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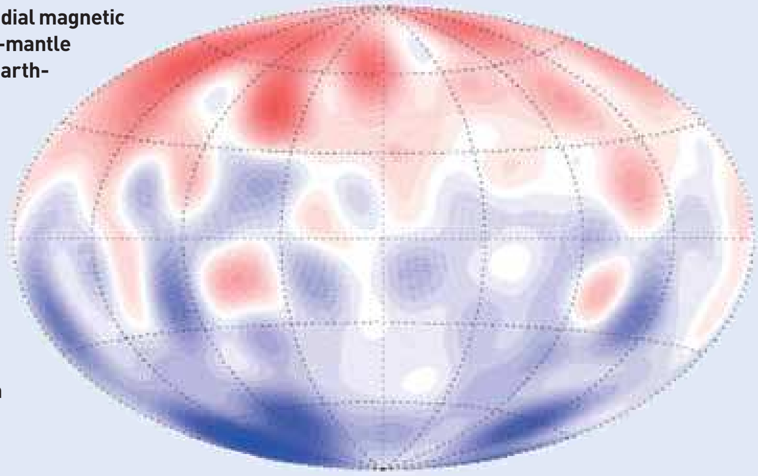
Changes in the magnetic field allow us to probe the Earth's iron core. Grace Cox and William Brown review how observations, modelling and theory combine.

Rapid dynamics o

The Earth's magnetic field is the largest feature of our planet, extending from within the solid inner core to the bow shock, where it meets the solar wind (approximately 90000km from the Earth's surface). Continuous measurements of the geomagnetic field have been made at the Earth's surface for several centuries, though spatial coverage was historically limited to the northern hemisphere. In recent years, satellite measurements have provided high-precision magnetic data with excellent spatial and temporal coverage. The observatory and satellite data are supplemented by less precise measurements of the remanent magnetic fields recorded in rocks and in archaeological artefacts that can become magnetized as they cool from high temperatures. The magnetic field that is observed using all of these methods has several sources: the core, crustal rocks, the ionosphere and the magnetosphere. Here we focus on short-timescale features of the magnetic field, recently reviewed by Finlay *et al.* (2010).

The geodynamo is the process by which the geomagnetic field is generated in the Earth's molten iron–nickel outer core. Fluid motions in the outer core are driven by both thermal and compositional gradients (e.g. Fearn and Loper 1981). Heat is released in the planet's interior by the solidification of the inner core, by radioactive decay and by the secular cooling of the whole Earth. This heats the outer core from below, causing hot material to rise up from the inner-core boundary (ICB) by thermal convection. As well as producing latent heat, inner-core solidification releases light elements into the outer core, because the heavier elements are preferentially incorporated into the inner core. These elements are compositionally buoyant (lighter than the ambient fluid) and rise up from the ICB to drive compositional convection.

In the presence of an ambient magnetic field, motion of an electrically conducting fluid induces electrical currents in the fluid. Such electrical currents circulating in the convecting iron–nickel outer core give rise to magnetic fields, which have associated electric fields that interact with the pre-existing magnetic field. This continuous interaction of electrical currents and magnetic fields is called a self-exciting dynamo, which constantly maintains the field against decay by converting kinetic energy into magnetic energy. The internally generated magnetic field is thought to produce the majority of the observable field, which is similar in structure to that of a bar magnet tilted approximately 11° from the rotation axis (e.g. Merrill *et al.* 1998).



1: A modelled radial magnetic field at the core–mantle boundary with Earth-like dipolarity and patches of reversed flux. This simulation used parameters and boundary conditions that facilitate the production of Earth-like dynamos. (From Teed *et al.* 2013)

This field undergoes significant variations in both space and time. Temporal variations in the geomagnetic field, called secular variation, occur on timescales from milliseconds to millions of years. Very short timescale signals typically originate from the influence of the solar wind and the interactions of the ionosphere and magnetosphere with the internal field. The total signal is therefore time-averaged to permit the study of the more slowly varying internal field. Observed secular variation provides a means of determining the behaviour of the geodynamo because the internally driven magnetic field is, to a high degree of approximation, "frozen in" to the fluid motions of the outer core. This is particularly important because the Earth's core is far too remote to be probed directly, and computational limitations prevent numerical simulations attaining the relevant parameter regime for the deep Earth.

Observations of the field

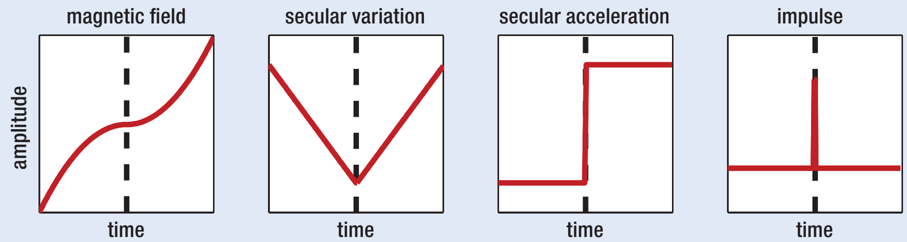
Historical field observations (see Jackson *et al.* 2000) consist of nautical logs, predominantly, with data from land-based observatories becoming more common from the 1840s onwards. As a result, the spatial bias in observations has shifted from the oceans to land – particularly to Europe. Nautical logs generally document declination (the angle between magnetic and geographic north) and, on occasion, inclination (the angle between the magnetic field vector and the horizontal). Measurements of the horizontal and total intensities of the magnetic field vector began to be recorded after the work of Gauss in 1832. Observatories switched to a convention of recording the x, y and z (north, east and vertically downward, respectively) components of the field in the 20th century. The most recent development in magnetic observations came with the satellite age, perhaps the most notable missions being MagSat (1979–80), Ørsted (1999 onwards), CHAMP (2000–10) and SWARM (to be launched in late 2013). These satellites provide data with excellent resolution, spatial and temporal, but have limited duration.

Geomagnetic jerks

Together these data show a magnetic field that changes on long and short timescales. Often it is the rate of change of the field, the secular variation, or the second time derivative, the secular acceleration, that are investigated to study the field's evolution over time. The most striking observations in palaeomagnetic data are geomagnetic reversals, which occur every few hundred thousand years and are recorded in rocks at mid-ocean ridges and on land. While these events are easily identifiable within the rock record, and are reproducible in numerical simulations of the geodynamo, they appear to occur spontaneously and a full explanation of their driving mechanism remains elusive. The dominant feature of present-day secular variation is the westward drift of several prominent features of the internally generated field at a rate of 0.2°/yr (Bullard *et al.* 1950). On an even shorter timescale are geomagnetic jerks. These are sudden changes in the generally linear trend of secular variation and may be observed regionally at just a few observatories or more globally, typically over periods of several months.

The magnetic field is generated by the constant evolution of Earth's molten outer core and it is

f the Earth's core



2: An example of a characteristic jerk morphology seen in a component of the magnetic field and its first three successive time derivatives; secular variation (d/dt), secular acceleration (d^2/dt^2) and impulse (d^3/dt^3). The dashed lines represent the time of the jerk.

believed that jerks are manifestations of rapidly changing flows at the surface of the outer core. While various generation mechanisms have been suggested for these rapid changes, none have conclusively explained them. A complete understanding of the observations in magnetic observatory data would help to form a stronger link to the causes of jerks. The characteristic morphology of a jerk is shown in figure 2, but there is no strict definition of their form or scale other than that they must be visible above the background noise level of the data. Therefore, they are hard to identify objectively.

Various techniques have been applied to the problem of jerk identification, some simple and others more complex, but generally the results vary depending on the particular data and analysis technique used (see Mandea *et al.* 2010 and references therein). This inconsistency between studies and the limited focus on portions of data makes it difficult to compare interpretations and ascertain if any overall patterns occur. Previously, jerks have been suggested to be rare occurrences, visible across the whole globe within a year or two and perhaps showing regular delays between certain regions. Combining a method to remove the contamination of external magnetic fields with a simple method to apply a fixed definition and identify jerks in a strict and consistent manner through all available observatory data from the past 50 years, Brown *et al.* (2013) show that jerks are far more frequent than previously suggested. They appear to be part of the more rapid end of a spectrum of core dynamics and not the rare and unusual event assumed in the past. The lack of a consistent pattern in the spatial distribution of jerks suggests that they have complex origins, that they interact with the electrically conductive mantle as they pass through, or that we observe the superposition of several discrete individual events at the Earth's surface.

Jerk amplitudes (equivalent to the step change in the secular acceleration) vary through time and their variations are periodic in Europe and North America. This could mean that the causes of jerks are related to the six-year periods detected independently in the secular variation (Silva *et al.* 2012) and length-of-day (LOD) (Abarca del Rio *et al.* 2000); this periodicity may constrain the source of jerks in the core.

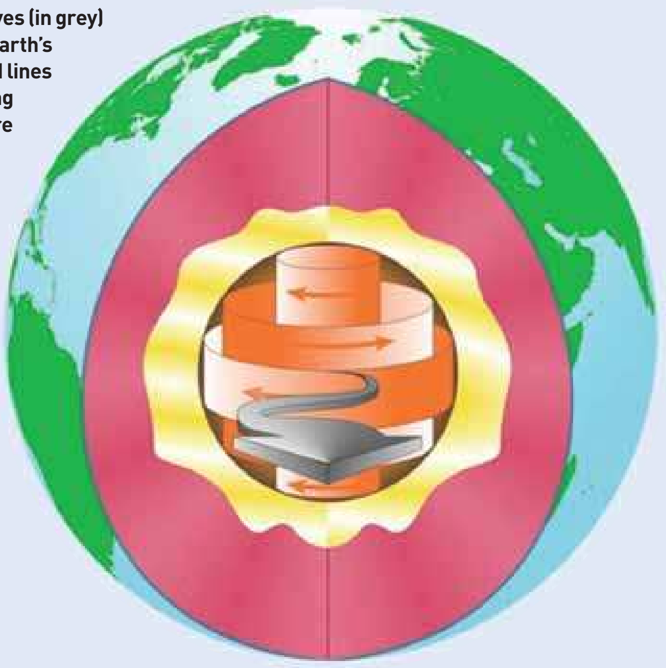
Satellite data provide detailed observation of individual events such as the jerk widely observed in 2003. Detailed knowledge of the magnetic field and its time variations allows extrapolation of the field down to the core–mantle boundary (CMB). This in turn, with several assumptions about the core's behaviour, allows the estimation of the horizontal flow and flow acceleration at the surface of the outer core – flow that is deemed responsible for generating the observed field. Estimation of the flow and flow acceleration jointly throughout the 2003 jerk shows that no steady flow can provide a satisfactory account of both the secular variation and secular acceleration (Silva and Hulot 2012). The secular acceleration cannot be satisfactorily explained by toroidal zonal flow accelerations alone and requires broader tangentially geostrophic flow acceleration, possibly also symmetric about the equator. It is hoped that such features of the flow acceleration are characteristic of jerks and can be used to help identify and compare other jerk events. Discovering a characteristic flow pattern during jerks could lead to a better understanding of the apparent correlation between jerks and changes in the rotation rate of the Earth, because the exchange of angular momentum between the core and mantle is linked to the motion of the fluid near the core surface (Holme and de Viron 2013).

Core flows can also provide information about longer-term aspects of core behaviour. While individual core flow estimates at any time are not unique solutions – they depend on the assumptions made – there are features of the large-scale flows, such as the westward drift of flux patches near the equator and the relatively quiet Pacific hemisphere, that are robust with different assumptions and throughout the past 170 years of observations. Using historical field measurements, core flows can be calculated back to 1600. Linking implications of a large eccentric gyre, similar to those of Pais and Jault (2008), and associating flow in the radial direction (i.e. into or out of the centre of the Earth) with thermal convection processes, may suggest that the eastern hemisphere of the inner core is hotter than the west. Though somewhat controversial, this is the first geomagnetic evidence linked to previously reported seismic observations of structural and dynamical differences between the two halves of the inner core (e.g. Tanaka and Hamaguchi 1997).

Background state

Timescale matters in many physical systems; for example, we can forecast the weather tomorrow without having to consider long-term climate evolution. While the whole weather system could, in principle, be studied in one go by making a forecast for a long enough period to encompass climate change, this is not computationally practical and chaotic effects would quickly invalidate the results. It makes sense to study the rapid dynamics and the slow background evolution separately, but the rapid dynamics depend on accurate knowledge of the background. Climate measurements provide the background state for weather forecasts, but what is the background state of the core? The dominant force balance in the Earth's core is thought to be magnetostrophic, which is between the Coriolis, pressure, buoyancy and Lorentz forces (e.g. Hollerbach 1996). This balance is of considerable interest because it describes the slow (millennial timescales) evolution of the magnetic field, and may explain dynamics such as geomagnetic reversals, and also the longstanding dominance of the axially symmetric dipolar component of the field. Superimposed on this background state are more rapid dynamics such as torsional Alfvén waves, which provide an indirect means of probing the Earth's core (see below).

Any magnetic field evolving in the magnetostrophic balance must satisfy a stringent class of constraints at all times, as Taylor identified in 1963. When a magnetic field is organized in such a way that it obeys these constraints, it is called a Taylor state. Such magnetic fields have been largely inaccessible to geodynamo models because of difficulties in finding an exact Taylor state to use as an initial condition, as well as the problem of ensuring that Taylor's constraint is obeyed at each time step. Formally, Taylor's constraint is a continuum of conditions that gives an infinite number of constraints on the field, but the condition can reduce to a finite and surprisingly small number (Livermore *et al.* 2008). Livermore exploited this fact to construct some example exact Taylor states, plausible snapshots of the dynamic balance of the core, in both a full sphere and spherical shell. Although isolated examples had previously been found (Fearn and Proctor 1987), this work represented the first generalized approach to constructing exact Taylor states. These examples were designed to be consistent with present-day geomagnetic field observations, and represented a way of downwards continuing the field inside the core. Livermore is currently extending these ideas with the goal of designing a time-dependent Taylor state model of the Earth's core. Ultimately, a time-evolving background state will be the starting point for models that can explore rapid instabilities that are superimposed on such a state. It is hoped that such models will shed light on what causes the observed secular variation.



3: Cartoon of torsional waves (in grey) propagating through the Earth's core. Radial magnetic field lines permeate the fluid; rotating cylinders of fluid in the core perturb the magnetic field which, in turn, provides a magnetic restoring force, allowing waves to propagate along the field lines.

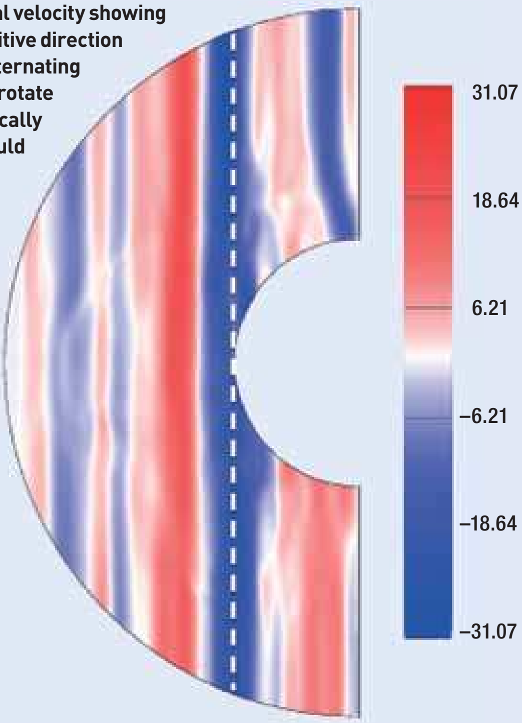
Torsional Alfvén waves

Departures from a Taylor state excite torsional Alfvén waves, essentially rigid accelerations of cylindrical surfaces that seek to re-establish the state by stretching radial magnetic field into azimuthal field (figure 3). Alfvén waves are transverse waves that propagate in an electrically conducting fluid in the presence of an ambient magnetic field. Studies of such waves in the Earth's interior are important because applying inverse methods to geophysical data allows us to infer aspects of the structure and physical properties of the core that would otherwise remain inaccessible.

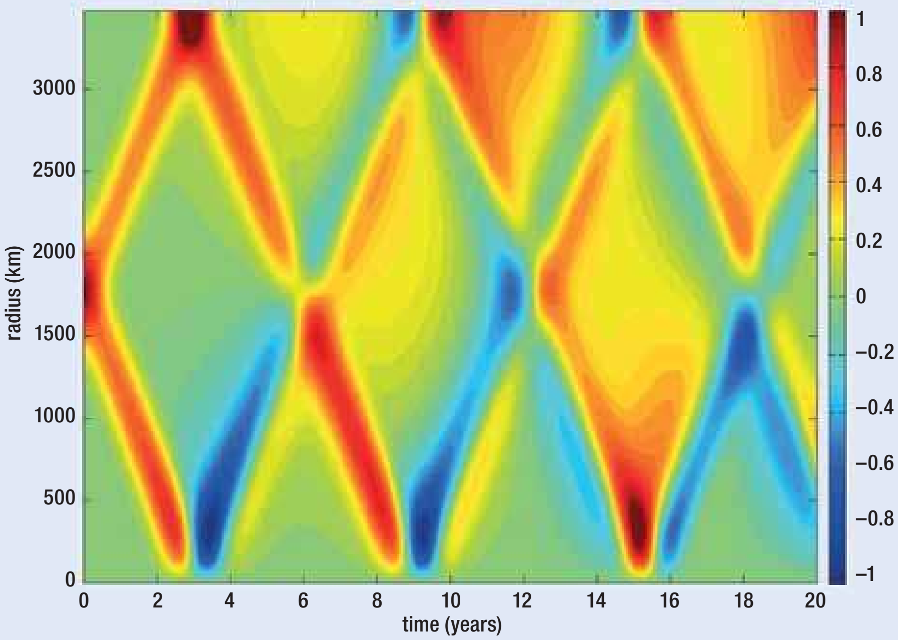
Torsional Alfvén waves have been thought to exist in the Earth's core since Taylor predicted their existence on theoretical grounds in 1963. Braginsky (1970) made the first link between theory and observations by using torsional normal modes to explain decadal signals in secular variation and in LOD. More recently, decadal signals in observations of secular variation and LOD have been attributed to the presence of these waves in the core, providing an important means of estimating core properties such as viscosity and internal magnetic field strength. Torsional waves can cause changes in LOD because their geostrophic motions transport angular momentum through the core. As this quantity must be conserved for the whole Earth, changes in core angular momentum lead to corresponding changes in mantle angular momentum, hence changing the length-of-day. According to Jackson *et al.* (1993) and Jault *et al.* (1988), there is good correlation between changes in core angular momentum carried by geostrophic motions extracted from core flow models based on secular variation, and observed changes in solid-Earth angular momentum (measured as LOD) between 1920 and the present day.

Previous studies of torsional waves inferred from geophysical data have raised several interesting questions about their location and mechanism of excitation (Braginsky 1984, Legaut 2005, Livermore and Hollerbach 2012), direction of propagation and perhaps most importantly, their period. Earlier work suggested that torsional waves have periods of several decades, giving estimates of internal cylindrically radial magnetic field strength of between 0.2 and 0.4 mT (Braginsky 1970; Zatman and Bloxham 1997, 1999; Hide *et al.* 2000; Buffett *et al.* 2009). Abarca del Rio *et al.* (2000) first identified a six-year signal in LOD data, which Gillet *et al.* (2010) have recently attributed to fast torsional waves. As the period of Alfvén waves depends on the internal magnetic field strength, this new work suggests that the magnetic field inside the core is much higher than previously assumed (up to 4 mT). Interestingly, the direction of propagation concluded by Gillet *et al.* (2010) was from the edge of the inner core outwards towards the outer core equator, whereas Hide *et al.* (2000) observed waves propagating in the opposite sense. According to torsional wave theory, there is no physically preferred sense of direction, which implies that observed torsional waves should travel in both directions. If this is not the case, and waves travel in only one direction, this would provide us with information about how and where torsional waves are excited in the Earth's core, their damping mechanisms and any reflections at the boundaries.

Numerical simulations are an important tool for studies of core flow and the internal magnetic field. They allow direct analysis of the entire flow field, investigation of force balances and searches for torsional waves using their expected Alfvén speed. Despite significant advances in parallel computing during the past few decades, the low-viscosity low-inertia regime relevant for the Earth's core is unattainable in geodynamo simulations due to small length-scale and short timescale features. As a result, torsional waves may not have the same importance in simulations as they do in the core, though it is possible that the required force balances for torsional waves may be achieved even if the magnitudes of the forces are incorrect (Wicht and Christensen 2010). Teed *et al.* (2013) performed 3D dynamo simulations in a spherical shell in parameter regimes where Earth-like magnetic fields are produced and found torsional waves, identified by their propagation at the correct Alfvén speed, in many of the simulations. The waves often have core transit times of between 4 and 6 years and propagate either inwards or outwards in the cylindrical radial direction, sometimes being excited at the tangent cylinder (a theoretical cylinder that is coaxial with the rotation axis and has a radius equal to that of the inner-core boundary, see figure 4). Teed *et al.* (2013) find that the frequency, location and direction of propagation of the waves are influenced by the choice of model parameters, concluding that excitation mechanisms for torsional waves must be available throughout the outer core in their models. They calculated the driving terms for the waves in an attempt to better understand these mechanisms and concluded that both the Reynolds force and ageostrophic (non-zonal) convection acting through the Lorentz force are important in driving torsional waves. The next step is to perform magnetoconvection simulations over short time periods in a sphere or in simplified geometries, allowing the use of more realistic parameters with the goal of establishing simulations that better reproduce observed



4: Meridional section of average azimuthal velocity showing columnar convection. Red indicates a positive direction of flow, blue the reverse direction. The alternating polarities indicate that adjacent columns rotate relative to each other, as shown schematically in figure 3. Travelling torsional waves would be observed as propagating columns of fluid through time, while standing oscillations would be more difficult to observe because the columns would remain stationary. The dashed line represents a section through the tangent cylinder. (After Teed *et al.* 2013)



5: Contour plot of the non-dimensional velocity of torsional waves in a full sphere, with cylindrical radius on the vertical axis. A positive pulse (red) splits into two smaller pulses. One travels outwards to the equator of the core–mantle boundary at 3480 km and reflects with no change of sign. The other pulse travels inwards to the rotation axis, where it undergoes a phase change that results in a partial sign change (blue represents negative velocity).

features of the geomagnetic field.

Despite their important role in the study of core dynamics, little previous work has been dedicated to understanding the fundamental properties and behaviour of torsional waves. Schaeffer *et al.* (2012) investigated Alfvén wave reflection properties and energy dissipation in boundary layers by considering the effects of the ratio of kinematic viscosity to magnetic diffusion. They found that while little energy is dissipated during a single reflection from the CMB, successive reflections may lead to significant damping. Cox *et al.* (2013) have now used forward modelling techniques to investigate the propagation characteristics of torsional waves in various geometries. For the first time, the work identifies that torsional waves undergo significant dispersion during propagation as a result of their geometrical setting. This study attempts to quantify and fully characterize this dispersion, and discusses the possible implications for torsional waves observed in geophysical data, notably from their finding that long-wavelength features are more dispersive than short-wavelength features. This result is particularly important because the torsional waves that have been inferred from secular variation are relatively long wavelength, and are therefore likely to undergo significant dispersion within the core.

The same study makes the first link between torsional waves and the phase shifts that occur when passing through the rotation axis. These phase shifts are observed in models and provide insight into how the shape of torsional wave pulses evolves through time, an aspect of their propagation that has never been considered. This work highlights that torsional waves display complicated behaviour during propagation, even in relatively simple models, and perhaps sheds light on why these waves have proved so difficult to identify in geophysical data.

Core–mantle links

Observation of a 5.8-year oscillation in LOD that cannot be accounted for by variations in atmospheric or oceanic angular momentum indicates that some dynamic process within the core exchanges angular momentum with the mantle on this timescale (Holme and de Viron 2013). One explanation is that the LOD signal arises from excitation of a normal mode of oscillation involving the mantle and the solid inner core, with gravitational coupling providing the restoring force and thus transferring the angular momentum (Mound and Buffett 2006). The period of the oscillation in this situation is determined by the strength of the gravitational coupling and does not depend on the strength of the magnetic field within the fluid outer core. If this is the case, decadal changes in LOD, which have also been observed, could be attributed to relatively slow torsional waves in the fluid core, implying a relatively weak (cylindrically) radial magnetic field (of approximately 0.2 mT). Conversely, observation of rapidly propagating torsional waves in the outer core suggests a much stronger radial magnetic field (>2 mT) and may provide an alternate explanation for the source of the 5.8-year LOD oscillation (Gillet *et al.* 2010). The rapid torsional waves imply that normal mode periods of the waves in the fluid core are a few years or less, implying that decadal LOD variations must arise for some other reason. A recent investigation into the propagation of similar seismic waveforms from repeated earthquakes through the inner core has quantified the varying rotation rate of the inner core over the past 50 years (Tkalčić *et al.* 2013). This variation correlates well to the observed decadal LOD oscillations and, when combined with core flow estimations of torsional waves, provides information on the rotational dynamics of all parts of the core–mantle system in recent decades. This should allow the evaluation of possible coupling mechanisms between each part

Scale problems in the solar dynamo

The Sun's dynamo has long been studied through observations of sunspots, known since the 18th century to occur in cycles, with periods of high activity (many sunspots) and periods of low activity (few sunspots) occurring in succession. The 11-year solar cycle shows spatial coherence over the entire solar surface, which indicates a remarkable level of organization given that the magnetic field is generated by turbulent flow in a highly conducting plasma.

Previous attempts at understanding how highly organized fields arise in an astrophysical setting have been hampered by the very high conductivities involved. At low conductivities, organized large-scale magnetic fields are readily generated because diffusion controls the growth of the field on small length-scales. However, at high conductivities, the smallest length-scales in a turbulent flow are the most efficient at amplifying the magnetic field, which results in fields being dominated by rapidly varying small-scale fluctuations that prevent large-scale organization. The traditional approach to this problem is to enhance the large-scale magnetic field by introducing a large-scale flow, such as a shear, but for sufficiently high conductivity, the small-scale features are still overwhelming.

Using a very different approach, Tobias and Cattaneo (2013) have recently made a major step towards solving this problem. Their high-resolution dynamo simulations run at high conductivities are able to produce large-scale magnetic structures that are organized in both space and time. This organization appears to arise due to interactions between helical flow and shear, with the shear acting to reduce the efficiency of the dynamo process at small scales. In effect, the shear acting on helical flow damps the small-scale fluctuations and permits the generation of large-scale organized fields. An important component of these fields are propagating dynamo waves, which have previously been used to model the solar cycle.

of the system and hence much improved estimates of properties such as inner-core viscosity. Better knowledge of the material properties of the deep Earth system will provide more useful constraints for numerical solutions to the geodynamo problem.

Several strands of observational evidence indicate that the boundary condition satisfied by the geomagnetic field departs from spherical symmetry in the long term. The outer core is laterally homogeneous, so it is likely that such long-term departures from spherical symmetry arise from lateral variations at the CMB affecting the geodynamo. Thermal convection in the lower mantle takes place on timescales much longer than any core timescale, but the outer core is well-mixed by vigorous convection. The result is a fixed temperature boundary condition at the CMB for the outer core, with spatial variation dictated by mantle structure and temperature. This heat-flux pattern can be obtained from seismic tomography by using seismic shear velocity as a proxy for heat flux. The resulting heat-flux map contains a range of length scales and is dominated by a large term of spherical harmonic degree and order 2, a significant departure from spherical symmetry. Thermal core–mantle coupling must therefore affect the geodynamo.

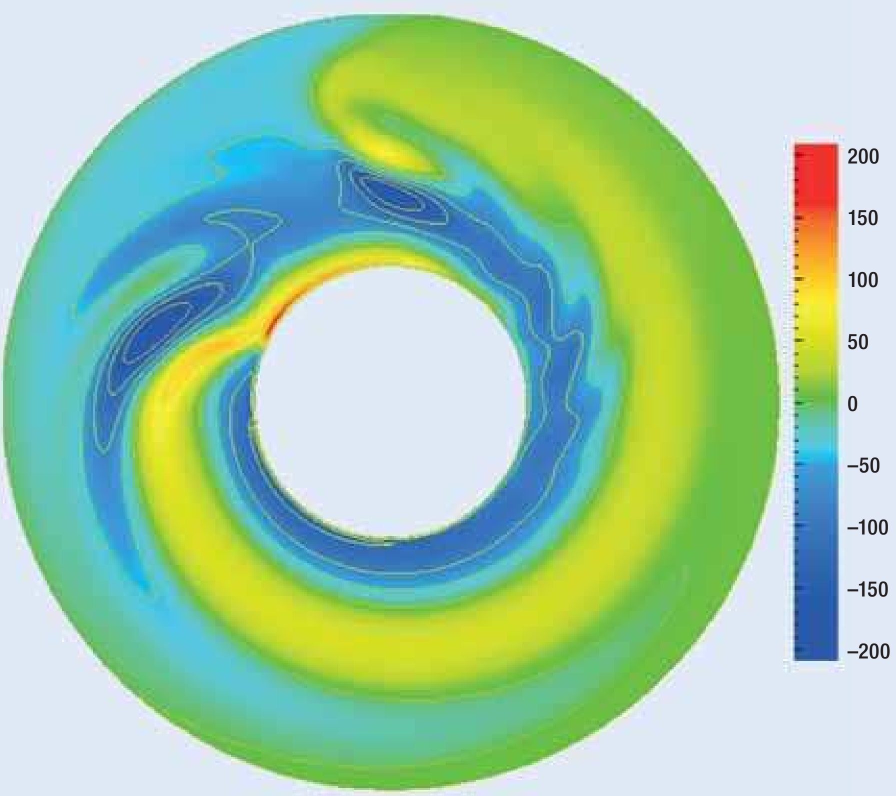
There is observational evidence for a lack of spherical symmetry in the boundary condition of the magnetic field: four "lobes" of intense magnetic flux at the CMB, symmetrically displaced about the equator at high latitudes, are observed in field models spanning various periods. In addition, palaeomagnetic data indicate that the virtual geomagnetic poles have a tendency to traverse one of two paths during geomagnetic reversals. Finally, variation of magnetic features is persistently low in the Pacific hemisphere compared to the Atlantic hemisphere.

Further insight has come from new core thermal and electrical conductivity estimates that are between two and three times higher than previous values, which suggest that a thermally stratified layer at the top of the core is likely (Pozzo *et al.* 2012). The conductivities for mixtures of liquid iron, oxygen, sulphur and silicon at core conditions were estimated from first principles using density functional theory – a quantum mechanical modelling method based on the atomic scale representation of material properties by functions of the electron density. Principally, these new conductivity estimates suggest that the heat flux out of the core, the power supply for plate tectonics, volcanism and the geomagnetic field, is higher than previously thought. This high core heat-flux implies that either the dynamo can operate stably on a lower power input than previous estimates, or that substantial additional heat comes from radiogenic decay in the core itself. A higher heat flux into the mantle would also result; that is, high enough to be near the upper bound of what is thought to be reasonable for mantle convection as it is currently understood. It may also affect estimates of when the inner core formed. Inner core formation, with thermal and compositional convection, is thought to be necessary for the generation of the magnetic field. Magnetized rocks have been found from more than 3.5 billion years ago. An early origin for the inner core would require substantial radiogenic heating within the core itself. For a young inner core formed, say, 400 million years ago, the thermal driving of the dynamo is not easily explained by the current understanding of core dynamics. With a stably stratified layer below the CMB, our understanding of the generation of the secular variation may need to be revised since this is attributed to the region near the surface of the outer core.

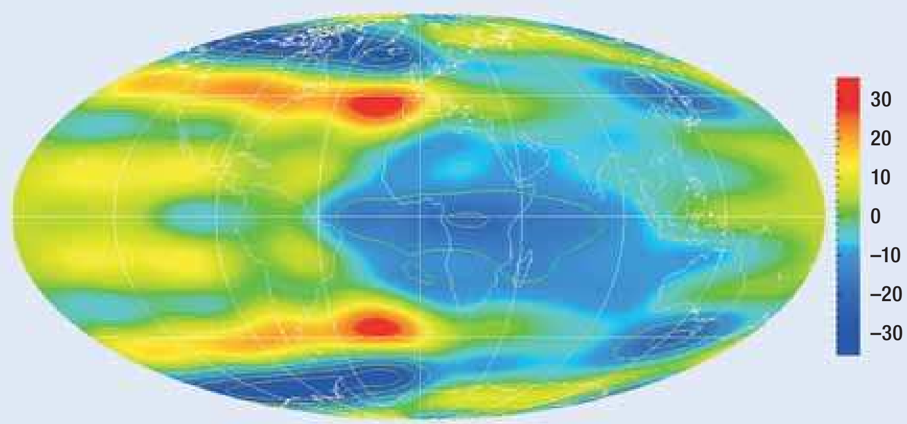
With the new estimates in mind, some previous geomagnetic constraints must be reconsidered. It had been suggested that the flux expulsion observed in reversed flux patches in the southern hemisphere requires either the core fluid to be upwelling near the boundary, or for there to be very strong poloidal (radial) field gradients in this region (Gubbins *et al.* 2007). The former case would limit a stratified layer to the top 100 km of the core, while the latter case would allow a much thicker layer. The probability of a thin stratified layer is enhanced by the new conductivity estimates, although the further implications will need to be considered. There are also implications for the process of flux expulsion through the CMB, recently suggested to be the cause of geomagnetic jerks, and for the coupling mechanisms between the core and mantle that produce contemporaneous changes in the rotation rate of the Earth (Holme and de Viron 2013).

While large-scale dynamical and magnetic features can be reproduced by geodynamo models run at unrealistic parameters, using more realistic parameters would perhaps generate Earth-like small-scale features. How these would interact to form the same persistent large-scale features is not known. One possibility is that lateral variations in heat flux at the CMB, suggested by seismically observed variations in mantle structure, make small-scale flows cluster into larger coherent features (Davies *et al.* 2009). These flow features would be responsible for generating the secular variation with the smaller scale features the probable source of the rapid variations while the larger features persist for longer durations.

As with the CMB, conditions at the inner-core boundary also affect the dynamo region. Differences in hemispheric heat flux from the inner core provide a possible lower boundary condition for the outer core and may contribute significantly to the dynamics of convection in this region (Davies *et al.* 2013). It has been suggested that such an asymmetrical structure could be evidence of a translating inner core, freezing and crystallizing on one side as it melts on the



6: An equatorial snapshot of azimuthal flow for an outer core convection model. The effects of a translating inner core (hemispherical melting and freezing) are approximated by imposing a spherical harmonic degree and order 1 heat-flux pattern at the ICB. In this example, the amplitude of the anomaly is high (red), which results in spiralling azimuthal jets that are driven from the ICB and span large regions of the outer core. Colour scale represents the amplitude of the flow.



7: Time-averaged surface flow below the CMB, in Molleweide projection, for an outer core convection model with an inner thermal boundary condition that incorporates a translating inner core. The surface expression of this thermal anomaly is an east–west hemispheric difference in flow direction at mid to low latitudes, and a hemispheric amplitude difference at high latitudes.

other (Alboussiere *et al.* 2010). Such a situation may limit radial flow to the hemisphere with greater heat flux and produce strong zonal flows elsewhere. What this means for the core surface flows that generate the observed secular variation remains to be seen, but observations such as the generally lower secular variation over the Pacific hemisphere may be related.

Outlook

Knowledge of the composition, properties and behaviour of the Earth's core depends entirely on indirect methods, combining seismology and mineral physics with observations and modelling of the magnetic field. This field is an outward expression of core dynamics and provides important constraints for geodynamo theory and simulations. The combination of historical records and global satellite data means that rapid changes in the Earth's magnetic field can now be mapped and used to estimate the properties and processes of the Earth's core. Short timescale changes in the secular variation and length of day point towards complex interchanges of momentum between the core and mantle, and between inner and outer core. Short timescale and small spatial-scale features have been shown to be significant in understanding how the magnetic field is formed and sustained. Continuous global satellite monitoring, currently provided by Ørsted and in future by Swarm, has played a major role in advancing our understanding of rapid core dynamics. ●

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