Earth's Eccentric Magnetic Field

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Earth's magnetic field is characterized by a puzzling hemispheric asymmetry. Calculations of core dynamo processes suggest that lopsided growth of the planet's inner core may be part of the cause.

The geomagnetic field is generated by motions in Earth's liquid metal outer core. The field has an east–west asymmetry, with a stronger magnetic field typically generated in one hemisphere compared with the other. This asymmetry is well described mathematically by a so-called 'eccentric' dipole, offset from the Earth's centre [1,2,3]. Reconstructions of the geomagnetic field suggest that, on average, this dipole has been offset towards the western hemisphere during the past 10,000 years [4,5]. Writing in Nature Geoscience, Olson and Deguen [5] propose the location of fastest inner core growth influences the dipole position and could have shifted position in the past 5 million years.

The Earth has cooled sufficiently since its formation, some 4.5 billion years ago, for iron alloy to solidify in its centre, where pressure is greatest. Crystallization progresses outwards, creating a dense, solid inner core. During crystallization of the inner core, light molten material is released into the liquid outer core. This drives convection, in which the fluid is forced by Earth's rotation to move in helical vortices. These vortices stretch and twist magnetic field lines, which converts kinetic energy into magnetic energy, and creates a new magnetic field. As a result, Earth's core acts as a giant self-sustaining dynamo.

A departure from spherical symmetry at the boundary between the outer core and mantle, for example, due to variable heat flux or the presence of topography, can influence the structure of Earth's magnetic field [6,7]. Yet little attention has been given to whether inhomogeneities in the release of light material at the inner core boundary could play a similar role. Previous calculations of the core dynamo process have assumed that the conditions at the boundary of the inner and outer core are uniform. However, seismic data reveal an asymmetry between the eastern and western hemispheres of the inner core and it has been proposed that as the inner core grows material moves laterally within it [8,9]. In this scenario crystallization and the associated release of light material occurs predominately in one hemisphere, whereas melting takes place in the other.

Motivated by this new idea of lopsided inner core growth, Olson and Deguen [5] simulate Earth's magnetic field using a numerical dynamo model with a boundary condition for the inner core that releases different amounts of light material in the eastern and western hemispheres. They numerically solve the equations of conservation of momentum, heat and light material transport, as well as electrodynamics, to calculate possible consequences for the Earth's magnetic field. Their calculations show that hemispherically asymmetric growth of the inner core can modulate the dynamo operating in the core, and hence influence the structure of the geomagnetic field. Specifically, if crystallization and the release of light material occur preferentially in one hemisphere, convection is stronger there and the magnetic field is also more vigorously stretched and twisted. This leads to a time-averaged preference for a stronger magnetic field in this region, and, in turn, an eccentric dipole position offset towards the location of fastest inner core crystallization (Fig. 1).

There may also be some observational support for the idea that lopsided inner core growth creates time-averaged eccentricity of the magnetic dipole, although ambiguity remains because of difficulties involved in reconstructing the details of Earth's magnetic field on the relevant timescales of thousands to millions of years. Reconstructions are based on the signature of the magnetic field captured in rocks or archaeological artefacts as they cool, or locked into sediments as they form. The geographical and temporal coverage of such records is sparse, and there are often limitations associated with dating. The most advanced field reconstructions [4] suggest that the Earth's magnetic field was

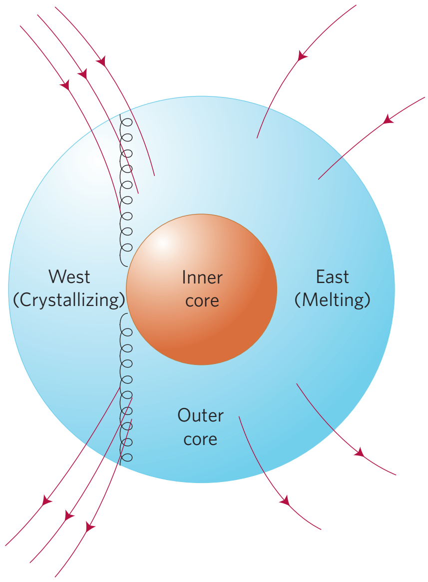

Figure 1: **East–west asymmetry in inner–core growth and magnetic field generation**. The western hemisphere of the inner core may be preferentially crystallizing, whereas the eastern hemisphere is melting. Olson and Deguen show that lopsided growth of the inner core leads to more vigorous helical convection and enhanced magnetic field generation in the hemisphere of most rapid crystallization. This, in turn, creates an asymmetry in Earth's magnetic field, with the eccentric dipole shifted towards that hemisphere.

on average stronger in the western hemisphere during this period. According to Olson and Deguen, this is consistent with the proposed faster solidification of the western hemisphere of the inner core at present [8,9].

Going further back in time and averaging over the past 5 million years, two field reconstructions tested by the authors suggest that the best-fitting dipole was offset towards the opposite, eastern, hemisphere at earlier times. The robustness of such time-averaged field models is debated [10], but if these results hold true, a change in the location of fastest inner core growth must have taken place over the past few million years. Such a change may have happened, for example, due to intermittent rotation of the inner core or due to changes in the flow within the inner core. To further test these ideas, more robust reconstructions of the Earth's magnetic field and its evolution on million-year time scales are needed; this requires a renewed effort to collect further high-quality magnetic records better covering all regions of the Earth.

A final, intriguing, aspect of the story concerns the current configuration of the Earth's magnetic field. The eccentric dipole axis now lies in the eastern hemisphere, apparently unusually within the past 10,000 years [3,4,5]. The recent rapid movement of the eccentric dipole towards the eastern hemisphere is associated with a gathering of magnetic field concentrations at high latitude in this region [3]. At the same time, a weak field anomaly in the south Atlantic region has grown and moved towards the west. According to the numerical dynamo simulations of Olson and Deguen, similar rapid changes in the eccentric dipole position often occur when there is a drop in dipole intensity, particularly before significant directional changes such as full reversals of polarity or temporary excursions.

Olson and Deguen [5] use a numerical dynamo model to show how asymmetric growth of Earth's inner core may contribute to the observed eccentricity of the geomagnetic dipole. Extrapolation of the details of simple numerical dynamo calculations to the Earth's core is controversial, but the prospect of fresh insights into the mechanism by which Earth's magnetic field operates is tantalizing.

References

1. Schmidt, A. *Gerl. Beitr. Geophys.* **41**, 346–358 (1934).
2. Bartels, J. *Terrest. Mag. Atmos. Elect.* **41**, 225–250 (1936).
3. Gallet, Y., Hulot, G., Chulliat, A., and Genevey, A. *Earth Planet. Sci. Lett.* **284**, 179–186 (2009).
4. Korte, M., Constable, C. G., Donadini, F., and Holme, R. *Earth Planet. Sci. Lett.* **312**, 497–505 (2011).
5. Olson, P. and Deguen, R. *Nature Geosc.* **?**, ? (2012).
6. Hide, R. *Science* **157**, 55–56 (1967).
7. Bloxham, J. and Gubbins, D. *Nature* **325**, 511–513 (1987).
8. Monnereau, M., Calvet, M., Margerin, L., and Souriau, A. *Science* **238**, 1014–1017 (2010).
9. Alboussiere, T., Deguen, R., and Melzani, M. *Nature* **466**, 744–747 (2010).
10. Aubert, J., Tarduno, J. A., and Johnson, C. L. *Space Sci. Rev.* **155**, 337–370 (2010).