

PLANETARY SCIENCE

Hot News on Mercury's Core

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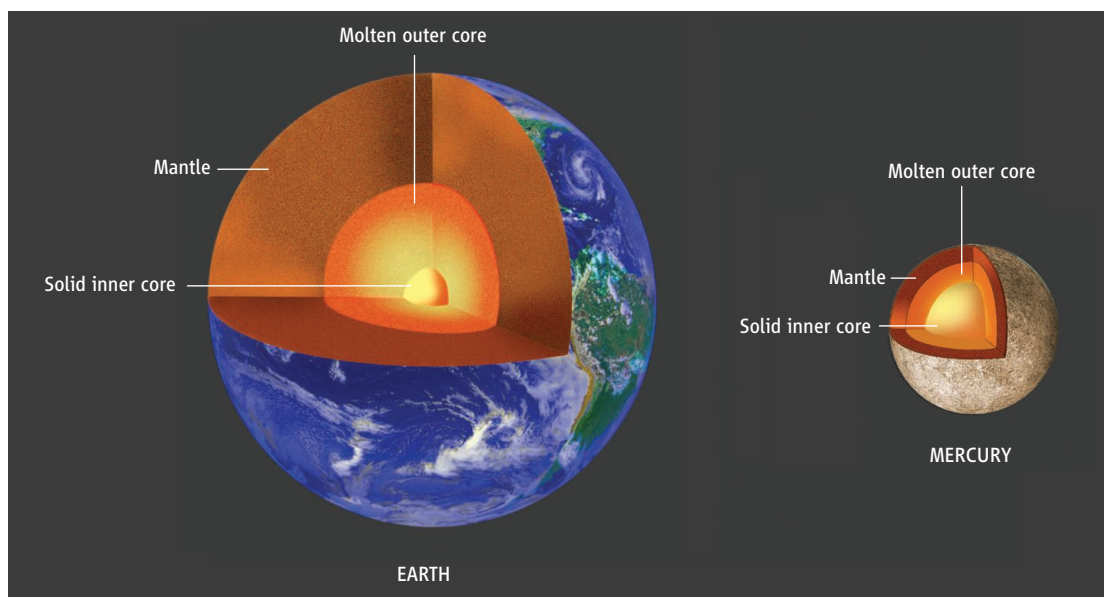
Some 30 years ago the planetary science community was surprised when the Mariner 10 spacecraft flew by the planet Mercury and detected an internal magnetic field (1). Earth's internal field is produced by a magnetic dynamo sustained by convective motions in the planet's molten, iron-rich outer core. Although Mercury's high bulk density indicates that its dominantly iron central core is the largest by fractional mass among the planets (2), the detection of its magnetic field was surprising because Venus has no field and Mars and the Moon show evidence only for ancient global fields. With a mass about 5% that of Earth, Mercury had been expected to have cooled internally to the point where either the core had solidified or core convection no longer occurs. A necessary condition for Mercury's magnetic field to arise from an active Earth-like dynamo is that at least the outer shell of its core be molten. On page 710 of this issue, Margot *et al.* report new observations of variations in Mercury's spin rate made with Earth-based radar, providing strong evidence that this condition is met (3).

The radar measurements constitute a triumph of two theoretical ideas developed decades ago. Shortly after the Mariner 10 discovery, Peale (4) outlined a procedure to determine whether the planet has a fluid outer core. His method was based on the observation that Mercury is in an orbital state in which the planet completes three rotations about its spin axis for every two revolutions around the Sun. The procedure requires the measurement of the small oscillation in the planet's spin rate (libration)—a few hundred meters in amplitude—forced by solar torques

as Mercury follows its 88-day eccentric orbit. Additional parameters that must be known include the tilt of the spin axis and the components of the planet's gravity field describing the degree to which the field is flattened at the poles and out of round along the equator. The last two quantities have been estimated, albeit with low precision, from Mariner 10 tracking observations made during the probe's three encounters with Mercury during 1974–75, but the libration

Radar measurements show that the outer core of Mercury is molten, providing insight into the planet's history and the origin of its magnetic field.

pairs of radio antennas in California, West Virginia, and Puerto Rico during more than 20 observation periods from 2002 through 2006, the group determined the position of Mercury's spin axis with a precision two orders of magnitude superior to the previous best estimate. Equally important, they detected Mercury's forced libration and determined its amplitude for the first time. The amplitude is sufficiently large that Mercury's solid mantle and crust must be decoupled



Core issues. The solid inner core and fluid outer core of Earth are shown to approximate scale. Mercury's outer core is now known to be fluid (3), but its radius and the nature and radius of any solid inner core remain to be determined.

amplitude and a sufficiently accurate pole position were not known before now.

The second theoretical development, by Green (5) and Holin (6), stems from the recognition that irregularities, or speckles, in the radar signal returned from a planetary target rotate in space as the planet spins. Under suitable geometric constraints, analysis of radar signals recorded at two stations on Earth can detect this rotation as the speckle pattern sweeps coherently across Earth's surface. By combining many such paired measurements at different times and observing geometries, the position of the target planet's spin axis and periodic variations in the spin rate may be ascertained.

Margot and his team (3) applied these two theories with spectacular results. From radar signals bounced off Mercury and recorded at

from the planet's core on an 88-day time scale. This result indicates that Mercury has a molten outer core at 95% confidence, a level limited at present by uncertainty in the knowledge of Mercury's gravity field.

The presence of a molten outer core is consistent with dynamo models for generating Mercury's magnetic field but does not prove the existence of such a dynamo or distinguish among competing models. One of the problems with an Earth-like dynamo is that the dipole strength of Mercury's field is some three orders of magnitude less than that of Earth. Explanations for the weak field involving a dynamo otherwise broadly similar to Earth's include a thin-shell dynamo (7) and a dynamo that operates only deep in a fluid outer core beneath an electrically conductive but stable layer of liquid metal (8).

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Possible alternatives include a dynamo sustained by electrical currents driven by temperature variations along an uneven core-mantle boundary (9) or an entirely fossil magnetic field in an outer shell whose thickness varies with insolation as functions of latitude and longitude (10). Distinguishing among models requires measurement of the geometry of Mercury's field, particularly the nondipole components.

The evidence for a liquid outer core on Mercury and the specific value of the forced libration amplitude (3), inversely proportional to the moment of inertia of Mercury's mantle and crust (4), provide important new constraints on models for Mercury's thermal history and bulk composition. From these observations we know that a light element alloyed with iron is necessary to prevent the outer core from freezing completely during Mercury's lifetime. A core sulfur content of several percent, for instance, would maintain a fluid outer core to the present and yet per-

mit the solidification of an inner core that would release energy or chemical buoyancy to stir a convective core dynamo (11). Mercury's bulk composition had previously been constrained only by its mean density. The new determination of the moment of inertia of the planet's solid outer shell (3) should narrow somewhat the constraints on the average density of that shell and on core radius, but these constraints will improve substantially when the gravitational field of the planet is better determined.

No spacecraft has visited Mercury since the Mariner 10 flybys, but that status is about to change. NASA's MESSENGER spacecraft (12) will fly by Mercury three times, the first next January, before achieving orbit about the planet in 2011. About 2 years later, the European Space Agency and the Japan Aerospace Exploration Agency will launch the BepiColombo mission to insert two spacecraft into coplanar Mercury orbits in 2019 (13). The latest discovery

from Earth-based radar has whetted the appetites of the planetary science community for these two missions.

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BIOCHEMISTRY

Photosynthesis from the Protein's Perspective

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Effective photosynthesis requires the efficient transfer of electrons across biomembranes (1). Yet, many aspects of how protein structure and dynamics control electron transfer—especially in the early stages of photosynthesis—remain only partly understood. On page 747 of this issue, Wang *et al.* (2) investigate the rate of the initial photosynthetic electron-transfer reaction in wild-type and mutant photosynthetic reaction centers of *Rhodobacter sphaeroides*. By combining their data with modeling of protein conformational changes in the photosynthetic reaction center, the authors show that protein motions modulate the electron-transfer rate.

The electron donor in the initial electron-transfer reaction of bacterial photosynthesis is a special pair of chlorophylls. When the latter are photoexcited, an electron transfers through a bridging chlorophyll to a pheo-

phytin acceptor within 2 ps (1 ps = 10^{-12} s) (see the figure). Experimental studies of this process have focused on understanding the speed and high efficiency of the reaction (an electron is transferred for each photon absorbed) (1). Conventional electron-transfer theory does not fully describe this kind of electron-transfer reaction, because the theory assumes that electron transfer is slow compared to the relaxation of the medium (protein and chromophore), and the medium is therefore assumed to be equilibrated before the electron-transfer step. The protein motion in the initial photosynthetic reaction, however, cannot keep up with the pace of charge separation.

The study of Wang *et al.* indicates that a model for electron transfer controlled by slow atomic motion, the Sumi-Marcus model (3), produces a satisfactory description of the initial photosynthetic electron-transfer kinetics (2). The Sumi-Marcus model assumes that electron transfer is affected both by fast atomic motions \mathbf{q} of the medium that are equilibrated before the electron-transfer step, and by motions \mathbf{X} that are slow on the electron-transfer time

Slow motions of proteins modulate electron-transfer rates during the early stages of photosynthesis.

scale. \mathbf{X} modulate the speed of electron transfer. This model is similar in spirit to descriptions of ligand binding to heme proteins, which are also understood in the context of the slow interchange among protein substates (4).

Wang *et al.* use the absorption spectra of the protein's 39 tryptophan residues to track the medium's response to photoexcitation and initial photosynthetic electron transfer. The spectra are essentially identical in the wild type and in the 14 mutants, with electron-transfer times varying from 2 to tens of ps. Therefore, the protein motion that is tracked by the spectra is not affected by the rate of electron flow. Further, the time evolution of the absorption spectra is multiexponential, with time constants (3, 10, and 190 ps) that are similar to or longer than the time scales of electron transfer.

The authors find that the Sumi-Marcus model describes the observed electron-transfer kinetics if the diffusion constant for the slow coordinate \mathbf{X} in the model is derived from the time evolution of the tryptophan absorption. The fit predicts changes in reaction free energy (ΔG) values that

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