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Short communication

Correlation of Earth's magnetic field with lower mantle thermal and seismic structure

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Abstract

Variations in the Earth's lower mantle appear to influence the geodynamo operating in the liquid core. We present a solution to the full dynamo equations with lateral variations in heat flux on the outer boundary defined by the shear wave velocity of the lowermost mantle. The magnetic field is almost stationary and locked to the boundary, with 4 symmetrical concentrations of flux sited beneath cold mantle. This allows for the first time a direct comparison between a dynamo solution and the main features of the present geomagnetic field. Of the four main equatorially symmetric flux lobes, two (the "Siberian" pair) are centered within 5° of the corresponding Earth's pair; the other two (the "Canadian" pair) are not quite so close but are more mobile, as the corresponding Earth's pair have been in the last 300 years. Our study strongly suggests that geomagnetic field morphology is dominated not only by geometry related to the inner core but also by structure in the bottom few hundred kilometres of the mantle, notably the seismically fast ring beneath the Pacific rim and large fast anomalies beneath Siberia and Canada. Tighter locking of one of the pairs of flux lobes suggests the seismic anomaly beneath the Siberian side of the ring is in some way stronger than the one on the Canadian side. These locked solutions only occur for a limited parameter range with the large Ekman numbers available to numerical experiments, which explains why none have been found earlier. This solution provides an important starting point for further searches for dynamos with realistic geomagnetic fields.

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Today's geomagnetic field at the core-mantle boundary (CMB) has 4 main lobes symmetrically placed north and south of the equator. They are centered away from the poles and are near regions of high seismic velocity in the adjacent mantle (Figs. 1 and 2 b). They have moved comparatively little during the last 400 years of direct observation (Jackson et al., 2000) and show up in the time average of paleomagnetic data from the last few million years (Gubbins and Kelly, 1993; Johnson and Constable, 1995; Carlut and Courtillot, 1998; Johnson et al., 2003). Geomagnetic field geometry is dictated to a large extent by Earth's rotation, which explains symmetry about the equator, and the tangent cylinder, which explains the location of the main flux concentrations away from the poles. If the mantle were perfectly spherically symmetric the core would be free to rotate

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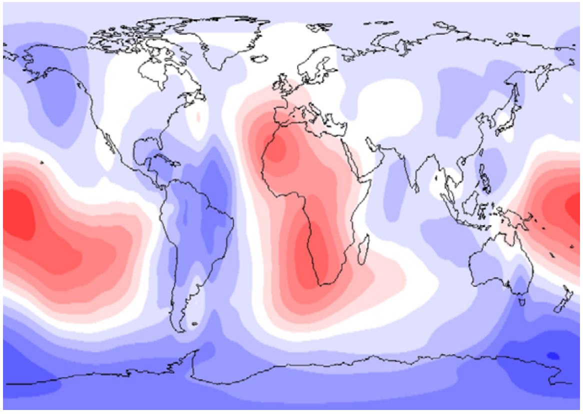

Fig. 1. Shear wave velocity in the lowermost 250 km of the mantle after Masters et al. (1996). Note the longitudes of high velocity, suggesting cold mantle, around the Pacific and particularly beneath Siberia and the Alaska/Canada border.

relative to it, eliminating any possibility of preferred longitudes. Hence, lateral variations are essential for any long term non-axisymmetric features in the magnetic field. There is further evidence to suggest that lower mantle variations affect the Earth's dynamo: the frequency of polarity reversals changes on the very long timescale of mantle convection (Merrill and McElhinny, 1996), the poles follow preferred paths during polarity transition (Laj et al., 1991; Love, 2000), and secular variation in the Pacific is low (Doell and Cox, 1972; Coe et al., 1978). These correlations are controversial (Dormy et al., 2000) but a single theory can explain all the above features. Several geodynamo computer simulations have incorporated lower mantle seismic shear wave velocity as a proxy for heat flux out of the core (Glatzmaier et al., 1999; Bloxham, 2000a, b; Olson and Christensen, 2002; Christensen and Olson, 2003; Aubert et al., 2007) but the generated fields have fluctuated too rapidly in time to allow a straightforward correlation with the observed geomagnetic field. Correlating the radial component of magnetic field, B_r, with the shear wave velocity of the lower mantle is suggestive (Gubbins, 2003) but circumstantial because it does not compare like with like: here we report a more meaningful comparison between two magnetic fields, the observed geomagnetic field and a nearly stationary magnetic field calculated from a geodynamo model incorporating the seismic velocity map in the boundary condition.

We assume variations in the seismic shear-wave velocity, V_S, are caused by temperature differences in a thermal boundary layer in the lowermost mantle. As the CMB itself is isothermal, these temperature differences yield lateral differences in the heat flux conducted through the boundary layer. We therefore adopt variable heat flux proportional to V_S as the upper boundary condition for our geodynamo model, the constant of pro-

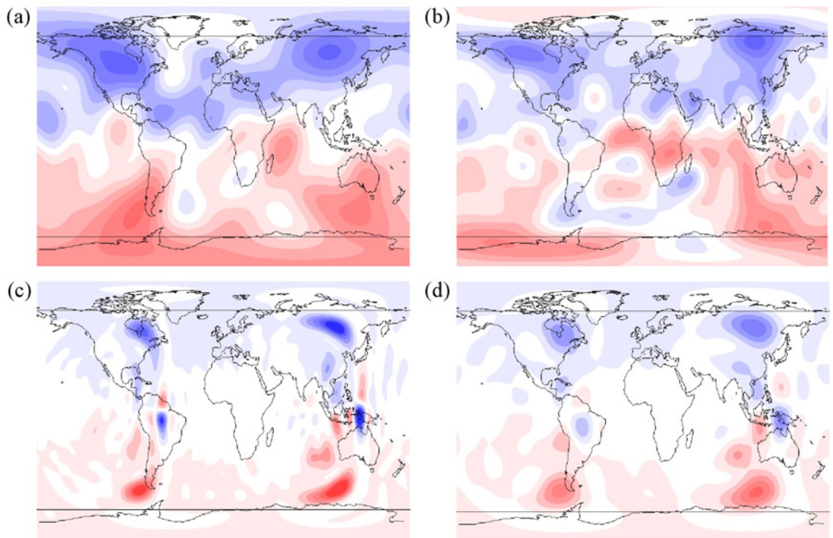

Fig. 2. Maps of radial component of magnetic field at the core surface for (a) Earth in 1750; (b) Earth in 1990; (c) Model at one time point, unfiltered; (d) Model, at the same time but truncated to spherical harmonic degree 14 to facilitate comparison with the geomagnetic field model, which is spatially damped and truncated at degree 14. The dynamo calculation was truncated at degree 36 and checked at higher truncation for convergence. The latitudes of the tangent cylinder are drawn for comparison with the centres of the 4 main lobes. *Movies of 3 numerical simulations* may be viewed or downloaded from http://earth.leeds.ac.uk/~earbs/movies.html. They each show the radial component of magnetic field at the fluid surface, for horizontal buoyancy parameters $Ra^H/Ra^V = 0.9, 0.6$ and 0.3. The solutions have been truncated to spherical harmonic degree 14 for direct comparison with the geomagnetic field.

portionality being measured by a horizontal buoyancy parameter Ra^{H}. Other boundary conditions are: fixed temperature at the lower boundary with the electrically conducting inner core, an electrically insulating mantle, and no-slip of velocity at both boundaries. The inner core is fixed and not free to rotate. The aspect ratio is 0.35, close to the ratio of inner to outer core radii in the Earth. Full details of the calculations are described in a companion paper (Willis et al., 2007). The dynamo model is determined by 5 further parameters, some of which are compromised by computer limitations—nobody has any hope of achieving the Earth's parameters in the foreseeable future because of the disparity of timescales involved, but we can hope to approach the correct dynamical regime by extrapolation from appropriate choices. To obtain simple locked solutions we chose the following:

- *Ekman number*, measuring strength of rotation, $E = 1.2 \times 10^{-4}$, chosen large enough to allow calculations for a large range of other parameters in a reasonable time but low enough for the Coriolis force to dominate in our calculations. This produces the type of equatorial symmetry seen in the geomagnetic field;
- *Rayleigh number*, measuring strength of buoyancy force, $Ra^{V} = 1.5 Ra^{c}$, where Ra^{c} is the critical value for the onset of non-magnetic convection with homogeneous boundary conditions ($Ra^{H} = 0$). The ratio Ra^{V}/Ra^{c} is made low because otherwise, with relatively large E, a strong buoyancy force would counter the Coriolis force. This is unlikely to happen in the Earth. Furthermore, a high Ra^{V} is unlikely to yield the simple type of near-stationary magnetic field that we seek;
- *Prandtl number*, measuring the ratio of fluid viscosity to thermal diffusivity, $Pr = 1$, Inertial forces kept large to reduce inertial forces, which upset the desired magnetogeostrophic force balance appropriate for the core (Sreenivasan and Jones, 2006). Inertial forces were also found to inhibit locking in non-magnetic convection (Zhang and Gubbins, 1996).
- *Roberts number*, measuring the ratio of thermal to electrical diffusivity, $q = 10$, which must be chosen large enough to generate dynamo action. Furthermore, locking seems to require a balance between diffusion and advection of heat near the outer boundary which, given the choices of the other parameters, also demands a high q.
- *Horizontal buoyancy number*, Ra^{H}, measuring the strength of lateral variations in heat flux across the mantle boundary layer. The ratio $\epsilon = Ra^{H}/Ra^{V}$, which quantifies the peak-to-peak lateral variation of heat flux relative to the average radial heat flux at the core surface, was increased from 0 to 1 to explore the effect of the boundary condition; this range is reasonable from both mantle convection studies and the amplitude of anomalies in V_S.

Table 1
Centres of the 4 main lobes, located by placing a cross on the maximum of each lobe, measuring the latitude and longitude, then averaging over time

	Canada	Siberia
Earth	52° N 110°W	59° N 108°E
Model	55° N 74°W	55° N 112°E
Earth	68° S 109°W	56° S 117°E
Model	56° S 74°W	56° S 114°E

The geomagnetic field ("Earth") was averaged every 50 years over the 400-year historical model (Jackson et al., 2000); the dynamo field ("Model") was averaged over 10 snapshots from the 3 magnetic diffusion times of the simulation.

No completely steady solution has been found but a strong inhomogeneity of $\epsilon = 0.9$ gives a field that varies very little over the whole calculation interval of 3 magnetic diffusion times, or about half a million years in dimensional units. This represents many turn-over times of the fluid. A snapshot from the model solution is shown in Fig. 2 c; Fig. 2 d shows the same solution truncated to spherical harmonic degree 14 for comparison with the geomagnetic field model. Given that we have successfully locked the model solution, the calculated and observed fields may be compared simply by comparing the centres of the 4 main lobes (Table 1); a more sophisticated procedure is not justified at this stage because of the simplicity of the model and because we only seek to explain the persistence of the main lobes. The coincidence of the two eastern lobes, the Siberian lobe and its southern hemisphere counterpart, is remarkable. The Canadian lobe is on average slightly further west in the Earth, however, this lobe split in half during the 19th century, making comparison difficult. Its southern counterpart is also further south and west, but it has been moving consistently southwest throughout the historical period and in 1750 A.D. was at 60°S, 96° W (Fig. 2a), much closer to the location of the corresponding patch in the model. The motion of this lobe is associated with the development of a patch of reversed flux to the northeast, dating from about 1770 A.D. Its present location may therefore be a recent temporary feature and its normal location may lie closer to that of the model. The relative instability of the Canadian pair seen in the historical record is also reflected in the model, where the corresponding pair is also more mobile than the Siberian pair. For a run with weaker mantle anomalies, $\epsilon = 0.6$, the Siberian pair remains fairly stable while the Canadian pair occasionally disappears altogether. This suggests the seismic anomaly is strongest for the Siberian locations, an idea supported by strong D'' seismic reflections from the region (Wysession et al., 1998).

Near the equator, flux tends to be concentrated near the favoured longitudes in a clover-leaf pattern (Fig. 2c). In the $\epsilon = 0.6$ model there is increased activity near the equator, and pairs of patches are often observed to migrate in longitude. This clover-leaf pattern is known to result from strong downwelling in kinematic studies (Gubbins et al., 2000). It arises when vertical shear twists the azimuthal toroidal field within the core into the vertical plane, producing a north–south pair of flux spots of sign opposite to that of the main dipolar field. Two further flux spots, which have the same sign as the main dipolar field, are produced to the west of this pair by concentrations of the toroidal field ahead of the downwelling. The spots can vary in strength depending on the strength of B_ϕ at their location. The toroidal field changes sign across the equator, so 4 spots are produced in a clover-leaf pattern. Something like this effect is seen in the Earth around Indonesia, where the magnetic equator at the CMB oscillates in what is reminiscent of a standing wave (Bloxham and Gubbins, 1985).

The Earth's magnetic field has not previously been correlated to a model magnetic field locked to boundary inhomogeneities. The surprisingly close correlation in position, both in latitude and longitude, plus the relative strength and variability seen in the model and observations, provides the strongest evidence yet that the lower mantle affects the geomagnetic field. Our choice of parameters is compromised yet produces a relatively steady magnetic field that can be compared with the main features of the Earth's field. The locked regime is hard to find and only exists for small ranges of the parameters. A future suite of calculations is planned when the new national supercomputing facility becomes available, to see whether our range opens out at lower Ekman numbers. This study also has implications for the structure of the lowermost mantle and D'' region. It suggests thermal, rather than compositional, variations have a dominant influence on V_S in the fast regions, although variations in thermal conductivity associated with compositional variations could also play a role.

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