GEOMAGNETISM

Influence of the inner core

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THE dynamo theory for the origin of the Earth's magnetic field is notoriously difficult. The equations are basically those of physical oceanography and meteorology with the added complications of the magnetic field; laboratory experiments involve large masses of dangerous liquid metals that are difficult to instrument; numerical simulations are comparable in scale to those of weather forecasting; and observations are scarce.

Against this background, progress must be made through highly simplified numerical models and success measured in terms of a general understanding of the underlying physics rather than specific matching of theory to observation. On page 541 of this issue, Hollerbach and Jones[1] pull out a couple of surprises from a relatively simple model· incorporating a solid inner core, they find, stabilizes the dynamo and establishes a constant polarity such as we have on the Earth; furthermore, the magnetic field solution oscillates strongly at depth within the core but fluctuates only mildly at its surface. Perhaps we see only the tip of the iceberg in terms of magnetic field changes during times of stable magnetic polarity, and the mild fluctuations occasionally exceed a threshold that triggers a magnetic reversal.

The core occupies the central 3,500 km of the Earth, about half the total radius; the outer core is liquid iron, whose flow generates the magnetic field. Towards the Earth's centre, both pressure and temperature increase; the increase in pressure raises the melting point of iron. At a radius of 1,216 km the melting point reaches the ambient temperature, and the central inner core of the Earth is solid iron. Its cooling supplies energy for the dynamo, but the inner core's inductive effect on the magnetic field has always been considered negligible because it is small and buried deeply within the rest of the core. The new results therefore come as something of a surprise.

Core dynamics are strongly influenced by rotation, and the governing law is the Proudman–Taylor theorem: flow of a rapidly rotating fluid dominated by Coriolis forces cannot vary along the rotation axis. These conditions certainly hold in the Earth's core, although we are unsure how far the magnetic field removes the Coriolis constraint. Convection in rotating spheres takes the form of rolls aligned with the rotation axis, thus satisfying the Proudman–Taylor theorem except near the ends, where the slope of the spherical boundary makes it impossible. In the presence of an inner core the most unstable convection rolls touch the inner core so that their ends are close to the 'flattest' part of the boundary[2]. The sphere can be thought of as splitting neatly into two distinct regions, inside and outside a cylinder inscribing the inner core and with its axis parallel to the rotation axis. In polar regions, inside the cylinder, the fluid attempts to rise along the rotation axis in order to carry heat (or light material) outwards but is immediately in violation of the Proudman–Taylor theorem. Light fluid in low latitudes (outside the cylinder) rises, but its flow is turned to the form of rolls by the Coriolis force. On the Earth this cylinder has a radius about the poles of around 21° and there is some evidence that the magnetic field is influenced by it, with magnetic flux at the core surface concentrated away from the poles and around this inner core circle[3].

Hollerbach and Jones's model makes a common assumption that magnetic field is generated through an 'α-effect'. The assumption, a drastic one, is that small-scale or non-axisymmetric flows act on the large scale to induce electric current parallel to the magnetic field — opposite to the macroscopic physical effect of an electrical conductor cutting magnetic field lines, which generates electric current perpendicular to the field. The underlying theory was developed independently for the Earth[4] and the Sun[5] and has formed the basis of most subsequent dynamo work. There are serious worries about its application to the Earth (the energy budget is inadequate and it predicts only axisymmetric magnetic fields, for example) but the model yields tractable equations that are probably a fair guide to the time evolution of the main dipole magnetic field and the macroscopic dynamics of the core, in particular its differential rotation and meridian circulation.

Meridian circulation seems to favour the generation of steady rather than oscillatory magnetic fields in kinematic dynamos, in which the fluid flow is prescribed rather than being obtained as a solution of the equations of motion[6]. The result appears to hold for full three-dimensional dynamos (D. G., manuscript in preparation), but it has proved exceedingly difficult to obtain a suitable form of meridian circulation from a dynamical model[7], and most such dynamos generate oscillatory or chaotic magnetic fields. Why should the Earth's magnetic field be so stable?

Hollerbach and Jones find that the inner core imparts that stability. First, dynamo action is restricted mainly to the region just outside the inner-core cylinder, with magnetic flux expelled from this entire cylinder. This, it seems, favours steady fields by generating the appropriate meridian circulation. Second, the electrical diffusion time of the inner core lengthens the timescale for change in the magnetic field and essentially averages out any wild fluctuations in the magnetic field that might lead to rapid reversal of the whole field. The result is a quasi-periodic solution that oscillates about a non-zero average.

A further remarkable property of Hollerbach and Jones's solution is the dramatic oscillatory changes deep in the core coupled with the rather mild variations in dipole moment. It suggests that the oscillations seen at present in the geomagnetic dipole, with a typical period of thousands of years[8], may be a symptom of much greater magnetic changes deep in the core. The authors suggest that particularly large oscillations may develop into full reversals, thus developing a train of speculation that began with Cox's[9] original phenomenological reversal model and continuing with the suggestion that the oscillations may be directly related to the flux expulsion going on at present beneath the South Atlantic[10]. Alas, the α-dynamo model is incapable of predicting such non-axisymmetric fields, but the new model is a big step forward in our understanding of how such a process might work.

It is an intriguing thought that the inner core can control magnetic reversals. Perhaps we should look towards a changing inner-core radius to explain the long-term change (over tens of millions of years) in reversal frequency, and the almost total absence of reversals for long intervals in the Cretaceous and Permian periods. These changes are normally attributed to changing conditions at the interface between core and mantle, but the inner-core radius will also vary on this timescale: if the core were colder at some point in the past, the melting point of iron would be reached further out and the radius of the inner core would be correspondingly larger, the condition favouring stable polarity in Hollerbach and Jones's model. ☐

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