Mercury: The Forgotten Planet

Although one of Earth's nearest neighbors, this strange world remains, for the most part, unknown

by Robert M. Nelson

The planet closest to the sun, Mercury is a world of extremes. Of all the objects that condensed from the presolar nebula, it formed at the highest temperatures. The planet's dawn-to-dusk day, equal to 176 Earth-days, is the longest in the solar system, longer in fact than its own year. When Mercury is at perihelion (the point in its orbit closest to the sun), it moves so swiftly that, from the vantage of someone on the surface, the sun would appear to stop in the sky and go backward—until the planet's rotation catches up and makes the sun go forward again. During daytime, its ground temperature reaches 700 kelvins, the highest of any planetary surface (and more than enough to melt lead); at night, it plunges to a mere 100 kelvins (enough to freeze krypton).

Such oddities make Mercury exceptionally intriguing to astronomers. The planet, in fact, poses special challenges to scientific investigation. Its extreme properties make Mercury difficult to fit into any general scheme for the evolution of the solar system. In a sense, Mercury's unusual attributes provide an exacting and sensitive test for astronomers' theories. Yet even though Mercury ranks after Mars and Venus as one of Earth's nearest neighbors, distant Pluto is the only planet we know less about. Much about Mercury—its origins and evolution, its puzzling magnetic field, its tenuous atmosphere, its

DON DIXON

DAWN ON MERCURY, 10 times more brilliant than on Earth, is heralded by flares from the sun's corona snaking over the horizon. They light up the slopes of Discovery scarp (*cliffs at right*). In the sky, a blue planet and its moon are visible. (This artist's conception is based on data from the Mariner 10 mission.)

possibly liquid core and its remarkably high density—remains obscure.

Mercury shines brightly, but it is so far away that early astronomers could not discern any details of its terrain; they could map only its motion in the sky. As the innermost planet, Mercury (as seen from Earth) never wanders more than 27 degrees from the sun. This angle is less than that made by the hands on a watch at one o'clock. It can thus be observed only during the day, but scattered sunlight makes it difficult to see, or shortly before sunrise and after sunset, with the sun hanging just over the horizon. At dawn or dusk, however, Mercury is very low in the sky, and the light from it must pass through up to 10 times as much turbulent air as when it is directly overhead. The best Earth-based telescopes can see only those features on Mercury that are a few hundred kilometers across or wider—a resolution far worse than that for the moon seen with the unaided eye.

Despite these obstacles, terrestrial observation has yielded some interesting results. In 1955 astronomers were able to bounce radar waves off Mercury's surface. By measuring the so-called Doppler shift in the frequency of the reflections, they learned of Mercury's 59-day rotational period. Until then, Mercury had been thought to have an 88-day period, identical to its year, so that one side of the planet always faced the sun. The simple two-to-three ratio between the planet's day and year is striking. Mercury, which initially rotated much faster, probably dissipated energy through tidal flexing and slowed down, becoming locked into this ratio by an obscure process.

The new space-based observatories, such as the Hubble Space Telescope, are not limited by the problems of atmospheric distortion, and one might think them ideal tools for studying Mercury. Unfortunately, the Hubble, like many other sensors in space, cannot point at Mercury, because the rays of the nearby sun might accidentally damage sensitive optical instruments on board.

The only other way to investigate Mercury is to send a spacecraft to examine it up close. Only once has a probe made the trip: Mariner 10 flew by in the 1970s as part of a larger mission to explore the inner solar system. Getting the spacecraft there was not a trivial task. Falling directly into the gravitational potential well of the sun was impossible; the spacecraft had to ricochet around Venus to relinquish gravitational energy and thus slow down for a Mercury encounter. Mariner's orbit around the sun provided three close flybys of Mercury: on March 29, 1974; September 21, 1974; and March 16, 1975. The spacecraft returned images of about 40 percent of Mercury, showing a heavily cratered surface that, at first glance, appeared similar to that of the moon.

The pictures, sadly, led to the mistaken impression that Mercury differs very little from the moon and just happens to occupy a different region of the solar system. As a result, Mercury has become the neglected planet of the American space program. There have been more than 40 missions to the moon, 20 to Venus and more than 15 to Mars. By the end of the next decade, an armada of spacecraft will be in orbit about Venus, Mars, Jupiter and Saturn, returning detailed information about these planets and their environs for many years to come. But Mercury will remain largely unexplored.

The Iron Question

It was the Mariner mission that elevated scientific understanding of Mercury from almost nothing to most of what we currently know. The ensemble of instruments carried on that probe sent back about 2,000 images, with an effective resolution of about 1.5 kilometers, comparable to shots of the moon taken from Earth through a large telescope. Yet those many pictures captured only one face of Mercury; the other side has never been seen.

By measuring the acceleration of Mariner in Mercury's surprisingly strong gravitational field, astronomers confirmed one of the planet's most unusual characteristics: its high density. The other terrestrial (that is, nongaseous) bodies—Venus, the moon, Mars and Earth—exhibit a fairly linear relation between density and size. The largest, Earth and Venus, are quite dense, whereas the smaller ones, the moon and Mars, have lower densities.

Vital Statistics

Mercury is the innermost planet and has a highly inclined and eccentric orbit. It rotates about its own axis very slowly, so that one Mercury-day equals 176 Earth-days—longer than its year of 88 Earth-days. Proximity to the sun combined with elongated days gives Mercury the highest daytime temperatures in the solar system.

The planet has a rocky and cratered surface and is somewhat larger than the Earth's moon. It is exceptionally dense for its size, implying a large iron core. In addition, it has a strong magnetic field, which suggests that parts of the core are liquid. Because the small planet should have cooled fast enough to have entirely solidified, these findings raise questions about the planet's origins—and even about the birth of the solar system.

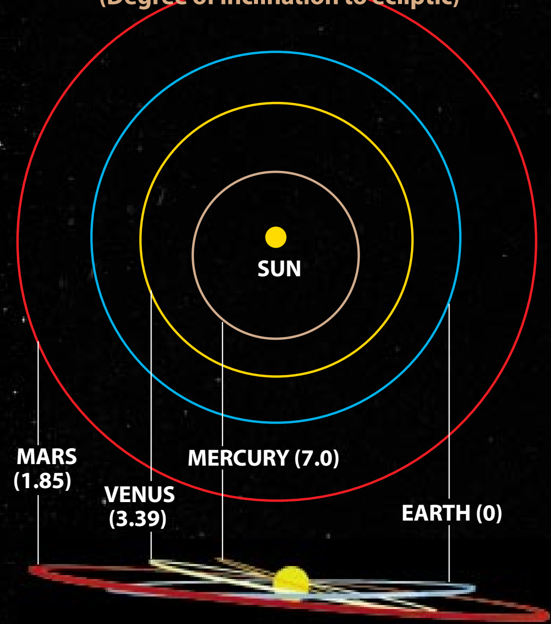
Mercury's magnetic field forms a magnetosphere around the planet, which partially shields the surface from the powerful wind of protons emanating from the sun. Its tenuous atmosphere consists of particles recycled from the solar wind or ejected from the surface.

Despite the planet's puzzling nature, only one spacecraft, Mariner 10, has ever flown by Mercury.

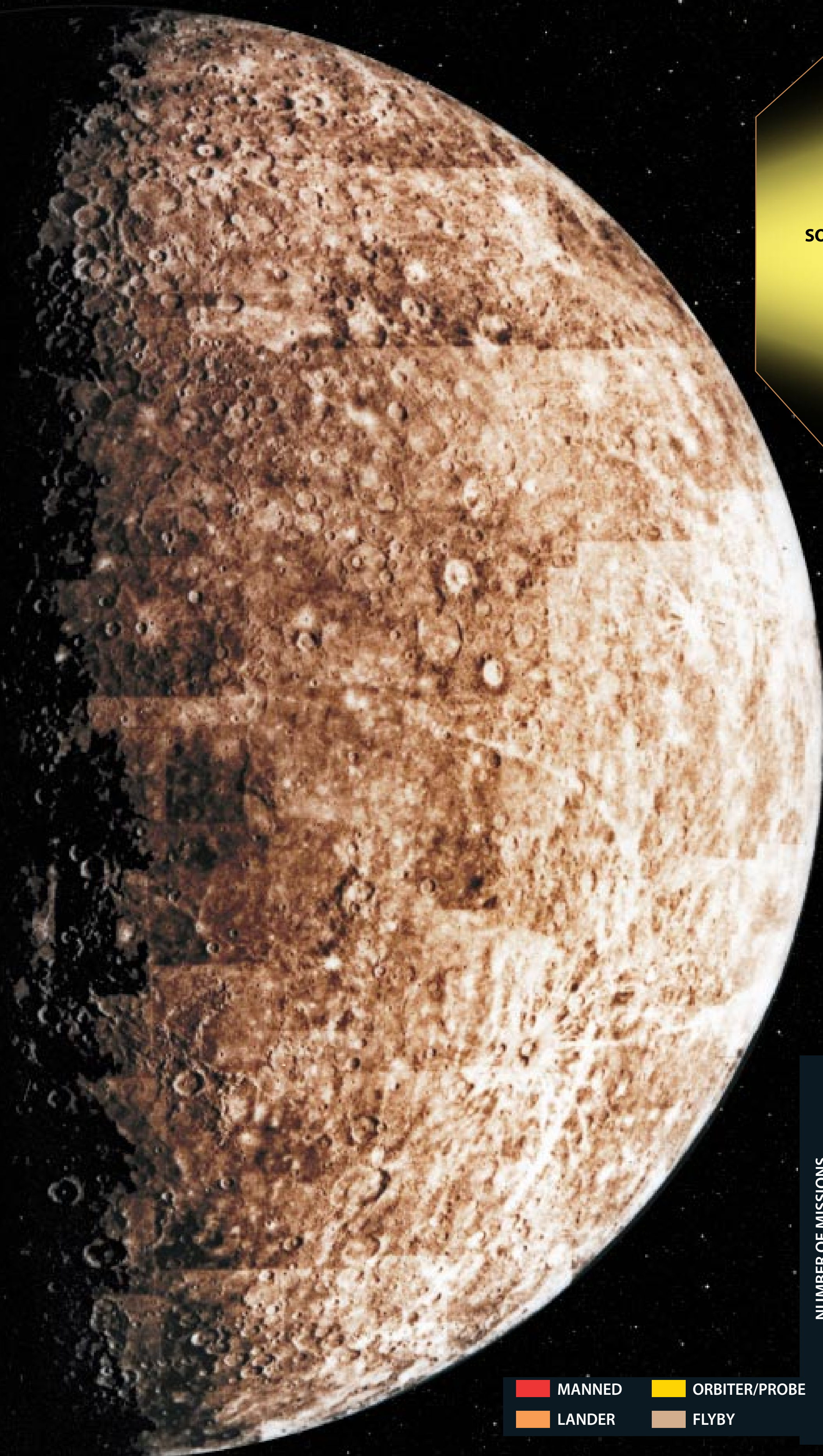
—R.M.N.

RELATIVE SIZES OF TERRESTRIAL BODIES

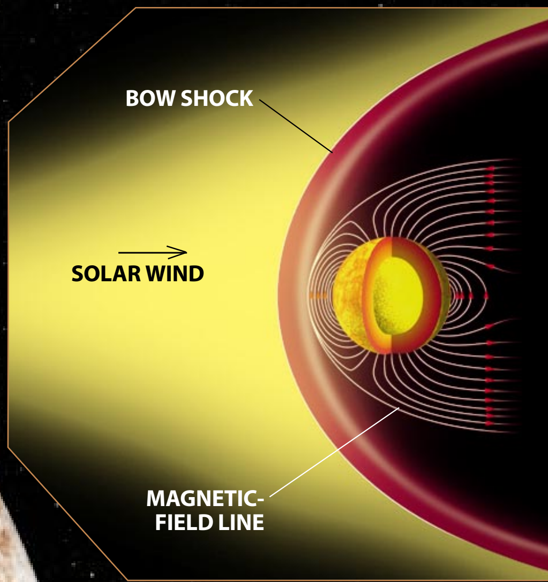
RELATIVE ORBITS OF TERRESTRIAL BODIES
(Degree of inclination to ecliptic)



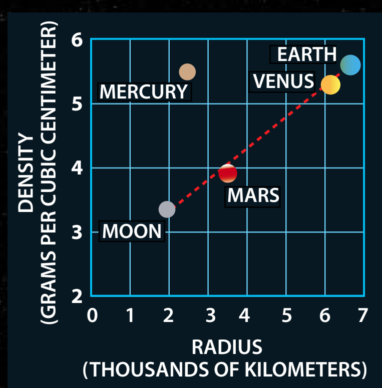
PHOTOGRAPHS BY NATIONAL AERONAUTICS AND SPACE ADMINISTRATION; ILLUSTRATIONS BY SLIM FILMS



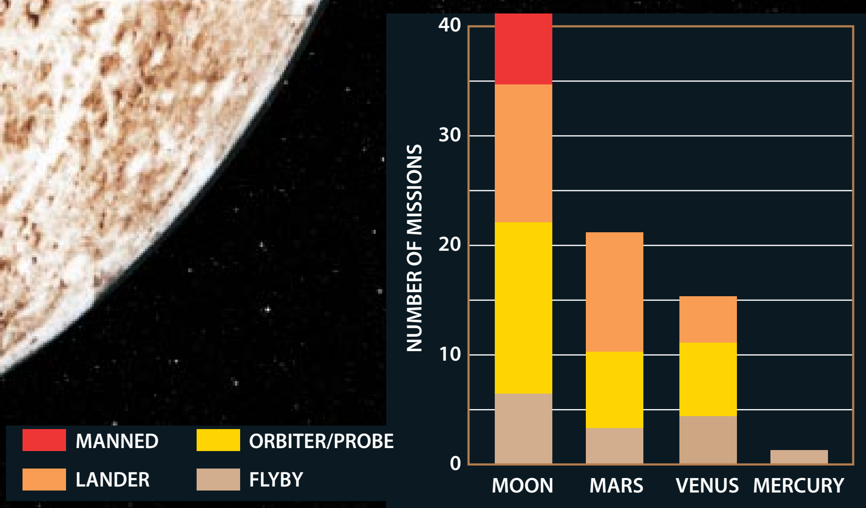
MERCURY'S MAGNETOSPHERE



DENSITY OF TERRESTRIAL BODIES



MISSIONS TO TERRESTRIAL BODIES



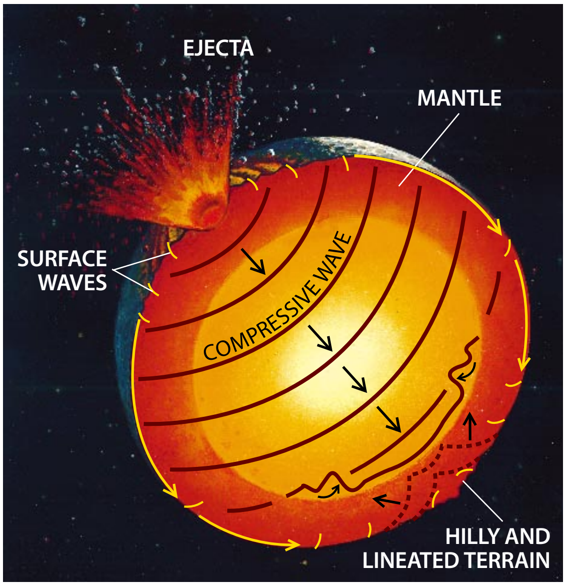
Mercury is not much bigger than the moon, but its density is typical of a far larger planet such as Earth.

This observation provides a fundamental clue about Mercury's interior. The outer layers of a terrestrial planet consist of lighter materials such as silicate rocks. With depth, the density increases, because of compression by the overlying rock layers and the different composition of the interior materials. The high-density cores of the terrestrial planets are probably made largely of iron.

Mercury may therefore have the largest metallic core, relative to its size, of all the terrestrial planets. This finding has stimulated a lively debate on the origin and evolution of the solar system. Astronomers assume that all the planets condensed from the solar nebula at about the same time. If this premise is true, then one of three possible circumstances may explain why Mercury is so special. First, the composition of the solar nebula might have been dramatically different in the vicinity of Mercury's orbit—much more so than theoretical models would predict. Or, second, the sun may have been so energetic early in the life of the solar system that the more volatile, low-density elements on Mercury were vaporized and driven off. Or, third, a very massive object may have collided with Mercury soon after its formation, vaporizing the less dense materials. The current body of evidence is not sufficient to discriminate among these possibilities.

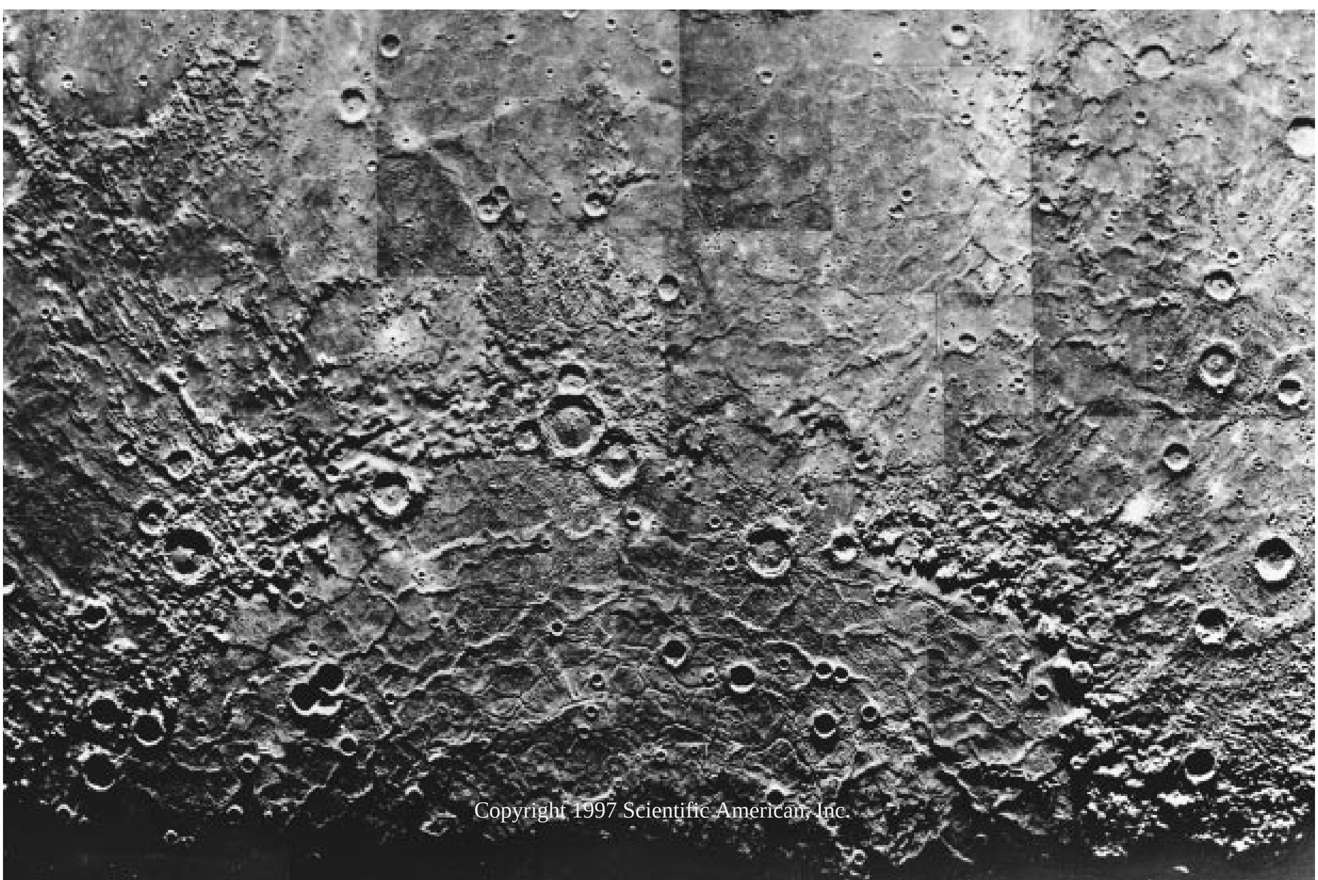
Oddly enough, careful analysis of the Mariner findings, along with laborious spectroscopic observations from Earth, has failed to detect even trace amounts of iron in Mercury's crustal rocks. The apparent dearth of iron on the surface contrasts sharply with its presumed abundance in Mercury's interior. Iron occurs on Earth's crust and has been detected by spectroscopy on the rocks of the moon and Mars. So Mercury may be the only planet in the inner solar system with all its high-density iron concentrated in the interior and only low-density silicates in the crust. It may be that Mercury was molten for so long that the heavy substances settled at the center, just as iron drops below slag in a smelter.

Mariner 10 also found that Mercury has a relatively strong magnetic field—the most powerful of all the terrestrial planets except Earth. The magnetic field of Earth is generated by electrically conductive molten metals circulating in the core, through a process called the self-sustaining dynamo. If Mercury's magnetic field has a similar source, then that planet must have a liquid interior.



ALFRED T. KAMAJIAN; COURTESY OF P. H. SCHULTZ AND D. E. GAULT

CALORIS CRATER was formed when a giant projectile hit Mercury 3.6 billion years ago (*above*). Shock waves radiated through the planet, creating hilly and lineated terrain on the opposite side. The rim of Caloris itself (*below*) consists of concentric waves that froze in place after the impact. The flattened bed of the crater, 1,300 kilometers across, has since been covered with smaller craters.



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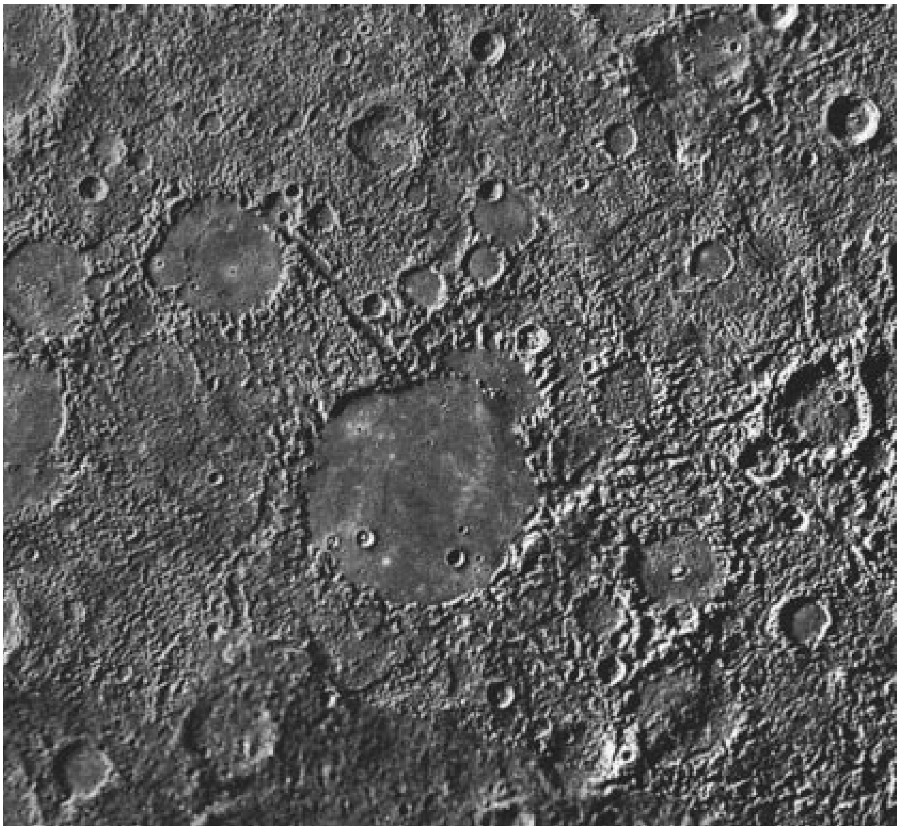
But there is a problem with this hypothesis. Small objects like Mercury have a high proportion of surface area compared with volume. Therefore, other factors being equal, smaller bodies radiate their energy to space faster. If Mercury has a purely iron core, as its large density and strong magnetic field imply, then the core should have cooled and solidified eons ago. But a solid core cannot support a self-sustaining magnetic dynamo.

This contradiction suggests that other materials are present in the core. These additives may depress the freezing point of iron, so that it remains liquid even at relatively low temperatures. Sulfur, a cosmically abundant element, is a possible candidate. Recent models, in fact, assume Mercury's core to be made of solid iron but surrounded by a liquid shell of iron and sulfur, at 1,300 kelvins. This solution to the paradox, however, remains a surmise.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ANTIPODE OF CALORIS contains highly chaotic terrain, with hills and fractures that resulted from the impact on the other side of the planet. Petrarch crater (*at center*) was created by a far more recent impact, as evinced by the paucity of smaller craters on its smooth bed. But that collision was violent enough to melt rock, which flowed through a 100-kilometer-long channel and flooded a neighboring crater.

Once a planetary surface solidifies sufficiently, it may bend when stress is applied steadily over long periods, or it may crack like a piece of glass on sudden impact. After Mercury was born four billion years ago, it was bombarded with huge meteorites that broke through its fragile outer skin and released torrents of lava. More recently, smaller collisions have caused lava to flow. These impacts must have either released enough energy to melt the surface or tapped deeper, liquid layers. Mercury's surface is stamped with events that occurred after its outer layer solidified.

Planetary geologists have tried to sketch Mercury's history using these features—and without accurate knowledge of the rocks that constitute its surface. The only way to determine absolute age is by radiometric dating of returned samples (which so far are lacking). But geologists have ingenious ways of assigning relative ages, mostly based on the principle of superposition: any feature that overlies or cuts across another is the younger. This principle is particularly helpful in establishing the relative ages of craters.

A Fractured History

Mercury has several large craters that are surrounded by multiple concentric rings of hills and valleys. The rings probably originated when a meteorite hit, causing shock waves to ripple outward like waves from a stone dropped into a pond, and then froze in place. Caloris, a behemoth 1,300 kilometers in diameter, is the largest of these craters. The impact that created it established a flat basin—wiping the slate clean, so to speak—on which a fresh record of smaller impacts has built up. Given an estimate of the rate at which projectiles hit the planet, the size distribution of these craters indicates that the Caloris impact probably occurred around 3.6 billion years ago; it serves as a reference point in time. The collision was so violent that it disrupted the surface on the opposite side of Mercury: the antipode of Caloris shows many cracks and faults.

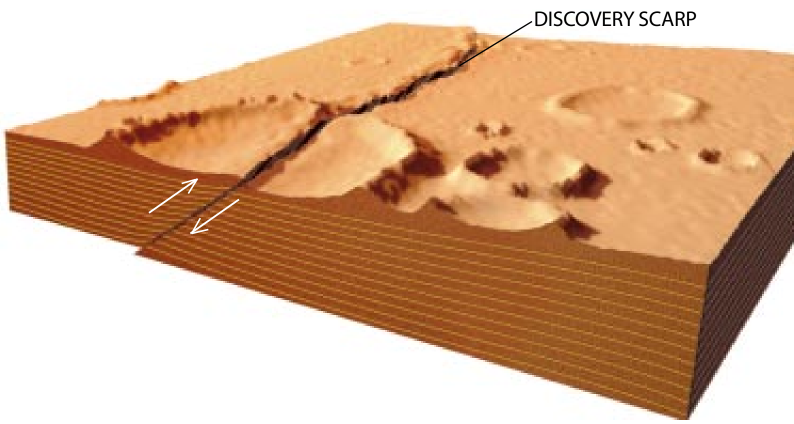
Mercury's surface is also crosscut by linear features of unknown origin that are preferentially oriented north-south, northeast-southwest and northwest-southeast. These lineaments are called the Mercurian grid. One explanation for the checkered pattern is that the crust solidified when the planet was rotating much faster, perhaps with a day of only 20 hours. Because of its rapid spin, the planet would have had an equatorial bulge; after it slowed to its present period, gravity pulled it into a more spherical shape. The lineaments likely arose as the surface accommodated this change. The wrinkles do not cut across the Caloris crater, indicating that they were established before that impact occurred.

While Mercury's rotation was slowing, the planet was also cooling, so that the outer regions of the core solidified. The accompanying shrinkage probably reduced the planet's surface area by about a million square kilometers, producing a network of faults that are evident as a series of curved scarps, or cliffs, crisscrossing Mercury's surface.

Compared with Earth, where erosion has smoothed out most craters, Mercury, Mars and the moon have heavily cratered surfaces. The craters on these three planets also show a similar distribution of sizes, except that Mercury's craters tend to be somewhat larger. The objects striking Mercury most likely had higher velocity than those hitting the other planets. Such a pattern is to be expected if the projectiles were in elliptical orbits about the sun: they would have been moving faster in the region of Mercury's orbit than they were farther out. So these rocks may have been all from the same family, one that probably originated in the asteroid belt. In contrast, the moons of Jupiter have a different distribution of crater sizes, indicating that they collided with a different group of objects.

A Tenuous Atmosphere

Mercury's magnetic field is strong enough to trap charged particles, such as those blowing in with the solar wind (a stream of protons ejected from the sun). The magnetic field forms a shield, or magnetosphere, that is a miniaturized version of the one surrounding Earth. Magnetospheres change constantly in response to the sun's activity; Mercury's magnetic shield, because of its smaller size, can change much faster than Earth's. Thus, it responds quickly to the solar wind, which is 10 times denser at Mercury than at Earth.



NASA; SLIM FILMS

DISCOVERY SCARP (*crooked line seen in inset above and on opposite page*) stretches for 500 kilometers and in places is two kilometers high. It is a thrust fault, one of many riddling the surface of Mercury. These faults were probably created when parts of Mercury's core solidified and shrank. In consequence, the crust had to squeeze in to cover a smaller area. This compression is achieved when one section of crust slides over another—generating a thrust fault.

The fierce solar wind steadily bombards Mercury on its illuminated side. The magnetic field is just strong enough to prevent the wind from reaching the planet's surface, except when the sun is very active or when Mercury is at perihelion. At these times, the solar wind reaches all the way down to the surface, and its energetic protons knock material off the crust. The particles thus ejected can then get trapped by the magnetosphere.

Objects as hot as Mercury do not, however, retain appreciable atmospheres around them, because gas molecules tend to move faster than the escape velocity of the planet. Any significant amount of volatile material on Mercury should soon be lost to space. For this reason, it had long been thought that Mercury did not have an atmosphere. But the ultraviolet spectrometer on Mariner 10 detected small amounts of hydrogen, helium and oxygen, and subsequent Earth-based observations have found traces of sodium and potassium.

The source and ultimate fate of this atmospheric material is a subject of animated argument. Unlike Earth's gaseous cloak, Mercury's atmosphere is constantly evaporating and being replenished. Much of the atmosphere is probably created, directly or indirectly, by the solar wind. Some components of the thin atmosphere may come from the magnetosphere or from the direct infall of cometary material. And once an atom is "sputtered" off the surface by the solar wind, it also adds to the tenuous atmosphere. It is even possible that the planet is still outgassing the last remnants of its primordial inventory of volatile substances.

Recently a team of astronomers from the California Institute of Technology and the Jet Propulsion Laboratory (JPL), both in Pasadena, Calif., observed the circular polarization of a radar beam reflected from near Mercury's poles. Those results suggest the presence of water ice. The prospect of a planet as hot as Mercury having ice caps—or any water at all—is intriguing. It may be that the ice resides in permanently shaded regions near Mercury's poles and is left over from primordial water that condensed on the planet when it formed.

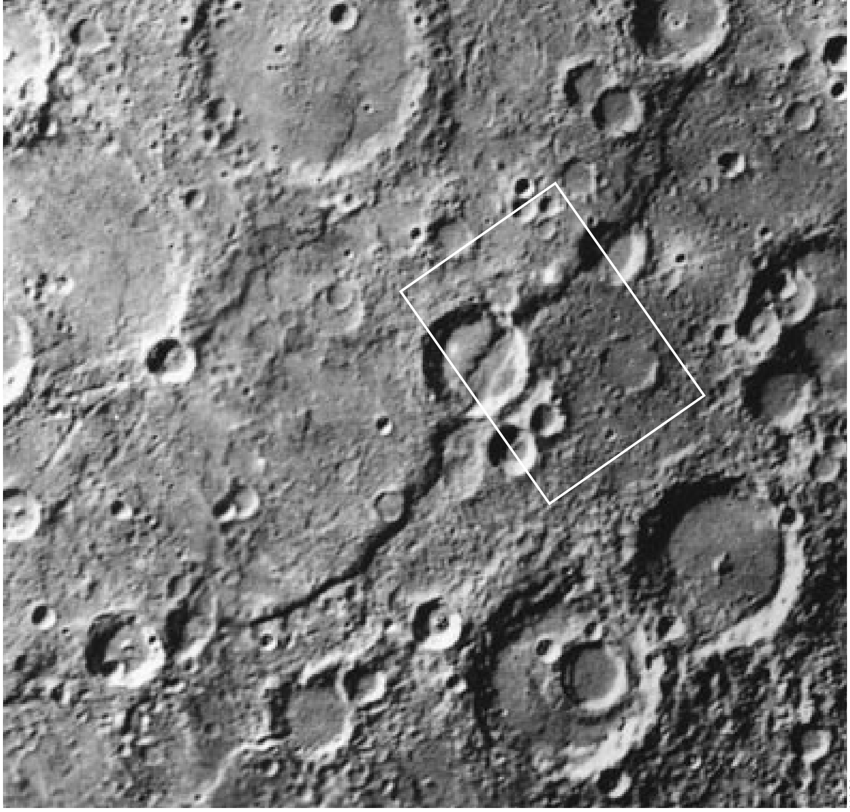
If so, Mercury must have stayed in a remarkably stable orientation for the entire age of the solar system, never tipping either pole to the sun—despite devastating events such as the Caloris impact. Such stability would be highly remarkable. Another possible source of water might be the comets that are continually falling into Mercury. Ice landing at a pole may remain in the shade, evaporating very slowly; such water deposits may be a source of Mercury's atmospheric oxygen and hydrogen. On the other hand, astronomers at the University of Arizona have suggested that the shaded polar regions may contain other volatile species such as sulfur, which mimics the radar reflectivity of ice but has a higher melting point.

Obstacles to Exploration

Why has Mercury been left out of the efforts to explore the solar system for nearly a quarter century? One possibility, as mentioned, is the superficial similarity between Mercury and the moon. Another, more subtle factor arises from the way planetary missions are devised. The members of peer-review panels for the National Aeronautics and Space Administration have generally been involved in NASA's most recent missions. The preponderance of missions has been to other planets, so that these planetary scientists have developed a highly specialized body of expertise and interests. In contrast to the planets thus favored, Mercury has a small advocacy group.

Another consideration is economics. The top levels of NASA are demanding that scientists propose missions that are "faster, better, cheaper," that focus on a limited set of objectives and that trade the science value against the total cost. In the present constrained budgetary environment, the largest deep-space exploration proposals that NASA is able to consider from individuals are those to its Discovery program. Interested scientists team up with industry to propose missions, some of which are selected and funded by NASA for further study. (Four of these missions have so far been undertaken.) The Discovery proposals are supposed to constrain the cost of a mission to $226 million or less. By comparison, NASA's Galileo mission to Jupiter and its Cassini mission to Saturn will both cost more than $1 billion.

A mission to orbit Mercury poses a special technical hurdle. The spacecraft must be protected against the intense en-



mitted the same payload while slashing the fuel mass, cost and time spent in interplanetary cruise. Their design called for a solar-powered ion thruster engine, requiring only 295 kilograms of fuel. This revolutionary engine would propel the spacecraft by using the sun's energy to ionize atoms of xenon and accelerate them to high velocity using an electrical field directed out of the rear of the spacecraft. This innovation would have made the interplanetary cruise time of Hermes '96 a year shorter than that for Hermes '94. Yet NASA did not consider Hermes '96 for further study, because it regarded solar electric propulsion without full backup from chemical propellant to be too experimental.

NASA has, however, selected one proposal for a Mercury orbiter for intensive consideration in the 1996 cycle of Discovery missions. This design, called Messenger, was developed by engineers at the Applied Physics Laboratory in Maryland. Like Hermes '94, it would rely on traditional chemical propulsion and carry similar sensors. Moreover, it would have two devices that could determine the proportions of the most abundant elements of the crustal rocks. Although these two instruments are scientifically attractive, their additional mass requires that the spacecraft swoop by Venus twice

ergy radiating from the sun and even against the solar energy reflected off Mercury. Because the spacecraft will be close to the planet, at times "Mercury-light" can become a greater threat than the direct sun itself. Despite all the challenges, NASA received one Discovery mission proposal for a Mercury orbiter in 1994 and two in 1996.

The 1994 proposal, called Hermes '94, employed a traditional hydrazine–nitrogen tetroxide propulsion system, requiring as much as 1,145 kilograms of propellants. Much of this fuel is needed to slow the spacecraft as it falls toward the sun. The mission's planners, who include myself, could have reduced the fuel mass only by increasing the number of planetary encounters (to remove gravitational energy). Unfortunately, these maneuvers would have increased the time spent in space, where exposure to radiation limits the lifetime of critical solid-state components.

The instrument complement would have permitted Mercury's entire surface to be mapped at a resolution of one kilometer or better. These topographic maps could be correlated with charts of Mercury's magnetic and gravitational fields. NASA initially selected the mission as a candidate for study but ultimately rejected it because of the high cost and risk.

In 1996 the Hermes team, JPL and Spectrum Astro Corporation in Gilbert, Ariz., proposed a new technology that per-

and Mercury three times before it goes into orbit. This trajectory will lengthen the journey to Mercury to more than four years (about twice that of Hermes '96). Messenger is also the most costly Discovery mission under consideration, with a current price tag of $211 million.

Officials awarding contracts for Discovery missions emphasize that they rely strongly on advice from reviewers outside NASA. When making decisions, these panels strive for consensus, a process that causes them to favor proved technologies and remain unreceptive to new ones. Fortunately, NASA has instituted a separate program that embraces futuristic ideas. The mission now planned under this program, called New Millennium Deep Space One, is designed to demonstrate in space all the groundbreaking technologies that have been previously proposed. In July 1998 Deep Space One, powered by a solar ion drive, will begin a three-year journey to fly by asteroid McAuliffe (named after *Challenger* astronaut Christa McAuliffe), the planet Mars and Comet West-Kohoutek-Ikamura. Deep Space One may prove that solar electric propulsion works as well as its supporters now expect. If so, then during the first part of the next century, solar engines should power many flights around the inner solar system—and will surely help solve the long-neglected mysteries of Mercury. SA

The Author

ROBERT M. NELSON has been a research scientist at the Jet Propulsion Laboratory in Pasadena, Calif., since 1979. He received his Ph.D. in planetary astronomy from the University of Pittsburgh in 1977. Nelson was co-investigator for the Voyager spacecraft's photopolarimeter and is on the science team for the Visual and Infrared Mapping Spectrometer of the Cassini Saturn Orbiter mission. He was also the principal investigator on the Hermes '94 and '96 proposals for a Mercury orbiter and is the flight scientist for the experimental New Millennium Deep Space One mission, to be launched in 1998. The author expresses his gratitude to the Hermes team members for their enlightening contributions.

Further Reading

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