Scott L. Murchie got interested in rocks because there were so many of them outside his family's house in New England. Now a geologist at the Johns Hopkins University Applied Physics Laboratory (APL), he analyzes the spectrum of reflected sunlight to work out the structure and history of planetary crusts.

Ronald J. Vervack, Jr., also at APL, traces his lifelong interest in planetary science to a four-inch telescope his grandparents gave him for Christmas. Having never really grown up, Vervack is fascinated by all things planetary, studying atmospheres, comets and asteroids at a variety of wavelengths.

Brian J. Anderson, at APL, too, specializes in planetary magnetic fields, magnetospheres and space plasmas. In his free time, he sings in community choruses. "Singing was my first love," he says, "but my natural aptitude was for science. So now I support my musical life with this amazing research career."

SPACE SCIENCE

Journey to the Innermost Planet

Mercury has never been orbited by a spacecraft before. That will change this month

By Scott L. Murchie, Ronald J. Vervack, Jr., and Brian J. Anderson

The old joke goes that the only thing worse than finding a worm in an apple is finding half a worm. Planetary scientists had a similar feeling on March 29, 1974, when the Mariner 10 space probe flew by Mercury and gave humanity its first good look at this tiny inferno of a world. It discovered, among other features, one of the largest impact basins in the solar system, later named Caloris. Yet its pictures captured only half the basin; the other half remained cloaked in darkness. In fact, between this visit and the second and third flybys later in 1974 and in 1975, Mariner 10 imaged less than half the planet's surface.

It was not until 34 years later that we finally saw the entire basin illuminated, and it was even more impressive than the early images suggested. On January 14, 2008, the MESSENGER spacecraft swung by Mercury, and the first image it transmitted to Earth was very nearly centered on Caloris. When our colleague Nancy Chabot showed the image to the team, everyone cheered—but only briefly, because then we launched into an intense discussion of what exactly we were seeing. It looked like a negative image of the moon. Although Mercury's cratered surface was reminiscent of the moon's, lunar basins have dark, lava-filled interiors, whereas Caloris was filled with light-colored plains—a difference we have yet to fully understand.

INSIDE MESSENGER
ScientificAmerican.com/mar2011/mercury

This month MESSENGER does what Mariner 10 was unable to: it will enter into orbit around Mercury to study the planet in depth, rather than just catching fleeting glimpses during flybys. Mercury is the least explored of the inner planets. Its landforms and brightness variations are only two of its mysteries. Launched in 2004, MESSENGER—for MErcury Surface, Space ENvironment, GEochemistry, and Ranging—is designed to answer six big questions: What is the composition of Mercury's surface? What is its geologic history? How can such a small planet have a global magnetic field? Is its metallic core molten? What are the radar-bright patches at the poles? What processes govern the tenuous atmosphere? MESSENGER should finish what Mariner 10 left half-done.

IN BRIEF

Mercury baffles scientists. Only half again as large as the moon, it has Earth-like features such as a global magnetic field. Its surface is heavily cratered yet has signs of comparatively young geologic activity.

In 2008 and 2009 NASA's MESSENGER space probe made the first flybys of Mercury since the mid-1970s. It captured images of a hemisphere never before seen in detail and saw unexpectedly turbulent plasma activity.

On March 18 it finally enters into orbit around Mercury and begins a one-year orbital mission. Just getting there has been hard, given the planet's high orbital speed and proximity to the sun.

Illustrations by Don Foley (MESSENGER) and Jen Christiansen (trajectory inset)

GETTING TO MERCURY

Descent to Hades

One reason it took three decades to follow up the Mariner 10 mission is that getting to Mercury and surviving there are technologically challenging. A spacecraft on a direct path from Earth falls into the sun's gravitational field and accelerates to almost 13 kilometers per second faster than Mercury's orbital velocity. A conventional rocket engine could not slow the spacecraft enough to be captured into orbit by the planet's gravity. In terms of energy, Mercury is harder to reach than Jupiter, even though Jupiter is much farther away.

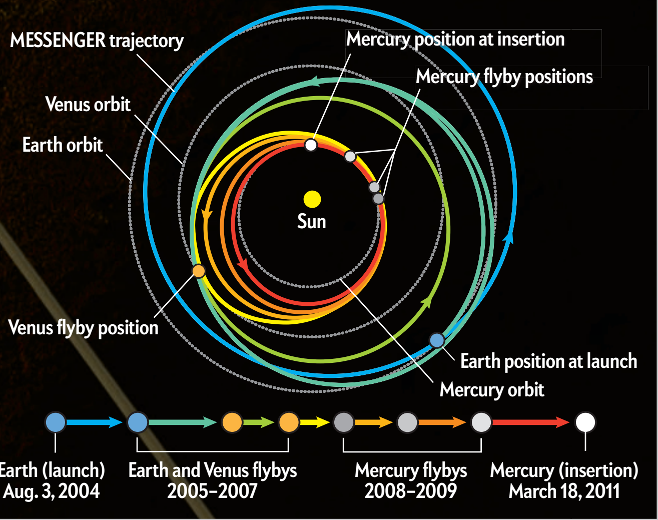
To pull it off, MESSENGER made one flyby of Earth, two of Venus and three of Mercury itself. Each time, some of the spacecraft's momentum was transferred to the planet. This procedure is the same as the gravitational slingshot effect used to propel spacecraft to the outer planets, except that the trajectory was designed to slow rather than speed up the spacecraft. Over six and a half years the sequence of flybys shed 11 kilometers per second.

MESSENGER's main rocket engine completed the task. The spacecraft is built like a flying gas tank, with a minimal and lightweight structure built around propellant tanks (①). At launch the total spacecraft mass was 1,100 kilograms, and more than half of that, 600 kilograms, was fuel.

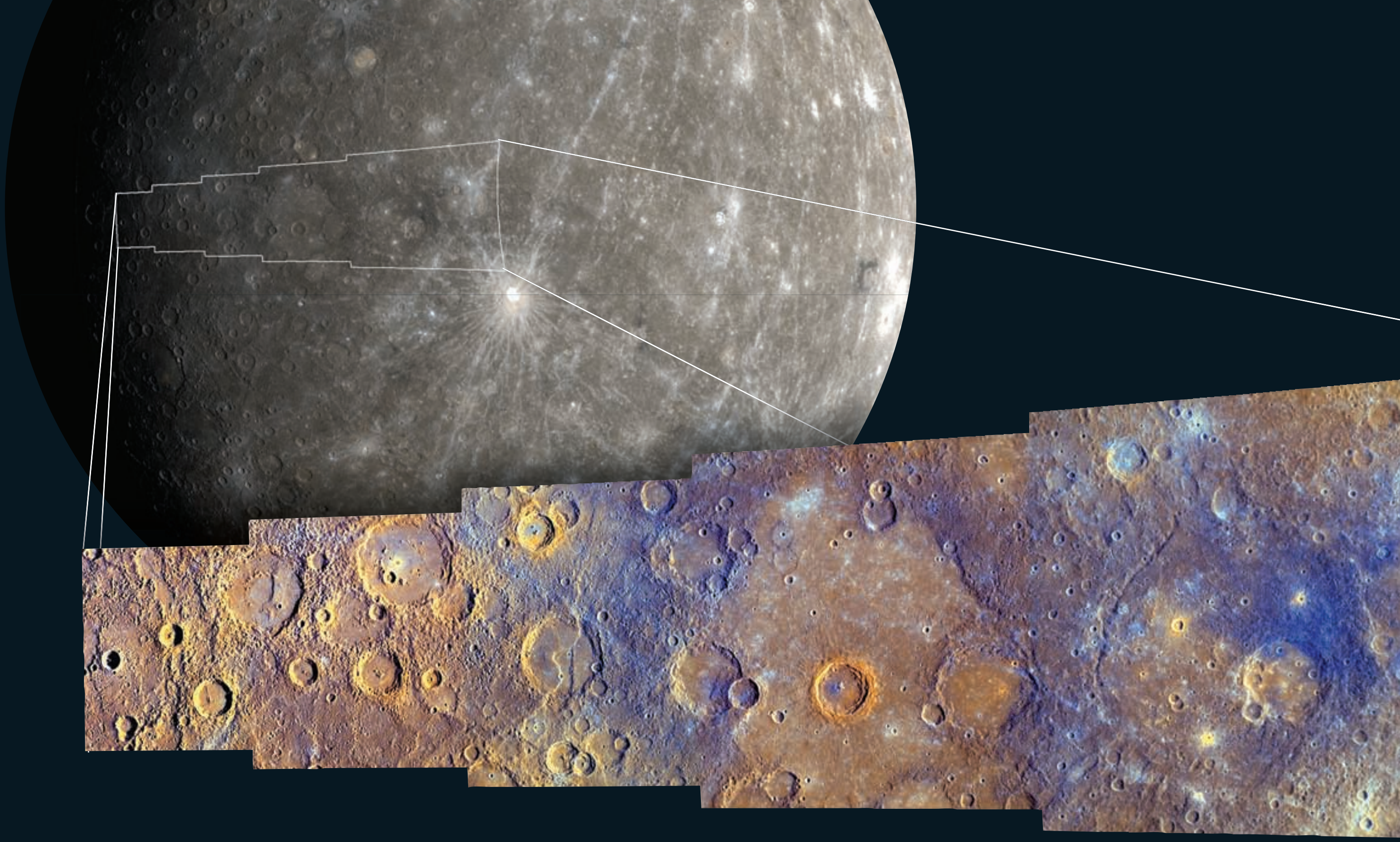
Getting there was only half the fun. At Mercury the sun is up to 11 times brighter than at Earth, and the surface of the planet reaches temperatures high enough to melt zinc. The spacecraft hides behind a sunshade (②) woven from ceramic fibers. The solar panels (③), of course, have to protrude beyond the sunshade, and even though the panels are designed to operate at high temperatures, we have to tilt them at a steep angle so that they absorb only a small fraction of the sunlight and do not overheat.

The scientific instruments must expose themselves to the surface. To withstand the roasting, the camera (④) sits on 400 grams of paraffin. When the spacecraft is low in its orbit, the paraffin melts, absorbing heat; when the spacecraft is at high altitude or over the night side, the paraffin refreezes for the next pass.

Yet another challenge is that Mercury rotates on its axis very slowly. A solar day on Mercury—sunrise to sunrise—lasts 176 Earth days. Many sites will be visible at their ideal viewing geometries for just a few short periods during the one-Earth-year mission.



SOURCES: NASA/JOHNS HOPKINS UNIVERSITY APPLIED PHYSICS LABORATORY/CARNEGIE INSTITUTION OF WASHINGTON



CRUST

Not as Dead as It Looks

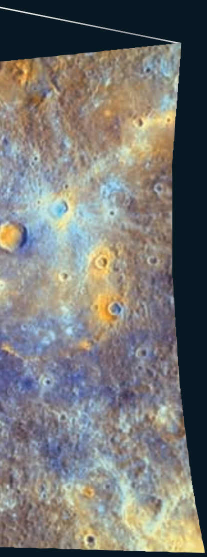
Prior to Mariner 10, some scientists expected Mercury to be as geologically dead as Earth's moon. Geologic activity grinds to a halt when a planet or satellite loses its internal heat, and size determines how fast that happens; smaller objects have larger surface areas in relation to their volume and therefore cool off faster. Because Mercury is only half again larger than the moon, its geologic history should have been similar. Mariner called this wisdom into question when it returned images of vast plains that appeared to be volcanic. But it was hard to tell. From afar, the Cayley Plains on the moon, too, looked like an unusual volcanic plain—but when *Apollo 16* astronauts landed there, all they found was debris ejected from an impact basin.

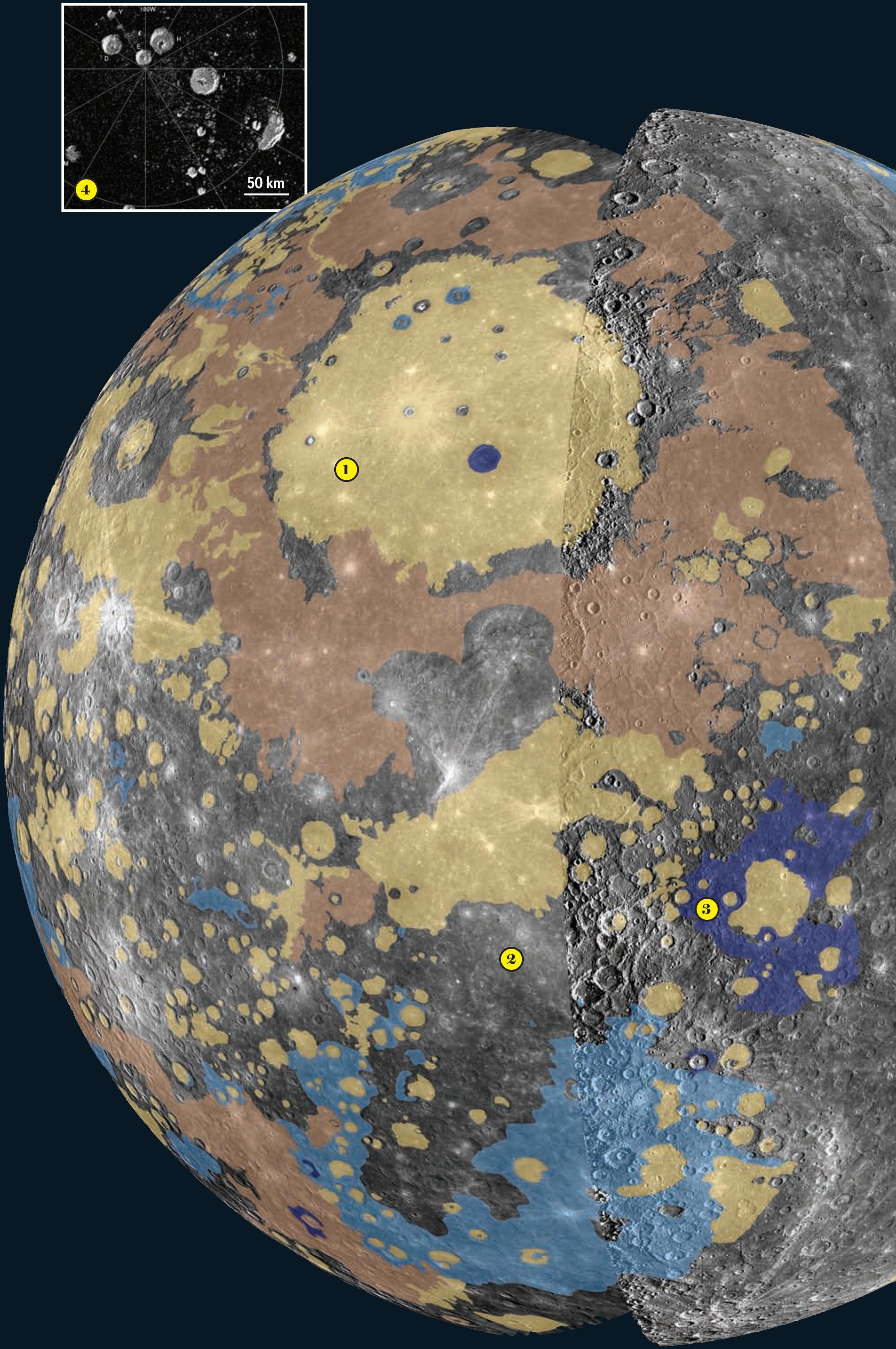
We never thought MESSENGER would settle the question as quickly as it did. It has seen clear evidence for lavas of various colors and composition, as well as for past pyroclastic eruptions like those at Mount St. Helens. Computer enhancement of the color variations (*in images above*) brings out these relations. Distinctly colored smooth material fills low areas inside craters. Smaller, younger craters have excavated multicolored materials from a range of depths in the crust. These images suggest that the upper few kilometers of Mercury's crust consist of layered volcanic deposits.

Tracing the boundaries of terrain with similar landforms and colors, mission scientists have made the first new MESSENGER-era map of Mercury's geology (*at right*). About 40 percent of the surface—including the interior of the Caloris impact basin (①)—consists of smooth plains, many of which are probably volcanic (*shades of brown on map*). Gray areas between the smooth plains are more cratered and may be older (②). A notable difference from the moon and Mars is how smooth plains are distributed. The moon's are concentrated on the near side, facing Earth; Mars's are mostly in the northern hemisphere and on a volcanic plateau. Mercury's are found all over the planet. The youngest may be just one billion years old, relatively new by lunar and Martian standards.

Scientists continue to puzzle over relatively blue regions that cover 15 percent of the surface, such as Tolstoj basin (③). These may contain iron- and titanium-bearing oxides that impacts have dredged up from great depth, or they may be the very oldest volcanic materials poking up above younger lighter-colored lavas.

The images MESSENGER takes from orbit will have three or more times better resolution than these flyby images, and instruments that had short times to operate during the flybys will finally begin to send back their highest-quality data. The Gamma-Ray and Neutron Spectrometer, for example, will follow up a discovery made in the 1990s from ground-based radar observations: the polar regions contain highly radar-reflective materials, possibly water ice (④). Ice seems like the last thing you would expect to find on a scorching planet, but perpetually shadowed regions near the poles could be sufficiently frigid to capture any wisps of water vapor from impacting comets or water-rich meteoroids.





SOURCES: NASA/JOHNS HOPKINS UNIVERSITY APPLIED PHYSICS LABORATORY/ARIZONA STATE UNIVERSITY/CARNEGIE INSTITUTION OF WASHINGTON; JOHN HARMON *Arecibo Observatory* (ice)

INTERIOR AND MAGNETOSPHERE

A Magnetic Mystery

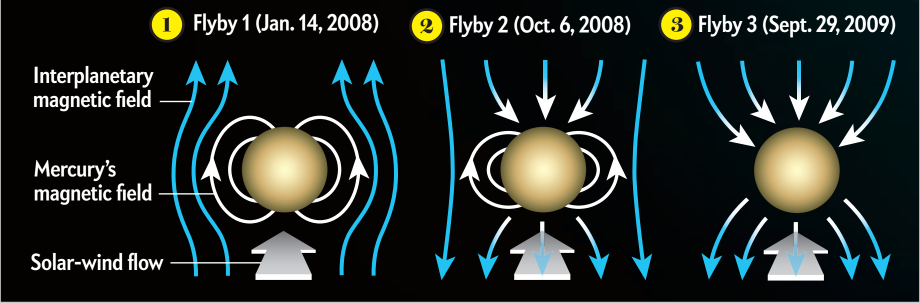
By tracking Mariner 10's trajectory, scientists measured Mercury's gravitational field and refined the estimate of its density. The value is oddly high, about 5.3 grams per cubic centimeter, compared with 4.4 for Earth, 3.3 for the moon and 3 for an average rock. (These values all correct for self-compaction caused by gravity, so that we can compare the intrinsic material properties.) Underneath the rocky veneer of Mercury must be a dense core dominated by iron. Earth also has an iron-rich core, but in relation to the planet's mass, Mercury's is twice as large. Perhaps Mercury once had a thicker rock layer and impacts stripped it off, or perhaps the material from which Mercury formed, by virtue of being so close to the sun, was rich in iron.

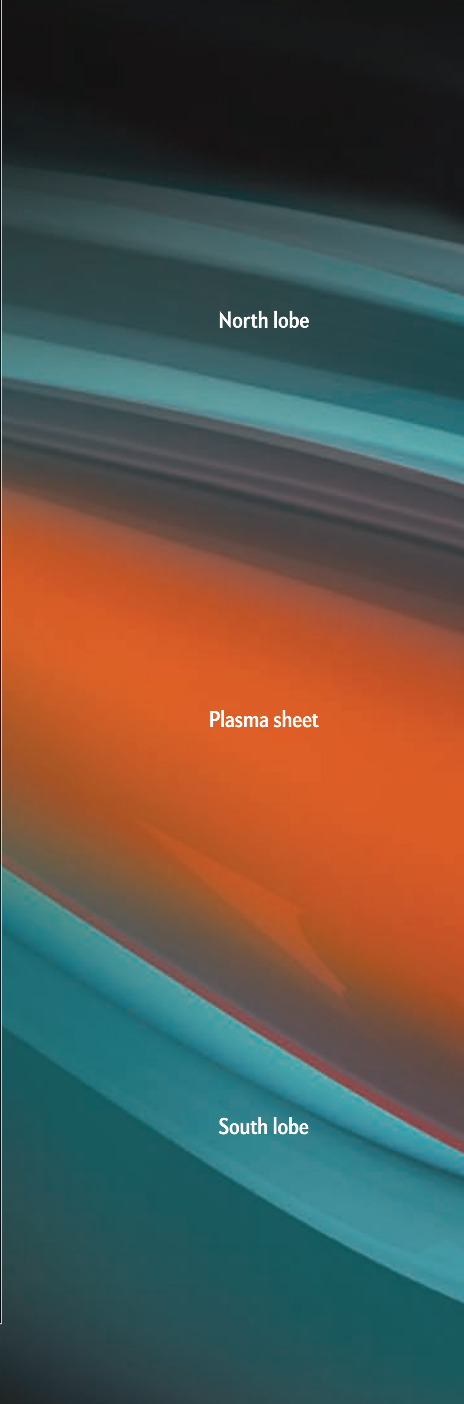
The large core surely is related to one of Mariner 10's most startling discoveries: a global magnetic field. The field is mainly dipolar, like that of a bar magnet. Although the field at the surface is only about 1 percent as strong as Earth's, it is remarkable that Mercury has a dipole field at all. No other solid-surfaced body in the solar system besides Earth and Jupiter's moon Ganymede does.

Earth's field is generated by circulating molten iron in the outer core, a "planetary dynamo." Mercury's field, as well as subtleties of how the planet changes its spin rate in the course of each revolution about the sun, indicates that the outer core has not completely solidified, even though Mercury's size suggests it should have. Mercury somehow evaded the fate of Mars, which had a global field early in its history and lost it. Figuring out why is a major goal of MESSENGER.

Apart from indicating what is happening within the planet, the magnetic field makes for some wild plasma physics around Mercury. The field deflects the solar wind, the stream of charged particles emanating from the sun, and creates a volume surrounding the planet dominated by Mercury's magnetic field rather than the interplanetary magnetic field carried by the wind. Mariner 10 detected bursts of energetic particles similar to those associated with Earth's dazzling auroral displays.

MESSENGER has found that the magnetosphere keeps changing. At the time of the first flyby, the interplanetary field pointed north, so that it was aligned with the planet's equatorial magnetic field (①). The magnetosphere was quiescent. At MESSENGER's second visit, the interplanetary field happened to be pointing southward, opposite to the direction of Mercury's magnetic field at the equator. Magnetic fields aligned in opposite directions can splice together in a phenomenon known as reconnection (②), which releases large amounts of energy and injects plasmas from each region into the other—in this case, jetting solar-wind plasma into Mercury's magnetosphere. MESSENGER measured a rate of magnetic reconnection 10 times stronger than that observed near Earth. On the third flyby, the observations suggested that the planetary field lines were profoundly distorted, alternately being linked entirely to the solar wind (③) and then, five minutes later, linking normally between the northern and southern hemispheres. Under such powerful dynamics, a compass needle would be of little use to navigate on the surface, because it would flip direction every few minutes. What else might Mercury's magnetosphere be capable of?





MORE TO EXPLORE

The Evolution of Mercury's Crust: A Global Perspective from MESSENGER. Brett W. Denevi et al. in *Science*, Vol. 324, pages 613–618; May 1, 2009.

The Magnetic Field of Mercury. Brian J. Anderson et al. in *Space Science Reviews*, Vol. 152, Nos. 1–4, pages 307–339; May 2010.

Mercury's Complex Exosphere: Results from MESSENGER's Third Flyby. Ronald J. Vervack, Jr., et al. in *Science*, Vol. 329, pages 672–675; August 6, 2010.

Illustrations by Don Foley (Mercury), Jen Christiansen (magnetic field inset), and Ronald J. Vervack, Jr. (exosphere inset)

EXOSPHERE

A Slow-Motion Strobe Light

Mercury does not have a traditional atmosphere in the sense of a thick blanket of air, but it does have an exosphere: an “atmosphere” so tenuous that atoms can bounce across the surface like billiard balls without colliding with one another. The atoms come from the surface via several processes. Sunlight knocks them out of mineral crystals and evaporates volatile elements such as sodium; ions from the solar wind bombard minerals and eject atoms from them; and the steady hail of micrometeoroids vaporizes surface materials. Processes involving sunlight are fairly low in energy, and the atoms they eject generally fall back to the surface (④).

The solar wind and micrometeoroid bombardment are more violent, and the atoms they expel remain aloft longer (⑤). Some, especially sodium, can form a cometlike tail as solar radiation pushes them away from the sun and the planet (⑥).

Through a fascinating combination of effects, the exosphere pulses slowly in brightness twice per Mercury orbit. The reason is that the elements making up the exosphere absorb sunlight at certain wavelengths and then emit some of that energy back at the same wavelengths. These elements are also present in the outer layers of the sun, however, where they absorb the wavelengths that stimulate exospheric emissions. But sometimes the required sunlight reaches Mercury after all, because the planet’s orbit is highly elliptical; when the planet is accelerating away from or toward the sun, the Doppler effect shifts the solar spectrum, so that more light of the requisite wavelengths reaches the exosphere and causes it to glow more brightly. Thus, when Mercury is closest to or farthest from the sun, the exosphere is barely visible (⑦). At intermediate points in its orbit, it is bright (⑧).

Over the coming year MESSENGER will watch as the exosphere goes through its orbital cycles. If past experience is any guide, Mercury will exhibit new phenomena that have yet to be imagined.