CORE PROCESSES

Earth's eccentric magnetic field

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.

Christopher C. Finlay

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, with the axis of the dipole offset from Earth's centre[1–3]. Reconstructions of the field suggest that, on average, the dipole axis has been offset towards the western hemisphere during the past 10,000 years[4,5]. Writing in *Nature Geoscience*, Olson and Deguen[5] propose that the location of fastest inner core growth influences this dipole position.

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 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 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 observations reveal an asymmetry between the eastern and western hemispheres of the inner core, and it has been proposed that material moves laterally within the inner core as it grows[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.

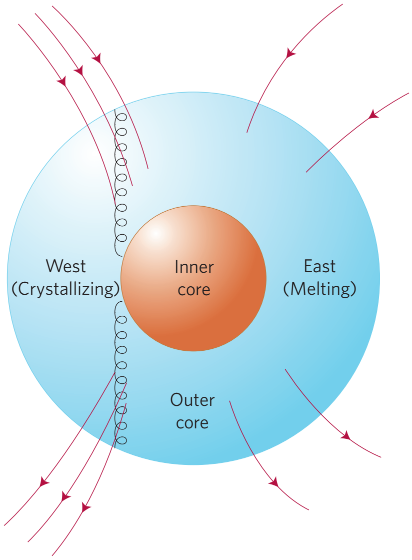


Figure 1 | East–west asymmetry in inner-core growth and magnetic field generation. The western hemisphere of the inner core may be preferentially crystallizing, whereas the eastern hemisphere may be melting[8,9]. Olson and Deguen[5] show that lopsided growth of the inner core leads to more vigorous helical 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.

Motivated by this new idea of lopsided inner-core growth, Olson and Deguen[5] simulate Earth's magnetic field using a numerical dynamo model that releases different amounts of light material in the eastern and western hemispheres at the inner core boundary. They solve the equations of conservation of momentum, heat and light-material transport, as well as electrodynamics, to calculate possible consequences for Earth's magnetic field. Their calculations show that hemispheric asymmetry in the 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 dipole eccentricity, 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 Earth's 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] spanning the past 10,000 years suggest that Earth's magnetic field has, on average, been 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[8,9].

Going further back in time and averaging over the past 5 million years, two field reconstructions tested by the authors suggest the dipole axis 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 Earth's magnetic field and its evolution on million-year timescales 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 Earth's magnetic field. The eccentric dipole axis now lies in the eastern hemisphere, an apparently unusual event within the past 10,000 years[3–5]. 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 hemisphere[3], and the appearance of a weak field anomaly in the south Atlantic region that 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 rather simple 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 numerical dynamo calculations to the conditions of Earth's core remains controversial, but the prospect of fresh insights into the mechanism by which Earth's magnetic field operates is tantalizing. ❐

Christopher C. Finlay is at the National Space Institute, Technical University of Denmark, Kongens Lyngby, DK-2800, Denmark.
e-mail: cfinlay@space.dtu.dk

References

1. Schmidt, A. *Gerl. Beitr. Geophys.* **41,** 346–358 (1934).
2. Bartels, J. *Terrest. Magn. Atmos. Electr.* **41,** 225–250 (1936).
3. Gallet, Y., Hulot, G., Chulliat, A. & Genevey, A. *Earth Planet. Sci. Lett.* **284,** 179–186 (2009).
4. Korte, M., Constable, C. G., Donadini, F. & Holme, R. *Earth Planet. Sci. Lett.* **312,** 497–505 (2011).
5. Olson, P. & Deguen, R. *Nature Geosci.* **5,** 565–569 (2012).
6. Hide, R. *Science* **157,** 55–56 (1967).
7. Bloxham, J. & Gubbins, D. *Nature* **325,** 511–513 (1987).
8. Monnereau, M., Calvet, M., Margerin, L. & Souriau, A. *Science* **238,** 1014–1017 (2010).
9. Alboussiere, T., Deguen, R. & Melzani, M. *Nature* **466,** 744–747 (2010).
10. Aubert, J., Tarduno, J. A. & Johnson, C. L. *Space Sci. Rev.* **155,** 337–370 (2010).

PLANETARY SCIENCE

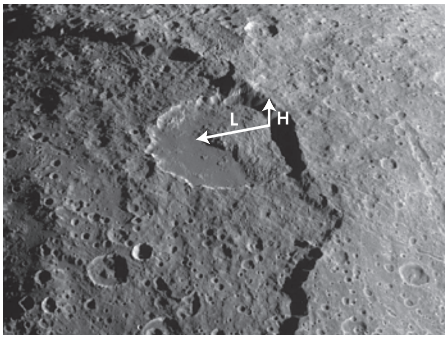
Slippery sliding on icy Iapetus

Enigmatically, some landslides flow farther than normal frictional resistance allows. Cassini images of Saturn's icy moon Iapetus reveal a multitude of long-runout landslides that may have been enabled by flash heating along the sliding surface.

Antoine Lucas

Friction is an unavoidable force of nature, on Earth and beyond. Some landslides, however, travel longer horizontal distances over shallow slopes than would be expected under the normal friction conditions of sliding rock. Several mechanisms have been proposed to temporarily reduce the friction for these long-runout landslides, such as lubrication by water or air, thermal pressurization, acoustic fluidization or flash heating[1–5]. An anomalous reduction in friction is not limited to Earth environments; mass wasting processes are common on other planetary bodies, and long-runout landslides have been observed on terrestrial planets and the icy satellites[6–8]. Combined, these different planetary environments make up a laboratory for testing hypotheses of landslide emplacement. Long-runout avalanches on cold and airless icy satellites challenge existing explanations for reduced friction. Writing in *Nature Geoscience*, Singer and colleagues[9] present analyses of long-runout landslides on Saturn's moon Iapetus and propose that frictional heating of icy avalanche rubble makes the interface between avalanche and ground slippery.

Landslides are often characterized by the ratio of drop height to runout length. This ratio has been frequently used to approximate the friction coefficient for terrestrial and martian landslides[6,10]. For landslides on Earth and Mars, the height–length ratio decreases with increasing landslide volume[6], starting from a value of 0.6 for a purely frictional sliding mass with a small volume of less than 100,000 m^3, and dropping to values lower than 0.07 for large volumes of more than 16 km^3.



© NASA / JPL / SPACE SCIENCE INSTITUTE

Figure 1 | Images from the Cassini ISS probe reveal numerous landslides across the surface of Iapetus. Originating from unstable slopes such as steep crater walls, these landslides often flow greater distances (L) than expected for their fall heights (H) under the normal frictional properties of ice. Singer *et al.*[9] propose that such long-runout landslides can be explained by a slippery sliding surface caused by frictional heating during the landslide.

Understanding these events is important for landslide disaster mitigation and management on Earth. However, the underlying mechanisms that control these landslides are the subject of an active debate, in part because of the limited available data. Planetary exploration has revealed that long-runout landslides are ubiquitous throughout the Solar System, and these far-flung landslides have much to teach us about their underlying causes.

Singer and colleagues[9] catalogued mass wasting deposits on icy Iapetus. They use data from the Cassini mission and photogrammetric techniques to map Iapetian landslides. In doing so, they assembled the largest data set of landslides beyond Earth and Mars. They found that, like Earth and Mars, Iapetus is rife with mass movements, including long-runout landslides. The conditions on Iapetus are particularly favourable for landslide triggering, both because topographic relief is great relative to the moon's small size and because the moon's surface is ancient. Therefore, there are many precarious slopes that are vulnerable to collapse. As a laboratory of mass wasting investigations, Iapetus is a rare gem in having a large number of long-runout landslides that formed in similar environmental conditions, and readily available spacecraft data to study them.

According to Singer and colleagues' measurements, typical height–length ratios of landslides on Iapetus lie between 0.1 and 0.3. On the lower end, this is analogous to terrestrial submarine landslides and