feature article

A new look at the planet Mercury

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The *MESSENGER* spacecraft goes into orbit around Mercury in March 2011, but its three flybys have already offered a fresh perspective on the planet's history, composition, and magnetic field.

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Although a sibling of Earth, Venus, and Mars, Mercury is an unusual member of the inner planet family. Among the planets of our solar system, it is the smallest, at about 40% of Earth's diameter and little more than 5% of its mass. But its uncompressed bulk density—the density in the absence of internal pressure—is the highest. Mercury's orbit is the most eccentric of the planets, and it is the only known solar-system object in a 3–2 spin–orbit resonance, in which three sidereal days are precisely equal to two periods of Mercury's revolution about the Sun. Mercury is the only inner planet other than Earth to possess an internal magnetic field and an Earthlike magnetosphere capable of standing off the solar wind. The closest planet to the Sun, Mercury also experiences a variation in surface temperature of 600 °C over the course of a solar day, which because of Mercury's slow spin rate equals two Mercury years. Nonetheless, the permanently shadowed floors of Mercury's high-latitude craters appear to be sufficiently cold to have trapped water ice and perhaps other frozen volatiles.

Created by the same processes as the other inner planets and at the same early stage in the history of the solar system, Mercury, with its unusual attributes, has long held out the promise of deepening our understanding of how Earth and other Earthlike planets formed and evolved. Yet Mercury is not an easy object to study. Never separated from the Sun by more than 28° of arc when viewed from Earth, Mercury is forbidden as a target for the *Hubble Space Telescope* and other astronomical facilities that would be severely damaged by exposure of their optical systems to direct sunlight.

Located deep within the gravitational potential well of the Sun, Mercury also presents a challenge to spacecraft mission design. The first spacecraft to view Mercury at close range was *Mariner 10*, which flew by the innermost planet three times in 1974–75. The encounters occurred nearly at Mercury's greatest distance from the Sun and were spaced almost precisely one solar day apart, so the same hemisphere of the planet was in sunlight during each flyby. *Mariner 10* obtained images of just under half the surface, assayed three neutral species (hydrogen, helium, and oxygen) in Mercury's tenuous atmosphere, discovered the planet's global magnetic field, and sampled the magnetic field and energetic charged particles in Mercury's dynamic magnetosphere.[1]

After the last *Mariner 10* flyby, Mercury was not visited again by spacecraft for nearly 33 years, in large part because

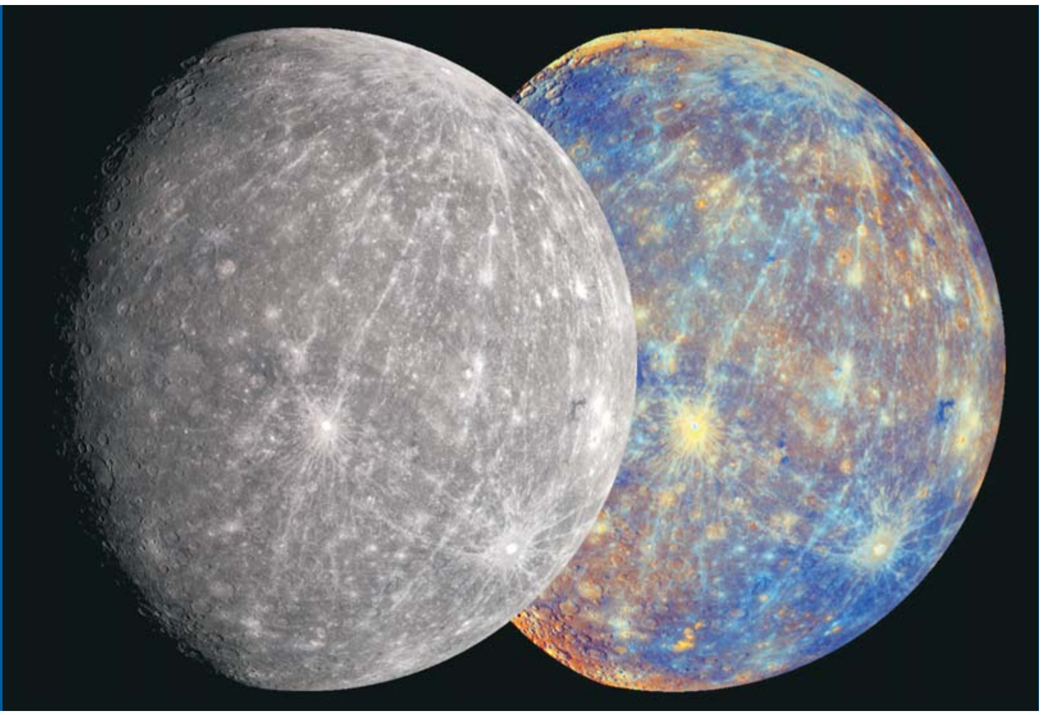


Figure 1. Two images of Mercury, obtained by *MESSENGER* during its second flyby of the planet on 6 October 2008. At left, images at three wavelengths (480, 560, and 630 nm) are combined to produce what might be seen by the human eye. At right is an enhanced-color image that uses all 11 narrowband filters of *MESSENGER*'s wide-angle camera and emphasizes variations in color and reflectance on Mercury's surface. (Courtesy of NASA/Johns Hopkins University Applied Physics Laboratory/Carnegie Institution of Washington.)

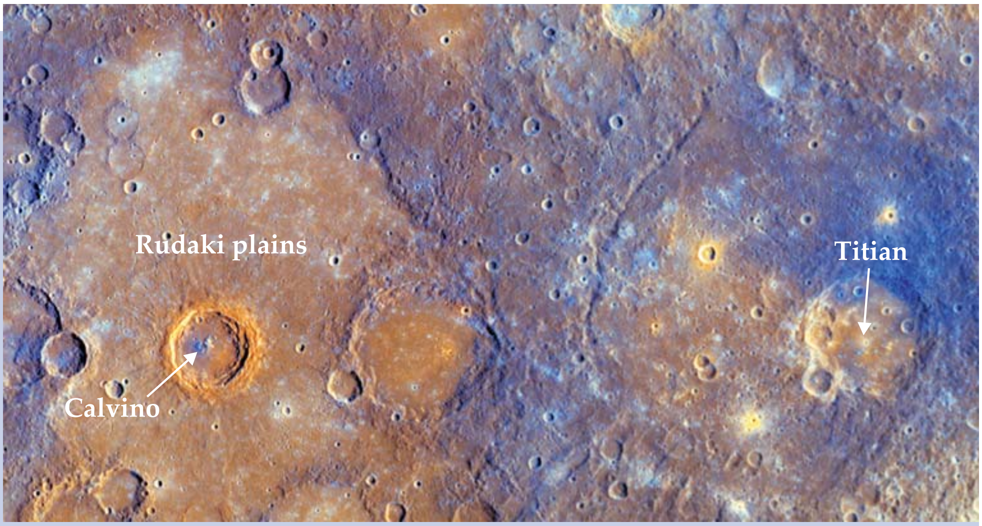


Figure 2. Mercury's near-equatorial region, shown in enhanced color from *MESSENGER*'s second flyby. The image illustrates some of the relationships between color and geological features—in particular, how impact craters can serve as probes of the variation of crustal composition with depth. At right, the floor of the 121-km-diameter Titian crater, named for the Italian Renaissance painter, is coated with material brighter in orange than the surrounding area. Material ejected from the crater appears blue, which represents a different composition. At left, Calvino crater, named for the 20th-century Italian writer, formed from an impact into the brown-appearing Rudaki plains; the impact explosion excavated the bright orange material that makes up the crater rim. The blue material on the crater's central peak is thought, on the basis of crater-formation models, to have been excavated from still greater depth. (Courtesy of NASA/Johns Hopkins University Applied Physics Laboratory/Carnegie Institution of Washington.)

of advances needed in mission design, thermal engineering, and miniaturization. Plans are now under way to place three spacecraft into orbit about the innermost planet. NASA's *MErcury Surface, Space ENvironment, GEochemistry, and Ranging* (*MESSENGER*) mission,[2] launched in 2004, has flown by Mercury three times en route to orbit insertion in March this year. In parallel, the European Space Agency and the Japan Aerospace Exploration Agency in 2000 selected the dual-orbiter *BepiColombo* mission,[3] scheduled for launch in 2014 and arrival at Mercury in 2020. *MESSENGER*'s three flybys, and several notable discoveries by ground-based astronomers in the years since the *Mariner 10* encounters, have provided a wealth of new information about Mercury that has whetted the appetites of planetary scientists for orbital observations (see figure 1).

Mercury's composition

Mercury's bulk density—about 5.3 Mg/m^3 after correcting for internal compression—has long been taken as evidence that the planet has an unusually large fraction of iron, the most abundant of the heavy rock-forming elements in meteorites and the Sun. By analogy with Earth, most of that iron is presumed to reside in a central metallic core. Interior-structure models indicate that the core radius is approximately 75% of the planetary radius and the fractional core mass is at least 60%, which is twice that for Earth.

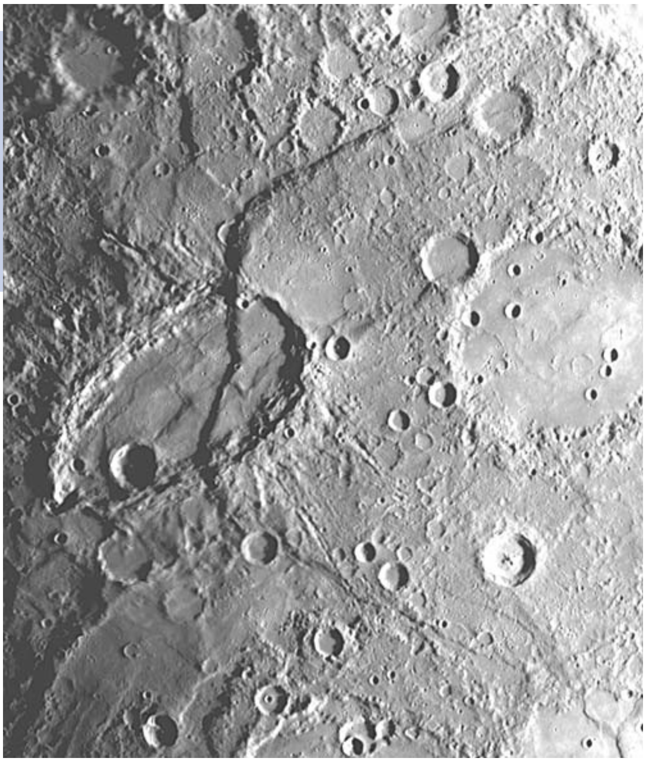
Earth-based radar measurements of Mercury's forced libration in longitude, the variation in spin rate driven by solar torques as Mercury follows its 88 Earth-day eccentric orbit, indicate an amplitude sufficiently large that only the planet's silicate shell can be participating in the libration. The core must be decoupled from the overlying silicate mantle on that time scale, a result possible only if the outer core, like that of Earth, is molten (see PHYSICS TODAY, July 2007, page 22). Models for Mercury's interior thermal history predict that a purely iron core would have solidified over the age of the solar system, but an outer iron core containing modest amounts of light elements that substantially lower the melting temperature—as seismic measurements indicate is the case for Earth's outer core—would be fluid.

Numerical simulations of the accretion of the terrestrial planets permit a wide range of outcomes for Mercury. (See the article by Robin Canup in PHYSICS TODAY, April 2004, page 56.) Given an early solar nebular disk of gas and dust, calculations indicate that solid planetesimals grow to kilometer size in some 10^4 years. Gravitational accumulation of planetesimals leads to runaway growth and the appearance of planetary embryos that reach the size of Mercury in roughly 10^5 years. During that growth, the bodies can experience substantial changes in their orbital parameters. Each of the terrestrial planets probably formed from material originally occupying a wide range in solar distance, although some correlation is expected between the final heliocentric distance of a planet and the composition of the planetesimals from which it formed.

Three specific explanations for the high metal fraction of Mercury have been put forward. The first invokes differences in the response of iron and silicate particles to aerodynamic drag by nebular gas at the onset of the planetary accretion process. The second and third explanations invoke processes at a late stage of planetary accretion, after the precursory Mercury protoplanet had differentiated silicate mantle and crust from metal core. In one proposal, Mercury's high metal content is attributed to preferential vaporization of silicates by radiation from a hot nebula and their removal by a strong solar wind. In the other, silicates are selectively removed as a result of a giant impact by an object nearly as large as the Mercury protoplanet.

The three hypotheses lead to different predictions for the bulk chemistry of the silicate fraction of Mercury. Under the giant impact hypothesis, the residual silicate material on Mercury would be predominantly of mantle composition. The loss of much of the original low-density silicate crust would deplete calcium, aluminum, and alkali metals. The vaporization model, in contrast, predicts strong enrichment of refractory elements and depletion of alkalis and oxidized iron. According to both predictions, the present crust should be the product of melting of the relic mantle. Under the aerodynamic sorting proposal, the core and silicate portions of Mercury can be prescribed by nebular condensation models, suitably weighted by solar distance. Determining the bulk chemistry of the silicate portion of Mercury thus offers an opportunity to learn about those early solar-system processes that had the greatest influence on producing the distinct compositions of the inner planets.

Figure 3. Beagle Rupes, a prominent scarp imaged during *MESSENGER*'s first Mercury flyby on 14 January 2008, is more than 600 km long and offsets the floor and walls of the elliptically shaped (220 km by 120 km) impact crater Sveinsdóttir, named for the Icelandic painter and textile artist. Beagle Rupes, named for the British naval vessel on which Charles Darwin sailed, is one of the most arcuate of the scarps seen on Mercury to date.[9] (Courtesy of NASA/Johns Hopkins University Applied Physics Laboratory/Carnegie Institution of Washington.)



Information on the silicate composition of Mercury, however, is limited.[4] Measurement of the surface reflectance at visible and near-IR wavelengths has been a productive tool for probing the surface composition of solar-system objects because a number of common minerals absorb radiation at characteristic wavelengths in that region of the solar spectrum. But most reflectance spectra of Mercury's surface obtained from ground-based telescopes and those from the *MESSENGER* flybys show no discernible absorption features. The spectral reflectance displays a continuously positive, or "red," slope from visible to near-IR wavelengths, consistent with the chemical and physical modification of surface material by micrometeoroid bombardment and sputtering by solar-wind ions—processes collectively termed "space weathering." The general absence, in particular, of an absorption feature at wavelengths near 1 μm—nearly ubiquitous on the Moon and rocky asteroids—indicates that the silicate minerals at Mercury's surface contain very little ferrous iron.

MESSENGER's spectral reflectance measurements (with high spectral resolution but comparatively low spatial resolution) and color imaging (with low spectral but high spatial resolution) nonetheless indicate that geological terrains on Mercury can be distinguished by spectral slope and average reflectance (see figure 2). Smooth plains, which occupy some 40% of the surface area, range from high-reflectance, relatively "red" material to low-reflectance, relatively "blue" variants. Rocks even bluer and lower in reflectance are seen in material excavated by impact craters. An interpretation consistent with variations in color and reflectance observations is that Mercury's surface material consists predominantly of iron-poor, calcium–magnesium silicates with a spatially varying mixture of spectrally neutral opaque minerals, the most likely candidates being metal oxides.

Elemental remote sensing by an orbiting spacecraft would determine the average composition of Mercury's surface and its regional variation and would also permit an assessment of current hypotheses for Mercury's unusual bulk composition. Both the *MESSENGER* and *BepiColombo* spacecraft carry spectrometers capable of such measurements.

Magnetic field

Mercury's internal magnetic field is strongly dipolar, and the axis of the dipole is closely aligned with the planet's spin axis.[5] As with Earth's internal field, Mercury's vector dipole moment points toward the planet's south geographic pole. The strength of the dipole moment, however, is a factor of about 1000 less than that of Earth. Since the discovery of Mercury's magnetic field by *Mariner 10*, a variety of explanations have been considered for the field's origin. The field cannot be externally induced, on the grounds that the measured planetary field is far greater in magnitude than the interplanetary field. The global field could be a remanent field acquired during cooling of the exterior of the solid planet in the presence of an internal or external field. Alternatively, it could be the signature, as is Earth's internal field, of a modern dynamo in which rotation and convection in the electrically conducting fluid outer core generate a magnetic field at the expense of fluid kinetic energy (see PHYSICS TODAY, January 1996, page 17).

Permanent magnetization of Mercury's outer rocky layers from an external source can be discounted on the grounds that a thick shell of coherently magnetized material is needed to match the observed dipole moment, but a shell with the required thickness would have been unable to cool below the Curie temperature of the dominant magnetic minerals during the time interval when strong solar or nebular fields were present. Mercury's magnetic field, however, might be a crustal field acquired during a time when a core dynamo was active. That hypothesis received renewed attention after the 1999 discovery of strongly magnetized regions in the most ancient portions of the crust of Mars.

Moreover, because Mercury's spin axis is nearly normal to its orbital plane and because of the planet's spin–orbit resonance, the thickness of the portion of Mercury's crust that is below the Curie temperature of a given magnetic mineral varies systematically with latitude and longitude. As a result, according to theory, there should be a strongly dipolar contribution to the external field from a crust magnetized by a past internal field, and specific ratios of multipolar to dipolar field components are expected.[6] However, today's best constraints on the geometry of Mercury's internal field indicate that the multipolar components are not those predicted for a fossil crustal field. Further, *MESSENGER*'s magnetic-field measurements closest to the planet have, to date, shown no evidence for short-wavelength magnetic anomalies over features such as large impact craters, where portions of the crust were modified comparatively recently in planetary history.

Attention has therefore focused on dynamo models for Mercury's internal magnetic field, but the weakness of the field poses a challenge to Earthlike models. Scenarios proposed to account for the weak field include thermoelectric dynamos generated by electrical currents along a topographically rough core–mantle boundary, interaction of the core field with external fields produced by magnetospheric cur-

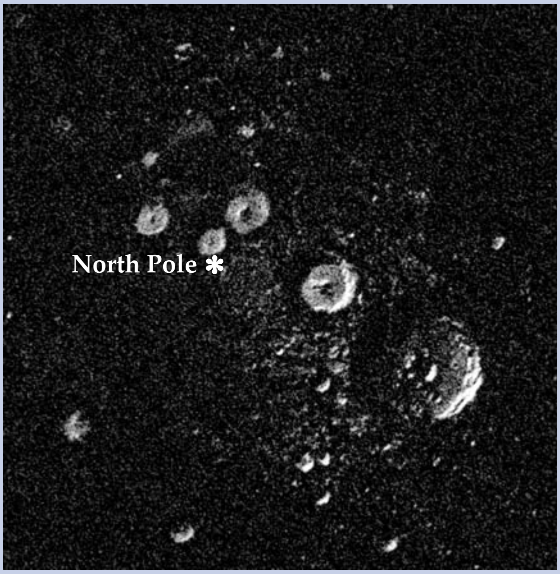


Figure 4. Mercury's north polar region. This radar image was obtained by the Arecibo Observatory in July 1999. The radar illumination direction is from the upper left; Mercury polar deposits are the radar-bright regions within crater floors.[10] (Courtesy of National Astronomy and Ionosphere Center, Cornell University.)

rents that are relatively stronger and closer to the top of the planetary core than at Earth, and convective dynamos in which the inner core size or outer core layering modifies the field seen outside the core.[7]

Those proposals make different predictions regarding the geometry of Mercury's global field, particularly the higher multipolar components, and the rate of temporal or secular variation in the field. Distinguishing among them calls for measurements of the planet's global field from one or more orbiting spacecraft over a time interval sufficient to separate internal and external contributions to the field measurements and to resolve changes in the internal field. Achieving those objectives will not be straightforward, however, because external fields at Mercury are comparable in magnitude to internal fields at typical spacecraft altitudes and change markedly on short time scales.

Volcanism

Volcanism on a terrestrial planet is an important signature of interior processes and properties. The distribution and ages of volcanic deposits illustrate the spatial scales and time frames over which the outer silicate portions of the planet were partially molten. The compositions of volcanic lavas constrain the compositions of their source regions at depth. *Mariner 10* images showed that Mercury has large expanses of smooth plains broadly similar in many respects to those on the Moon known to consist of ancient volcanic lavas. Unlike the lunar plains, however, the plains on Mercury are not markedly darker than surrounding terrain, and most of the images of Mercury obtained by *Mariner 10* were at too coarse a resolution to discern such diagnostic volcanic features as vents and flow fronts. An impact origin for smooth plains on Mercury could therefore not be ruled out.

That many of the smooth plains on Mercury were emplaced as volcanic lavas was settled by the higher-resolution images obtained during the three *MESSENGER* flybys.[8] The 1500-km-diameter Caloris impact basin, imaged in its entirety for the first time by *MESSENGER*, was an important source of key information. Smooth plains that partially fill the basin interior differ in color and, presumably, composition from the basin rim and ejecta, which were formed from surface and subsurface rocks of the target area at the time of the impact. Moreover, both those interior plains and a broad expanse of plains outside the basin have fewer impact craters of a given size range per area than deposits formed at the time of impact, indicating that they are younger than the basin.

Although Caloris is one of the better-preserved large impact basins on Mercury, its size and the density and size distribution of younger impact craters on the basin rim indicate that it dates from the so-called late heavy bombardment of the inner solar system, a period that ended about 3.8 billion years ago, during which many impact basins formed within a short time interval on the Moon and other inner planets. The volcanic plains associated with Caloris may date from nearly as early in Mercury's history. In contrast, in the central floor of the markedly younger, 290-km-diameter Rachmaninoff basin are smooth plains that differ in color from, appear to have once flowed over, and display a lower density of superposed impact craters than other portions of the basin floor. Those inner plains are among the youngest volcanic deposits on Mercury and indicate that the planet was most likely volcanically active well into the second half of its history.

Arrayed around the outer margin of the Caloris basin floor are a number of volcanic vents identified from high-resolution images obtained by *MESSENGER*. Bright regions surrounding the vents have been interpreted as explosive volcanic deposits, on the basis of comparison with analogous features on the Moon. Such eruptions on Earth and the other inner planets occur when magmatic volatiles under reduced pressure come out of solution as expanding bubbles of gas. However, current theories for the formation of Mercury—particularly the scenarios advanced to account for the planet's anomalously high fraction of iron—predict that Mercury's interior should be extremely depleted in volatiles. The volcanic deposits thus indicate that such theories must be modified to account for at least local concentrations of interior volatiles at abundances sufficient to drive explosive volcanic eruptions on the scales observed.

Surface deformation

The nature and distribution of major deformational features—the surface expressions of shallow faults and other structures that accommodate crustal strain—also provide important information on the evolution of a planetary interior. Images obtained by *Mariner 10* showed that most of the deformational features viewed were contractional, produced as a result of failure of crustal rock in response to horizontal shortening. Most prominent among those contractional features were linear to arcuate scarps that have 1–2 km of relief and are up to hundreds of kilometers long, like the scarp in figure 3.

Such scarps are thought to be the surface manifestations of great thrust faults formed when one block of crust moves up and over another. Because the scarps were seen on all terrain types and showed no preferred orientations across the 45% of the surface imaged by *Mariner 10*, the consensus following that mission was that they are the product of global contraction. Such contraction is predicted by models of interior evolution characterized by cooling from a hot initial state over most of Mercury's history, and an implication of such models is that contractional landforms would be seen over most of the remaining 55% of the surface once global imaging coverage became available.

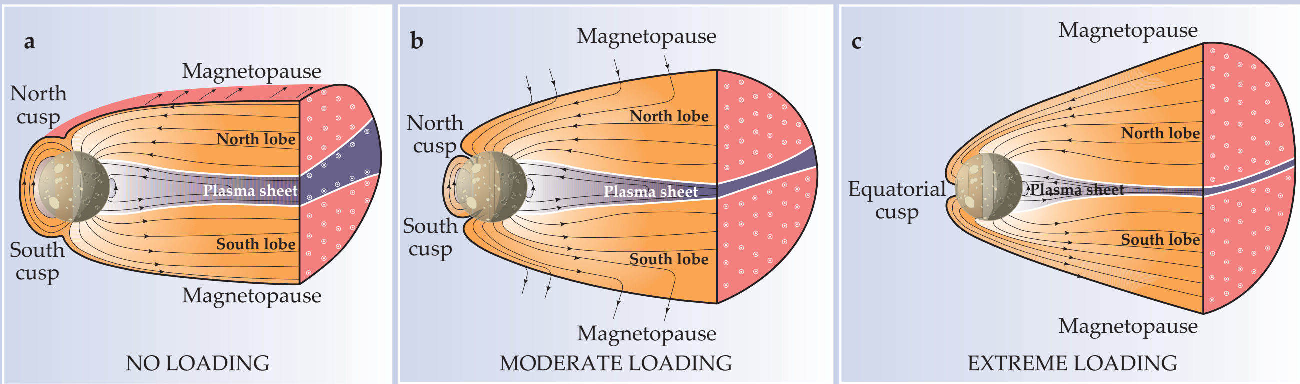


Figure 5. Mercury's magnetosphere, in schematic cross section. As closed magnetic-field lines in the dayside magnetosphere are opened by reconnection at the magnetopause, magnetic flux is pulled back into the tail lobes by the solar wind—a process known as tail loading. During moderate tail loading, the dayside magnetopause contracts to lower altitudes and the north and south magnetic cusps are displaced toward the equator. During extreme loading, observed during *MESSENGER*'s third flyby on 29 September 2009, the closed dayside magnetosphere disappears, the magnetopause flares strongly, and the north and south cusps merge into a single broader cusp at the equator. (Adapted from ref. 13.)

Images from *MESSENGER*'s three flybys confirmed that surface deformational features are predominantly contractional.[9] Moreover, the scarps' cumulative length per area, their typical relief, and estimates of fault displacement from the foreshortening of impact craters are greater than estimated from *Mariner 10* images, indicating an extent of global contraction larger than previously deduced. In contrast, the interiors of four impact basins, including Caloris, show evidence for floor extension and uplift. The emerging view of the deformational history of the planet is one of generally compressive horizontal stress driven by interior cooling and contraction, but these conditions were disrupted locally at large impact basins by the relief of preexisting stress and the deposition of heat during impact that served to focus later volcanic and deformational activity.

Polar deposits

The discovery in 1991 of radar-bright regions near Mercury's poles and the similarity of the radar reflectivity and polarization characteristics of these regions to those of icy satellites and the southern polar cap of Mars led to the proposal that the regions contain deposits of surface or near-surface water ice. Subsequent radar imaging at improved resolution, as pictured in figure 4, confirmed that the radar-bright deposits are confined to the floors of near-polar impact craters.[10] Because the tilt of Mercury's spin axis is nearly zero, the floors of sufficiently deep near-polar craters are always in full or partial shadow and are predicted to be at temperatures at which water ice is stable for millions to billions of years. Although a contribution from interior outgassing cannot be excluded, calculations have shown that the vaporization of water from cometary or meteoroid impacts followed by transport of water molecules to the crater floors can provide sufficient polar ice to match the observations.

Two alternative explanations for Mercury's polar deposits have been suggested. One is that they are composed of elemental sulfur rather than water ice, because sulfur would also be stable in cold traps and the presence of sulfides on the surface could account for a high index of refraction and low microwave opacity of surface materials inferred from Earth-based astronomical observations. The second proposal is that the permanently shadowed portions of polar craters are radar bright not because of trapped volatiles but because of unusual surface roughness or unusual radar characteristics of near-surface silicates at extremely cold temperatures.

Determining the nature of the polar deposits from an orbiting spacecraft will pose a challenge because the deposits will occupy a comparatively small fraction of the viewing area for most remote-sensing instruments and because any polar volatiles may be buried beneath a thin layer of soil. Among the most promising measurements are searches of the polar atmosphere for signatures of excess hydroxyl or sulfur and neutron-spectrometer observations of any near-surface hydrogen.

The exosphere and neutral tail

Mercury's atmosphere is an exosphere—that is, its density is so low that atoms and molecules rarely collide—whose composition and behavior are controlled by interactions with the magnetosphere and the surface.[11] A UV airglow spectrometer on *Mariner 10* detected hydrogen and helium and set an upper limit on oxygen. Later ground-based spectroscopy led to the discovery of emission lines of sodium, potassium, and calcium excited by the resonant scattering of sunlight. *MESSENGER*, in turn, detected emissions from neutral magnesium and Ca^+, the latter a product of the particularly rapid photoionization of neutral Ca.

The exosphere is not stable on time scales longer than a few days, so sources must exist for each of the constituents. Hydrogen and helium are likely to be dominated by solar-wind ions neutralized by recombination at the surface. The other species are derived either from impact vaporization of micrometeoroids hitting Mercury's surface or directly from Mercury's surface materials as a result of thermal and solar radiation processes acting on the dayside, sputtering of the surface by solar wind and magnetospheric ions, and diffusion of volatile species from the planet's interior.

In 2002, astronomers reported the discovery that Mercury has an antisunward tail of neutral Na. Later observations showed that the comet-like tail extends more than 2 million kilometers from the planet. The tail is thought to be the result of solar radiation pressure acting on energetic atoms lofted high off the planet's surface. Observations by *MESSENGER* documented that Ca and Mg are present along with Na in the tail, which provides one of the major routes by which exospheric species are lost from Mercury's vicinity.

Strong variations in Mercury's exosphere and tail as functions of time, solar distance, and level of solar activity, as seen by telescopic observations from Earth, indicate that multiple processes supply material from the surface. Measurements by *MESSENGER* revealed a still greater complexity to the mix of governing processes. For instance, the comparatively volatile Na and the comparatively refractory species Ca and Mg all exhibit different distributions over Mercury's poles and tail region. A spacecraft in orbit about Mercury will provide a range of opportunities to further understand the nature of the exosphere and its relation to the temporal variation of the magnetosphere and spatial variations in source processes.

The magnetosphere

As a result of Mercury's small dipole moment, the planet's magnetosphere is among the smallest in the solar system and stands off the solar wind just 1000–2000 km above the dayside surface. Although the magnetosphere shares many features with that of Earth, the time scales for wave propagation and convective transport are much shorter in Mercury's magnetosphere because of its small size, and the proximity to the Sun renders the driving forces more intense.[12] Strong variations in magnetic-field and particularly energetic charged-particle characteristics observed by *Mariner 10* were interpreted as evidence of magnetic substorms and magnetic reconnection in the tail (see the article by Forrest Mozer and Philip Pritchett in PHYSICS TODAY, June 2010, page 34).

Although *MESSENGER*'s three encounters with Mercury occurred during the recent deep minimum in solar activity, the planet's magnetosphere was markedly different each time. During the first flyby, the interplanetary magnetic field (IMF) had a northward component (parallel to the internal magnetic field lines at low latitudes), the magnetosphere was comparatively steady, and there was little energy input from the solar wind. Models of magnetospheric behavior under a northward IMF predict that sputtering of the surface by solar-wind ions is greatest at high northern latitudes. That result is consistent with the latitudinal distribution of Na emission seen during the first flyby. During the second flyby, in contrast, the IMF was southward (antiparallel to the internal magnetic field lines at low latitudes), a geometry leading to the connection of solar wind and planetary-field lines over the poles. The input of solar-wind energy to the magnetosphere was much higher during that encounter, with magnetic-reconnection rates about 10 times greater than is typical at Earth.

During the third flyby, the IMF direction was variable, and *MESSENGER* found evidence for the "loading" and "unloading" of magnetic energy in the tail at time scales of 1–3 minutes, which is much shorter than at Earth, where it occurs over 1–3 hours. The tail energy is so intense during loading events (see figure 5) that the ability of Mercury's dayside magnetosphere to shield the surface from solar wind ions is substantially curtailed at low as well as high latitudes. Both the supply of material to the exosphere by ion sputtering and the rate of space weathering of Mercury's dayside surface are expected to be sharply enhanced during such tail-loading episodes. Despite the intensity of those events and their similarity to magnetic substorms at Earth, no energetic charged particles, such as are seen during terrestrial substorms and had been reported by *Mariner 10*, were observed.

Prognosis

The *MESSENGER* spacecraft is scheduled to start orbiting Mercury this March, and the two *BepiColombo* spacecraft are slated to arrive at the innermost planet less than a decade later. Those platforms will each permit continuous measurements that will build up a global view of the planet, its environment, and their interactions. We can anticipate being able to determine the composition of Mercury's surface and obtain substantially improved information on the geometry of Mercury's internal magnetic field and the nature of the planet's polar deposits.

High-resolution color imaging and measurements of the planet's topography and spectral reflectance will markedly advance our understanding of the volcanic, deformational, and cratering history of Mercury. In addition, being able to continuously observe Mercury's exosphere, external magnetic field, and charged-particle environment, particularly during different phases of the solar cycle, will further illuminate the workings of the coupled magnetosphere–exosphere system and its extremely dynamic response to changes in solar-wind conditions. A member of our planetary family is about to become much better known.

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