmichael, 1968, 1970), but it appears that in the core of the Earth the effect would be negligible (Lilley and Smylie, 1968). Crossley and Smylie (1975) have shown, in fact, that the electromagnetic damping of core oscillations is likely to be so slight that the converse possibility arises of core oscillations contributing significantly to a dynamo process (see "Energy sources for the geodynamo" in Section 2.4).

## 3.2. Oscillations of a Core Stable against Convection

Slichter (1961) pointed out a possible oscillation of the whole Earth in which the inner core moves about its equilibrium central position. The restoring force is not predominantly elastic but gravitational, so that the inner core floats (or more precisely, sinks), backwards and forwards. Fundamental to this process is the central gravitational force field experienced by a particle in the Earth's core.

The inner core represents a basic stratification within the core. It has to be slightly denser than the outer core (more precisely to depart from the Williamson–Adams equation with positive $\eta$, see "Stability of the fluid core against convection" in Section 2.3), or else it would be neutrally buoyant and not confined to the Earth's centre. If the fluid in the outer core is also stable against convection a whole range of extra oscillations are allowed, similar to the basic Slichter mode in that the dominant restoring forces are due to buoyancy. These modes have become known as the "gravitational undertones" of Earth oscillation; although arising in the core they will in fact affect the whole Earth because the mantle–core boundary is not rigid. Streamlines for the basic Slichter mode and one undertone are shown in Fig. 7.

Such modes have been the subject of much study (e.g. Crossley, 1975; Smith, 1976). In a recent paper, Johnson and Smylie (1977) discuss the theory for computing all different oscillation modes of a model Earth. Also important are the inertial modes, arising in a fluid core simply as a result of its rotation. These inertial modes do not depend on stable stratification for their existence, but are influenced by self-gravitation and compression.

The general effect of rotation is to couple different modes together, in particular into two distinct chains. The coupling is weak at periods of 1 h or less (for the normal elastic modes) but strong at periods of several hours or more (for the gravitational undertones and inertial oscillations).

A very weak gravity signal of appropriate frequency and amplitude should occur at the Earth's surface if these modes can exist and if they are excited by a strong-enough earthquake (Jackson and Slichter, 1974). There is currently much interest in developing ultra-sensitive gravimetric techniques because of this possibility of collecting new data pertaining to the Earth's core.

## 3.3. Biological Effects of Geomagnetic Reversals

The solar wind, a stream of particles continually flowing off the Sun's surface, interacts with the geomagnetic field to produce two main effects: (i) the solar wind is deflected clear of the Earth's surface, and (ii) the geomagnetic field is contained within a region about the Earth known as the magnetosphere. This situation is depicted in Fig. 8.



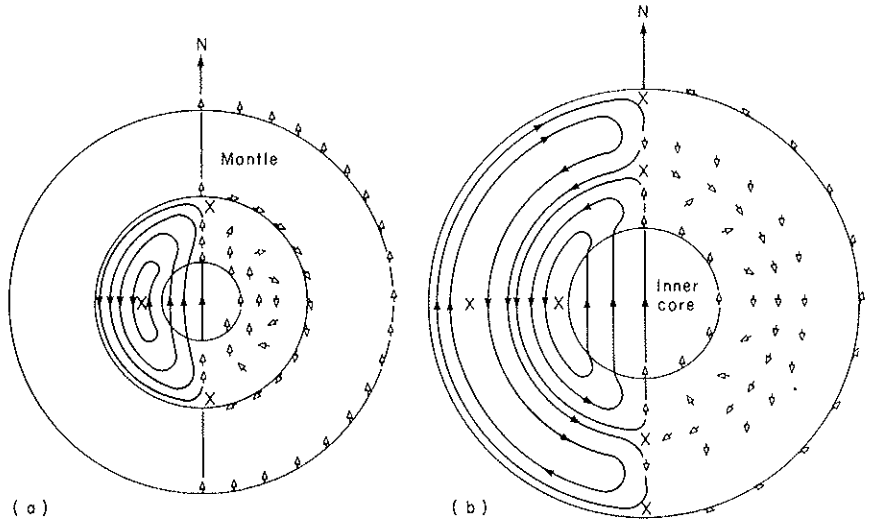


Fig. 7. (a) The Slichter mode of inner core oscillation (often denoted $_{-1}S_1^0$); (b) the second undertone ($_{-2}S_1^0$). (From Crossley 1975). Note different scales of (a) whole Earth and (b) the core only. The right half of each ~~figures~~ figure shows instantaneous motion and the left half the corresponding streamlines.

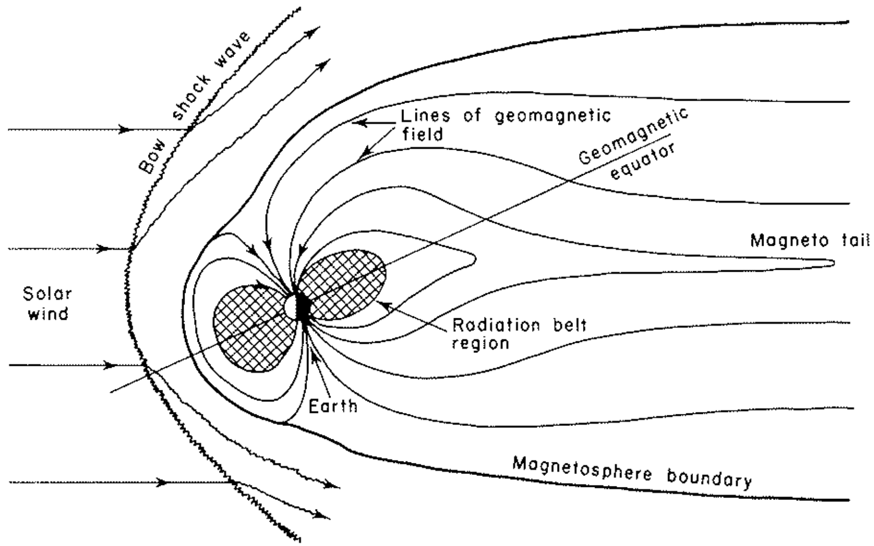


Fig. 8. The magnetosphere formed by flow of the solar wind around the Earth's magnetic field. (After Ness, 1970.)

A reversal of the main geomagnetic field will cause gross changes in the magnetosphere. If the poles of a weakened geomagnetic field migrate along lines of geographic longitude (as palaeomagnetic studies have shown that they may, see "Palaeomagnetic evidence for the geodynamo" in Section 2.4), then as the magnetic poles approach the geographic equator substantial changes in the magnetosphere will occur during each day. If the field reverses by weakening to near zero in one axial direction and then growing in the other there will be a time of near-zero field when the magnetosphere will be greatly reduced, if not collapsed completely (cf. McCormac and Evans, 1969; Siscoe *et al.*, 1976).

Uffen (1963) first pointed out that by thus removing or at any rate much reducing the magnetosphere, a geomagnetic reversal could have biological effects. He identified two mechanisms during a reversal: (i) charged particles would be dumped on Earth's surface from the Van Allen radiation belts in the magnetosphere where they are normally trapped, and (ii) with the magnetospheric "solar-wind shield" removed, the charged particles of the solar wind would be able to reach Earth's surface directly. Both sources of charged particles could induce genetic mutations in living organisms at the Earth's surface, and thus exert a pressure on evolution.

Uffen's model was qualitative, and more quantitative estimates (Sagan, 1965; Waddington, 1967; Black, 1967) did not support his particular mechanisms as being likely. However, detailed evidence of coincidences of faunal extinctions and geomagnetic reversals began to accumulate, especially from analyses of deep-ocean sediment cores (Harrison and Funnell, 1964; Opdyke *et al.*, 1966; Watkins and Goodell, 1967; Steuerwald *et al.*, 1968; Hays, 1971). In seeking an intermediate process in a possible chain of causes it was noticed that climate patterns also correlated in some instances (Harrison, 1968; Wollin *et al.*, 1971; Harrison and Prospero, 1974; Fairbridge, 1977).

Most recently, Reid *et al.* (1976) have re-examined the question of ultra-violet light received at the Earth's surface during a geomagnetic reversal. Knowledge of the Earth's stratospheric ozone layer which normally absorbs much of the ultra-violet radiation from the Sun has increased recently, due to its relevance in various topical environmental matters. Reid *et al.* now estimate that during a geomagnetic reversal the number of solar protons reaching the stratosphere may be greatly increased and consequently the ozone concentration there greatly reduced. Such a mechanism is only one step from Uffen's original hypothesis: the solar protons may not cause mutations directly but they affect the atmosphere and so allow in an increased flux of potentially harmful ultra-violet radiation.

In as much as it involves the Earth's atmosphere, the solar proton process may also be expected to affect climate. Indeed, on the shorter time scale of recorded history there is much current interest in the possible influences which the geomagnetic field and its solar relationships may have on terrestrial weather (Wilcox *et al.*, 1974; King, 1974; Wollin *et al.*, 1973).



## Acknowledgements

For advice on topical matters concerning the geomagnetic field and the core I am grateful to many people, especially J. R. Cleary, D. Gubbins, J. A. Jacobs, M. W. McElhinny, A. E. Ringwood, M. G. Rochester, D. E. Smylie, F. D. Stacey and D. J. Stevenson: several of these I thank also for comments on a first version of this manuscript.

The diagrams in this review have come from a variety of sources, and I thank the authors of the original articles concerned for permission to reproduce their diagrams here.

Finally, in this article, I should like to acknowledge the pleasure it has been to work for the last ten years in the stimulating atmosphere for earth science engendered at the Australian National University by J. C. Jaeger and A. L. Hales.

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