Fluctuating gravity of Earth's core

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For centuries, we have known that Earth's magnetic field varies with time. Edmond Halley (better known for his eponymous recurring comet) first recognized this time variation of magnetic compass needle direction and even offered a remarkable theory that required an intervening fluid between Earth's solid outer shell and a hypothesized innermost solid core (1). For decades, consensus has emerged for an explanation of this time variation that depends on the dynamics of Earth's liquid metallic outer core. In this dynamo theory (2), the fluid motions responsible for field regeneration arise because of density differences within the fluid, much as density and pressure differences in Earth's atmosphere or ocean can drive circulation and vertical motions in those regions of Earth. Density differences necessarily imply changes in Earth's gravity field, so it is only a small step in logic to imagine that there could be changes in the gravity field that correlate with changes in the magnetic field, with both changes arising from fluid flow in the core. In PNAS, Mandea et al. (3) claim to have found possible evidence for such a correlation on a time scale of a few years to a decade.

There are large and easily detected density anomalies within Earth. For those with dimensions of thousands of kilometers, we attribute them primarily to the density anomalies that naturally arise from convection in Earth's mantle. To explain Earth's heat flow, very slow motions of the mantle have associated density anomalies that are typically of an order of 1% or less, but the resulting gravity anomalies will not fluctuate on a time scale of years because the motions are so slow (i.e., with characteristic time scales of tens to hundreds of millions of years). Small but much more time-variable density anomalies can arise because of changes in the near surface atmosphere, ocean, groundwater, and ice. The current highest-sensitivity gravity data are obtained by the Gravity Recovery and Climate Experiment mission (http://www.csr.utexas.edu/grace), which consists of two spacecraft in low Earth orbit linked by a microwave signal and also tracked by GPS. The Gravity Recovery and Climate Experiment mission has, for example, detected the partial melting of the Greenland ice sheet through changes in the gravity field, and this contributes to our understanding of global sea level change (4).

Fig. 1. Anticyclonic motion at the top of the core in the northern hemisphere produces a pressure (P) high and associated gravity high. The fluid flow will also cause a change in the magnetic field. This figure illustrates a general principle and is not intended as a specific explanation for the data discussed in the work of Mandea et al. (3).

To understand why the possible detection of a time-dependent gravity core signal is remarkable and perhaps unexpected, it is necessary to have an appreciation of the numbers. Suppose there were a large blob of fluid in the core with a fractional density contrast ε relative to its surroundings. The resulting acceleration εg would cause it to achieve a velocity v of $\sim(\varepsilon gL)^{1/2}$ after traversing a distance L, where g is the full gravitational acceleration. Core fluid is expected to have a viscosity not enormously different from the viscosity of water (typical of liquid metals), so there is no need to consider viscosity in making these estimates. If the time it took to travel a distance L were T, then ε is $\sim(5\ \mathrm{min}/T)^2$, or $\sim10^{-10}$ if T$\sim$1 y, the order of magnitude of the smallest time scales one thinks may be associated with large-scale fluid motions in the core. Indeed, these numbers naturally emerge from simple theories of turbulent convection and are required to explain likely heat flows from the core. The essential point is this: Heat flows in core and mantle are comparable and scale with the product of fluid velocity and density anomaly. Mantle convection (i.e., very viscous flow) has very slow motions and large density anomalies, and core convection (i.e., low viscosity) has rapid motions and correspondingly small density anomalies.

The density anomalies associated with core fluid flow are not straightforwardly related to heat flow, however, because Earth is rotating and the Coriolis effect profoundly changes the flow state in the core, just as rotation controls the large-scale circulation in Earth's atmosphere and ocean. In the core, the Lorentz force arising from electrical currents and associated magnetic fields can also have a large influence (although perhaps not a dominant effect) on the flow. There may be "winds" that do not carry heat but provide pressure and thus cause density variations that are not a direct result of thermal expansion or compositional differences. An important (although imperfect) concept in the core is geostrophy, according to which the primary dynamical balance is between pressure gradients and the Coriolis force. In this balance, typical dynamical pressure variations would be $\sim2\rho\Omega vL$, or approximately a few thousand Pascal (for fluid density ρ of $\sim10^4$ kg/m^3, Earth's angular velocity Ω of $\sim10^{-4}\cdot s^{-1}$, flow velocity v of $\sim10^{-3}$ m/s, and L of $\sim10^6$ m). Imposed on the underside of the mantle, this would elastically deform that interface by as much as 1 cm, or it might change core density by a few parts in 10^9, possibly larger than the thermal expansion effect. In the units commonly used in geophysics, where a nanogal is approximately one part in 10^{12} of total gravitational acceleration, these kinds of motions could, in principle, produce a change in gravity at Earth's surface on the order of order of tens to hundreds of nanogals (Fig. 1). As Mandea et al. discuss (3), there are indeed gravity changes of this approximate magnitude over a time of a few years, although it is not clear how much can be attributed to the core and how much could arise from the oceans or other sources. It is also not clear whether winds in the core would be as time-variable as the large-scale turbulent motions primarily responsible for carrying heat. An interesting comparison could perhaps be made with Jupiter, where the Juno mission expects to detect the gravity signal associated with the strong zonal winds (5) but may not detect the fluctuations in gravity caused by unsteady convection.

The magnetic data also benefits from Earth orbit missions, notably the Challenging Mini-Satellite Payload for Geo-Scientific Research and Applications

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program (http://science.nasa.gov/missions/champ), which collected gravity and magnetic field data. The ambiguities of interpretation are less for magnetic field than for gravity because only the core can be a significant contributor to secular variation (the term used to describe the temporal variation of Earth's magnetic field). Earth's oceans and ionosphere provide a small but separable effect. The observed field changes are on the order of 10 nT/y; by comparison, Earth's dipole is less than 100,000 nT. Although a full understanding of the dynamo requires consideration of field diffusion, some aspects can be appreciated by considering field that is advected by flow of highly conducting fluid. A change in field in one region of one part in 10^4 might, for example, be accomplished by advection of a 1% spatial anomaly in the field by 1% of its spatial scale. The data suggest, however, that a simple advection explanation will not work.

As Mandea et al. (3) acknowledge, the observed correlation is a puzzle. The issue lies not so much with the order of magnitude of the observed effect, which seems large but not highly implausible based on the order-of-magnitude arguments discussed here. Rather, it is that the observed correlation is between the secular

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acceleration (the second time derivative of the magnetic field in some regions near the core/mantle boundary) and the gravity field. It is not at all clear why these two quantities should be correlated or why the correlation should be positive rather than negative. This cries out for more theoretical work. The only major existing theoretical work on the possible core gravity signal (6) does not predict or explain the observations, but this should not be regarded as a disproof, as the nature of core dynamics is still hotly debated.

The work of Mandea et al. (3) could well be pioneering because it offers the exciting prospect of providing a new window into core dynamics. At present, dynamo theory suffers from a puzzling impediment: we know existing computer models can do quite well in describing the nature of Earth's field, but we also know these models are far removed from the correct regime in terms of the various dimensionless numbers that characterize the system. A different window into core dynamics could help remove this impediment in our progress toward an understanding of core dynamics. There is a great need to follow this up with further analysis and improved data. In part, this will also require a separation of core signal from other sources of "noise" in Earth's gravity.

1. Halley E (1686–1692) An account of the cause of the change of the variation of the magnetic needle; with an hypothesis of the structure of the internal parts of the earth. *Phil Trans* 16:563–578.
2. Gubbins D, Roberts PH (1987) Magnetohydrodynamics of the Earth's core. *Geomagnetism*, ed Jacobs JA (Academic, London), Vol 2, pp 1–183.
3. Mandea M, et al. (2012) Recent changes of the Earth's core derived from satellite observations of magnetic and gravity fields. *Proc Natl Acad Sci USA* 109:19129–19133.
4. Jacob T, Wahr J, Pfeffer WT, Swenson S (2012) Recent contributions of glaciers and ice caps to sea level rise. *Nature* 482(7386):514–518.
5. Kaspi Y, et al. (2010) Gravitational signature of Jupiter's internal dynamics. *Geophys Res Lett* 37:L01204.
6. Dumberry M (2010) Gravity variations induced by core flows. *Geophys J Int* 180:635–650.