

implants that require only intermittent power. Those can include devices to stimulate nerve-cell clusters called ganglia to relieve pain (their first human trial will be on ganglion stimulation) and sensors to monitor various biological functions. Miniature pacemakers are a possibility, too, though they'd need to include an onboard rechargeable battery. But because that battery

need only carry enough power to last weeks, rather than years, it can be made small.

Johanna Miller

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# Model dynamo may solve Mercury mystery

Simulations suggest that the planet's top-heavy magnetic field derives from the unusual chemistry of its core.

In March 2011, nearly seven years after its launch, NASA's *MESSENGER* probe became the first manmade object to orbit Mercury, where it began a detailed survey of the planet's geochemistry, topography, and space environment. (See the article by Sean Solomon, *PHYSICS TODAY*, January 2011, page 50.) Within a few months, the spacecraft delivered a surprise: Mercury's magnetic field is top heavy—three times as strong at the north pole as it is at the south pole.<sup>1</sup>

Of the planets in our solar system that possess a global, dipolar magnetic field, only Mercury exhibits the north-south asymmetry. The finding is all the more puzzling because by most every other measure, including gravitational field strength and surface temperature, Mercury's northern and southern halves are essentially identical. Now, with new insights from simulations of the planet's dynamo—the turbulent, magnetic-field-inducing flow of molten material in the planet's core—Hao Cao,

Christopher Russell (both at UCLA), and coworkers think they've uncovered the recipe for the symmetry breaking that gave Mercury its unique magnetic field.<sup>2</sup>

## Uncommon core

Planetary dynamos feed on motion. As molten metal churns in the core, it stretches and bends existing magnetic field lines, thereby inducing additional magnetic field. If the motion were to stop, the planet's field would decay and vanish. (See the article by Daniel Lathrop and Cary Forest, *PHYSICS TODAY*, July 2011, page 40.)

In Earth's dynamo, core flows are thought to be sustained partly with energy supplied by phase changes at the interface between the solid inner core and the fluid outer core (see figure 1a). As the planet cools, the inner core grows; it incorporates iron and other heavy elements from the outer core and leaves behind a fluid rich in low-density elements such as sulfur. That

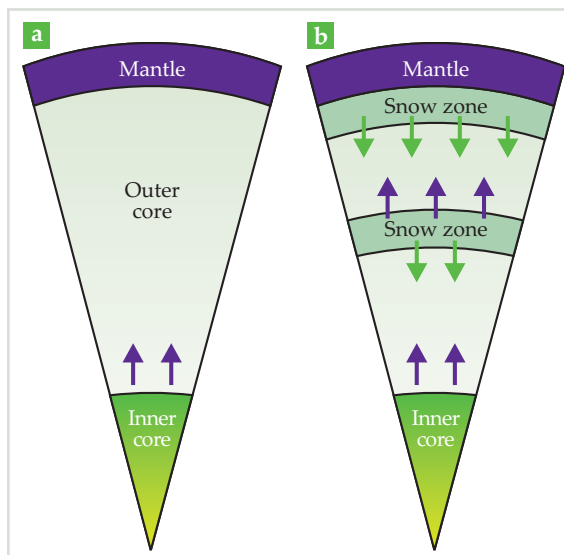
hot, buoyant fluid rises to the overlying mantle and generates the convective motion that powers the dynamo. (See the article by Peter Olson, *PHYSICS TODAY*, November 2013, page 30.)

Traditionally, Mercury's dynamo has been assumed to operate in similar fashion. But there are reasons to suspect that convective forcing in Mercury's core may be significantly more complex than it is in Earth's. For starters, Mercury's core is thought to contain a much higher concentration of light elements; their depression of the core's freezing point is currently the only viable explanation for why the relatively small core hasn't already frozen completely solid. (See *PHYSICS TODAY*, July 2007, page 22.)

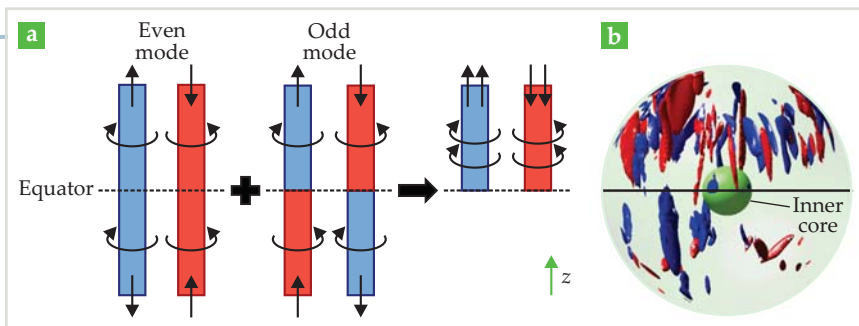
In 2008 Bin Chen, Jie Li (both then at the University of Illinois at Urbana-Champaign), and Steven Hauck II (Case Western Reserve University, Cleveland, Ohio) showed that when molten iron contains a sufficiently large admixture of sulfur and is compressed to Mercury-like pressures, iron can spontaneously precipitate—even when there's no solid-liquid interface to seed the phase change.<sup>3</sup> They predicted that precipitation could potentially occur in two layers, so-called snow zones, inside Mercury's core. Sources of heavy precipitates and buoyant light elements, the snow zones (depicted in figure 1b) would further stir the dynamo.

Newer assessments of Mercury's geochemistry hint at still more complicated forcing patterns. Spectroscopic measurements indicate that Mercury's silicate surface is poor in iron and rich in sulfur, which suggests that the planet formed under highly reducing chemical conditions. Laboratory experiments mimicking those conditions demonstrate that Mercury's core likely acquired substantial admixtures of both sulfur and silicon as it formed. If so, the liquid part of the core could consist of two immiscible layers—an iron-sulfur phase and an iron-silicon phase—each of which could spawn snow zones and potentially give rise to other exotic phase behavior.

To see how different forcing patterns influence dynamo-generated magnetic fields, Cao and his coworkers teamed with a numerical modelling group led by Johannes Wicht (Max Planck Institute for Solar System Research, Göttingen, Germany). The researchers didn't attempt to simulate every possible scenario, just two extreme cases: An Earth-like scenario in which the dynamo is stirred from below and a so-called vol-



**Figure 1. Planetary** dynamos are driven in part by convective circulation resulting from phase changes in the planet's interior. **(a)** In Earth, for example, light elements (purple arrows) are expelled into the molten outer core as the solid inner core grows. Those light elements stir the core as they rise to the mantle. **(b)** In Mercury, light elements (purple arrows) and heavy solids (green arrows) can also originate in localized regions of precipitation known as snow zones. (Adapted from ref. 3.)



**Figure 2. Symmetry breaking** in dynamos. **(a)** Interactions between even and odd flow modes in a planetary dynamo tend to enhance flow in one hemisphere and diminish it in the other. (Straight black arrows indicate the velocity component in the direction  $z$  of the spin axis; curved arrows indicate vorticity.) **(b)** In a dynamo simulation, the interactions between modes manifest as an asymmetry in helicity—a measure of the flow’s combined velocity and vorticity. (In both panels, red and blue denote regions of positive and negative vorticity, respectively.) (Adapted from ref. 2.)

umetric buoyancy scenario, which simulates a fully pervasive iron snow. Whereas the Earth-like forcing always yielded a symmetric magnetic field, volumetric buoyancy consistently gave rise to asymmetries similar to that observed for Mercury.

“It’s somewhat counterintuitive, because all of the boundary conditions are symmetric; we don’t know *a priori* if the system will be stronger in the north or in the south,” says Cao. “But once the system chooses a hemisphere, it stays in that state. It’s a classic example of spontaneous symmetry breaking.”

### Odds and evens

Planetary dynamos are generally thought to be organized into helical flows along columns aligned parallel to the spin ( $z$ ) axis. In a typical dynamo, such as Earth’s, the flows in neighboring columns are alternately directed toward and away from the equator, as depicted schematically at the left of figure 2a. (Straight black arrows indicate the axial velocity; curved arrows indicate vorticity, a measure of the fluid’s spinning motion.) In mathematical parlance, the flow configuration is known as an even mode, since the flows in the northern hemisphere mirror those in the south.

Fluid mechanical theory predicts that under strong forcing, dynamos can also host an odd mode, in which fluid travels through the equator, reversing vorticity along the way. Cao and company noticed that although the odd mode itself does not distinguish between northern and southern hemispheres, its superposition with the even mode does. That superposition provides a possible route to magnetic-field asymmetry. Although the precise structure of the magnetic field depends on complex interactions between the three-dimensional flow and preexisting

field lines, the field strength correlates roughly with helicity, the dot product of velocity and vorticity. When the odd and even modes overlap, their superposition enhances helicity in one hemisphere and diminishes it in the other. Indeed, that theoretical picture is consistent with helicity profiles obtained in the team’s dynamo simulations, as shown in figure 2b.

The researchers aren’t the first to see symmetry breaking in dynamo simulations. Three years ago, Maylis Landeau and Julien Aubert (both then at the University of Paris Diderot) reported a similar magnetic asymmetry in simulations of the ancient Martian dynamo.<sup>4</sup> Landeau and Aubert, however, specifically considered the case of a planet with an all-fluid core; the asymmetry resulted from a particular flow mode in which fluid passes through the center of the planet as it travels between poles. Such a mode is plausible for early Mars but not for planets that, like Mercury, have sizeable solid inner cores.

At first glance, the mechanism that Cao and company propose for Mercury’s symmetry breaking seems to contradict previous theoretical studies that predict that the dynamo’s columnar flow structure should destabilize before convective forcing becomes strong enough to excite the odd mode. But those studies assume Earth-like forcing, notes Jonathan Aurnou (UCLA), co-author of the new paper. “The volumetric buoyancy essentially acts to keep the columns stable.”

Another facet of the team’s model may have been central to symmetry breaking. The researchers tried imposing a variety of boundary conditions for the core’s outer edge, including the customary uniform heat-flux condition and less traditional scenarios in which heat escapes faster near the equator

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than at mid and high latitudes. Although north–south asymmetries could occur with uniform heat fluxes, the resulting dipoles tended to lie off-center with the spin axis, fluctuate wildly over time, and exhibit a weaker asymmetry than exists on Mercury. When heat was assumed to escape faster near the equators, the fields looked nearly identical to Mercury's.

To some extent, then, the theoretical explanation of Mercury's asymmetry hinges on the unproven assumption that the core cools fastest at the equator,

probably by way of enhanced convection in the mantle. According to Sean Solomon, principal investigator of the MESSENGER mission, the assumption isn't too far-fetched. "If there were sustained, enhanced upwelling of the mantle in the equatorial zones—and if that pattern persisted over most of Mercury's history—then you might expect to see a thicker crust in the equatorial regions. That is, in fact, what we see."

Solomon cautions, however, that it's not a given that Mercury's mantle is convecting at all—much less that it is

removing heat fastest near the equator. "Most but not all Mercury models have mantle convection turning off sometime before the present," he says. "Our ignorance is vast."

Ashley G. Smart

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# Charged polymers form unusual nanostructures

A hybrid theoretical description provides a roadmap to designing better battery electrolytes.

**D**iblock copolymers—made up of a chain of monomer A bound to a chain of monomer B, as shown in figure 1a—are of great theoretical and practical interest. When the A and B monomers are sufficiently immiscible, they can segregate into self-assembled periodic nanostructures such as alternating layers or hexagonally ordered rods. The morphology of those two-phase structures depends on the phase immiscibility, the relative lengths of the A and B chains, and other factors. Choosing the A and B phases with complementary properties enables a variety

of applications. (See the article by Frank Bates and Glenn Fredrickson, *PHYSICS TODAY*, February 1999, page 32.)

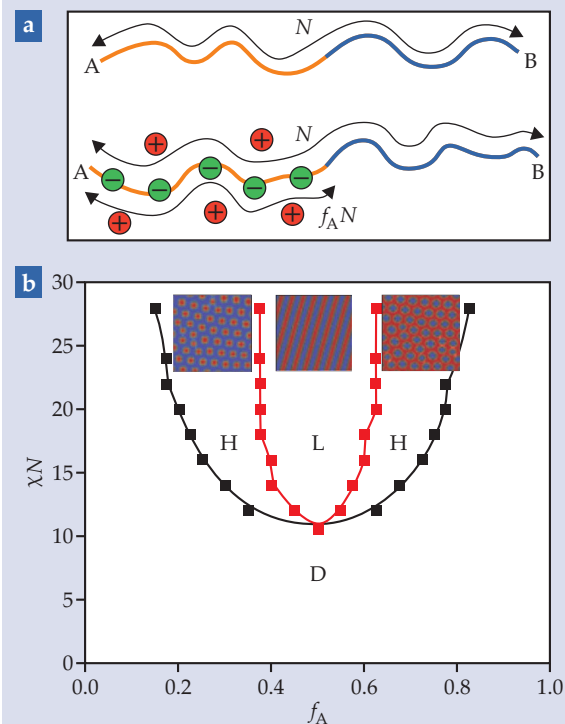
For example, to make a solid-state electrolyte for a battery or fuel cell, one can optimize the A phase for ionic conductivity, with negative ions bound to the polymer chains balanced by unbound positive ions, and the B phase for mechanical stability. Numerous experiments, however, have shown that the theoretically derived phase diagram that predicts the nanophase morphology no longer applies when one of the phases is charged.<sup>1</sup>

Monica Olvera de la Cruz and colleagues at Northwestern University have developed a new theory that accurately describes the ion-rich A phase by accounting for correlations among the charged monomers and ions.<sup>2</sup> Tuning the strength of those correlations, which depends, most importantly, on the dielectric constant of the A phase, can induce qualitative changes in the A phase's morphology.

## Ionic effects

The canonical phase diagram for neutral diblock copolymers, shown in figure 1b, illustrates how, as a function of the fraction  $f_A$  of A monomers and phase immiscibility  $\chi$ , the polymers can be disordered or can form layered or hexagonal structures. The phase boundaries are derived from self-consistent field theory (SCFT), which is founded on the assumption that as the polymers move around, each one responds to the mean density of all the others—so instead of solving the many-body problem of all the polymers simultaneously, one need only look at the problem of a single polymer moving in an applied field. For neutral-polymer systems, that assumption seems to be good: SCFT has been successfully used for decades to describe various aspects of phase segregation in neutral polymers and copolymers.

Applying SCFT to a charged polymer system means assuming that each charge—whether free or bound to a polymer—feels the average electric field of all the other charges. Such a treatment results in a phase diagram of the same shape as the one in figure 1b, but shifted down by an amount proportional to the fraction of charged monomers in the A phase.<sup>3</sup> That is, the immiscibility  $\chi$  is replaced by an effective



**Figure 1. Neutral and charged diblock copolymers** (a) are characterized by their overall length  $N$  and the fraction  $f_A$  of that length that's made up of monomer A. (b) In the canonical phase diagram for neutral diblock copolymers, if the immiscibility  $\chi$  of the A and B monomers is sufficiently low, the polymers form a disordered phase (D). At higher immiscibilities, the polymers form self-assembled ordered nanostructures such as hexagonally arranged rods (H) or alternating lamellae (L). (Adapted from ref. 2.)