PLANETARY SCIENCE RESEARCH
PSRD Discoveries

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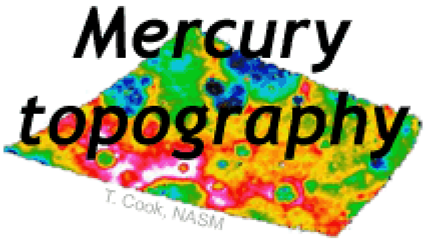
New Data, New Ideas, and Lively Debate about Mercury



--- A hundred scientists gathered to share new data and ideas about the important little planet closest to the Sun.

Written by ***G. Jeffrey Taylor***
Hawai'i Institute of Geophysics and Planetology

Mercury is an important planet. It is closest to the Sun, so its chemical composition helps us test ideas for how the planets formed. In contrast to Venus and Mars, Mercury is generating a magnetic field today--useful in understanding Earth's magnetic field. It has a huge metallic core compared to the other rocky planets. Its cratered, lunar-like surface records a fascinating geologic history.

A hundred scientists attended a conference about this important little planet. It was held at the Field Museum in Chicago, Illinois, and was sponsored by the Museum, the Lunar and Planetary Institute, and the National Aeronautics and Space Administration. Mariner 10, the only space mission to Mercury, flew by it three times in 1974 and 1975. Reworking the data in light of a better understanding of remote sensing and using new image analysis techniques is leading to amazing new insights about the planet's origin and geological evolution. And although we have had only one mission to the planet, there are a growing number of astronomical observations from Earth to study the tenuous and complicated mecurian atmosphere. Radar observations are providing dramatic new views of the surface and have revealed mysterious deposits (probably of water ice) in the polar regions. New ideas about Mercury's formation, geologic history, interior processes, magnetic field, and atmosphere will be tested by two missions that will examine the planet in detail.

Reference:

Workshop on Mercury: Space Environment, Surface, and Interior, *LPI Contribution No. 1097,* Lunar and Planetary Institute, Houston, 2001. (Available from the Order Department of the Lunar and Planetary Institute, order@lpi.usra.edu. Also online from LPI as a .pdf file.

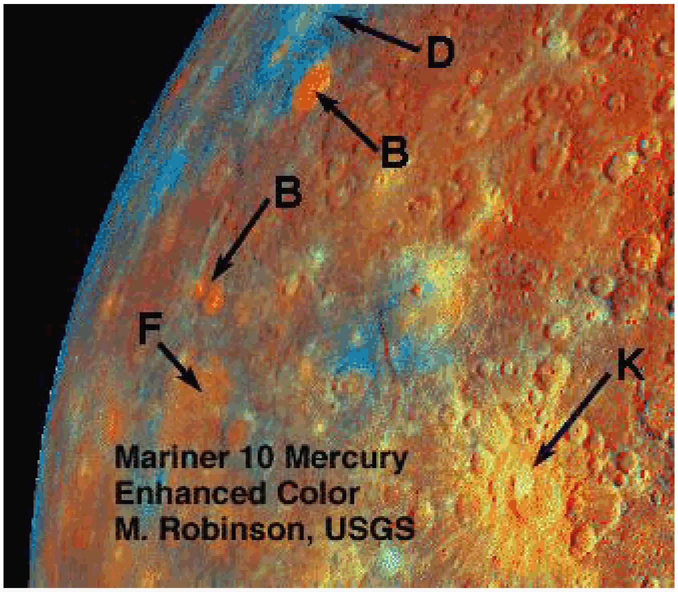
Mercury's Surface

Mercury has a pockmarked, moonlike surface with impact craters up to 1300 kilometers across. Smooth plains occur between the craters and inside many of them. Some of the plains are almost certainly lava flows. The planet's surface is also decorated with fault scarps, produced when the crust contracted as the planet cooled, causing one part of the crust to be thrust over another.

Mariner 10 Image: NASA PIA02940

Mercury has impact craters, smooth plains, and fault scarps. [Click on image for high-resolution options from NASA's Planetary Photojournal.]

During its fly-bys of Mercury in 1974 and 1975, the Mariner 10 spacecraft took pictures using three color filters. Mark Robinson (Northwestern University) recalibrated the old Mariner 10 color data using techniques not available in the mid-1970s, and applied modern image processing tools to them. The result is a collection of three-color images that allow us to determine compositional variations across Mercury's seemingly drab face. [See **PSRD** article: Mercury Unveiled.] Presentations at the conference by Robinson and by B. Ray Hawke (University of Hawai`i) show a planet with a compositionally complex surface.



NASA/JPL/Northwestern University. Image PIA 02440

D = relatively dark and blue unit consistent with enhanced titanium content.

B = bright red unit that may represent primitive crustal material.

F = color unit that follows plains boundaries, interpretated as lava flow.

K = crater Kuiper shows color consistent with fresh material excavated from a subsurface unit that may have an unusual composition.

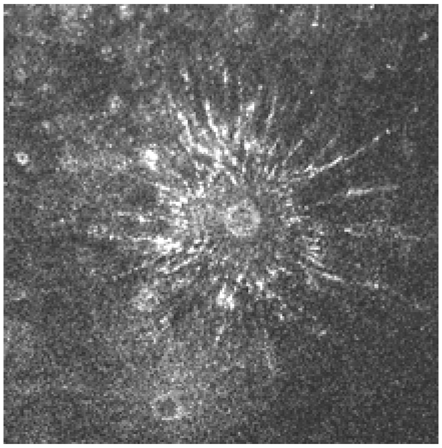
(Caption from NASA Planetary Photojournal, click on image for high resolution options.)

A central question about Mercury is the amount of iron oxide (FeO) in its rocky portion. Measurements made in the 1970s with earth-based telescopes of the amount of light reflected in different wavelengths, suggested that the amount of FeO is no more than about 6 wt%. Results reported at the conference refine that estimate. David Blewett (NovaSol, Inc. in Honolulu) compared the spectra of light reflected from regions of the Moon with known FeO contents to similar spectra of Mercury. His assessment is that lunar regions with about 3 wt% provide good spectral matches to Mercury. Johan Warell used the Swedish Vacuum Solar Telescope to measure the spectrum of reflected visible and near infrared light. He also concludes that Mercury has little FeO, possibly none, on its surface. Bruce Hapke (University of Pittsburgh), the grand master of planetary reflectance spectroscopy, concurred with these estimates on the basis of an analysis of the effects of space weathering. Tom Burbine (Smithsonian National Museum of Natural History) measured the light reflected from meteorites called aubrites, which contain no FeO. He concluded that such totally FeO-free materials are not likely to be present on Mercury. Thus, Mercury appears to have some FeO, but it is certainly less than 6 wt%. There seems to be a consensus that the amount is about 3 wt%. This has important implications for the composition of the entire rocky portion of Mercury and for its formation, as outlined below.

The surface of Mercury is a harsh place. When illuminated its temperature soars to almost 500 degrees Celsius. Because it is close to the Sun, projectiles, including the ubiquitous cosmic dust, hit it much faster than they do the Moon, and a larger number of dust grains hit it. The result is likely to be a surface that contains more glass and material condensed from impact-produced vapor than does the Moon. This is consistent with the spectra of energy in the mid-infrared (8 to 13 micrometers in wavelength), as reported in an interesting poster presentation by Bonnie Cooper (Oceaneering Space Systems, Houston) and her colleagues. Cooper's data show few or no spectral features, indicative of a small abundance of crystalline material. On the other hand, other investigators using different telescopic instruments have observed spectral features that suggest minerals are present on the surface. These discrepancies may be due largely to different capabilities of the instruments used. Given the small amount of telescope time devoted to observations of Mercury, the debate about the amounts of glass and minerals on the surface will continue.

Planetary scientists call the combination of these effects "space weathering." One of the products of space weathering is ultra-tiny blobs of metallic iron. These little droplets measure only a few billionths of a meter across and are known to be the cause of a characteristic slope of the spectra of reflected light from the Moon. Sarah Noble and Carle Pieters (Brown University) are studying the effect the high surface temperature might have on the minute metal grains. Noble calculated the rate at which the grains grow by a process called solid-state coarsening during the daytime (which lasts 44 days earth days on Mercury). The metallic nanoblebs might double in size in only centuries, thus affecting the way light reflects. The surface in the equatorial regions would be affected more than colder polar regions. This work is only in its early stages, but might lead to a better assessment of the amount of space weathering that has occurred.

Mariner 10 imaged only one hemisphere of Mercury. Tantalizing views of the mysterious other hemisphere from Earth-based imaging radar suggested that there might be at least one large volcano. However, John Harmon (Arecibo Observatory) described new observations made with the upgraded Arecibo radio telescope. These startling clear images demonstrate that the suspected volcanic feature is actually an impact crater. Much of the unexplored hemisphere appears to be like the imaged hemisphere, but there are still too few observations to be sure of this.

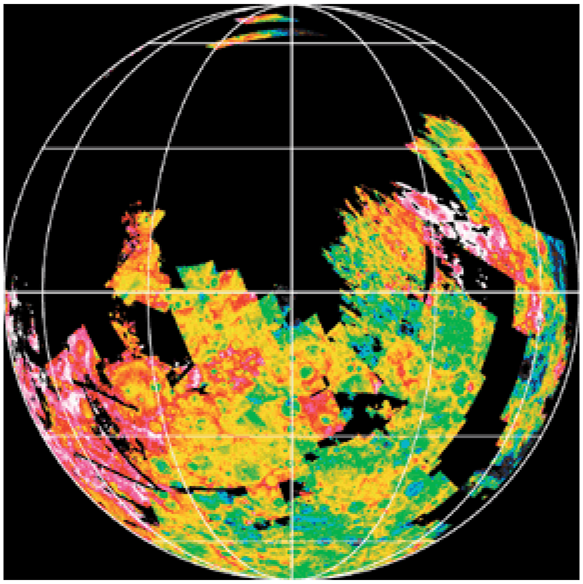


Raw delay-Doppler image of Mercury
Courtesy of John Harmon,
National Astronomy and Ionosphere Center,
Arecibo Observatory, Puerto Rico.

Radar image of impact crater on Mercury with a prominent ejecta blanket and ray system. Click on image for a larger version.

Topography and the Nature of the Rocky Subsurface

Tony Cook and Tom Watters (Smithsonian National Air and Space Museum) and Mark Robinson presented a striking digital elevation model (DEM) mosaic (a topographic map) of Mercury, shown below. They used a semi-automated technique to match points on 1709 pairs of stereo images obtained by the Mariner 10 mission. The mosaic covers about 25% of the mercurian surface. More information is available from the Center for Earth and Planetary Sciences.

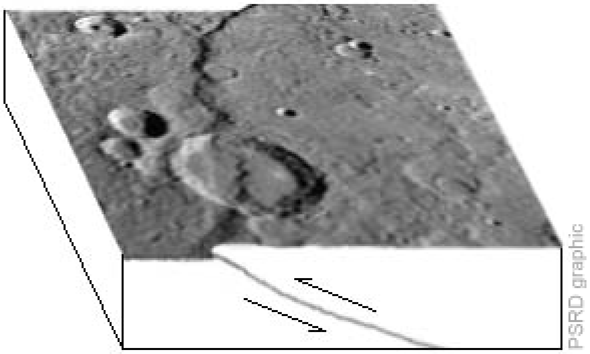


Digital Elevation Model mosaic of Mercury

(Courtesy of T. Cook and T. Watters, Smithsonian National Air and Space Museum)

In this hemispheric projection of a DEM mosaic of Mercury, elevations from lower to higher are colored blue, green, yellow, orange, red, and white.

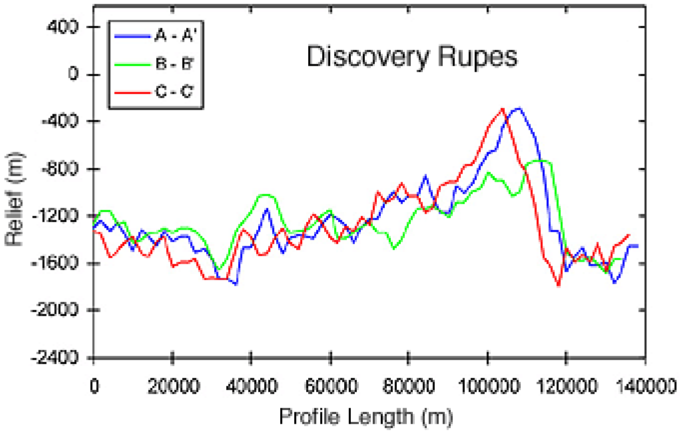
Tom Watters has used the new topographic map to study an impressive feature on Mercury, the Discovery Rupes scarp. Planetary geologists interpret this feature and others like it as a thrust fault. Thrust faults are places where one part of the crust has been pushed over another. Discovery Rupes is over 500 kilometers long. Watters and his colleagues Cook, Robinson, and Richard Schultz (University of Nevada, Reno) show that the scarp is up to 1.5 kilometers high and they use the topographic data to interpret the depth of the rigid outer portion of Mercury.



Discovery Rupes schematic

Representation of the thrust fault at Discovery Rupes.

Using assorted values for the amount of displacement along the fault, the angle the fault makes with the surface, and the depth to which the fault cut, Watters and his colleagues calculated the resulting topography on the surface. They compared this to the measured topography. Watters obtained the best agreement with the real topography when the fault depth was between 35 and 40 kilometers. This suggests that at a depth of about 40 kilometers the crust was too weak to support the fault surface at the time the faulting occurred. Because rocks soften sufficiently at about 600 degrees Celsius, Watters suggests that this implies that the temperature inside Mercury's crust increased about 11 degrees C per kilometer when the faulting took place billions of years ago.



(Courtesy T. Watters, NASM)

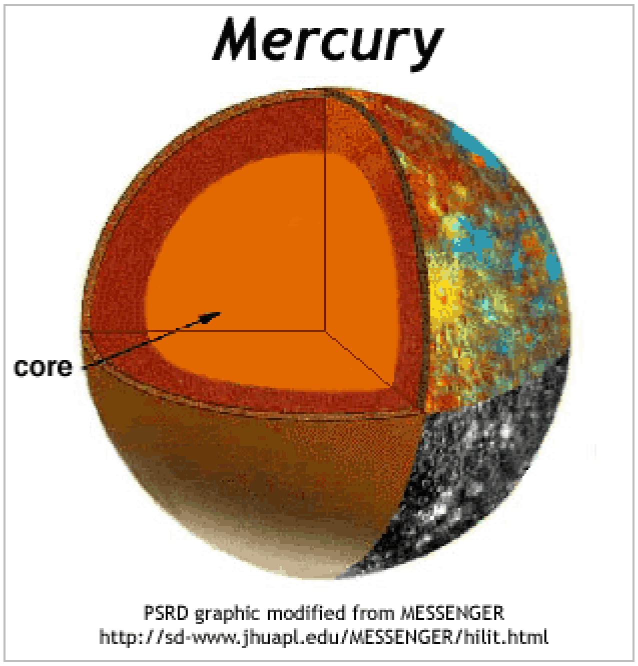
Plot of topographic profiles across Discovery Rupes.

Steve Hauck (Washington University in St. Louis) and colleagues at Washington University and the Carnegie Institution also investigated the features of lobate scarps. He concludes that the amount of strain indicated by their sizes can be accomplished by only 60 degrees Celsius of cooling since the end of the period of intense impact bombardment (about 4 billion years ago). The calculation assumes that all the strain that results in thrust faulting resulted from contraction of the planet as it cooled. The fault scarps may be caused by contraction of the metallic core by crystallization of a solid, inner core. (The solid core would be about 5% less dense than the outer liquid core, thereby taking up less volume and contracting the whole planet.) Hauck also drew attention to the effect contraction might have on the efficiency of magma delivery to the surface. It would seal off pathways to the surface, making eruption more difficult. Jim Head (Brown University) and Lionel Wilson (Lancaster University) discussed theoretical aspects of magma ascent and also raised the possibility that under certain circumstances little magma will have reached the surface to erupt as lava flows. This suggestion sparked some spirited debate because most geologists who have examined images of mecurian smooth plains conclude that many are certainly volcanic. Nevertheless, Head argued that it is important to study alternative theoretical frameworks that can be tested by the missions that will observe Mercury up close.

V. Solomatov and C. Reese (New Mexico State University) discussed their analysis of processes operating inside Mercury. Careful consideration of how the planet cools lead them to conclude that convection does not take place in the silicate mantle. Because convection drives plate tectonics and produces volcanic hot spots on Earth (such as the Hawaiian island chain), this indicates that Mercury never experienced a period when huge blocks of rock roamed and collided. The surface shows no evidence of either plate tectonics or isolated volcanic hot spots.

Mercury's Big Metallic Core and Its Magnetic Field

Mercury's high density (5.43 grams per cubic centimeter) indicates the presence of a large metallic core. Depending on the details of its composition (especially on how much sulfur it contains), geophysicists calculate that the core makes up 70 to 80 wt% of the planet. For comparison, Earth's metallic core makes up only about 32 wt% of the planet.



The diameter of Mercury's core may be three quarters of the diameter of the planet.

Measurements by Mariner 10 surprised everyone by showing that Mercury has a magnetic field. Small planets are not supposed to have magnetic fields. On Earth, geophysicists think that the Earth's magnetic field results from convection of liquid metallic iron. The convection is driven by cooling of the core at its boundary with the rocky mantle. The cooling causes crystallization of solid metallic iron at the top of the solid inner core. This releases heat, causing the liquid metal to become slightly hotter and hence more buoyant, so it rises, producing the motions necessary for generating the field. The fact that Mercury has a magnetic field suggests that things are more complicated. M. Aurnou (Carnegie Institution) and F. M. Al-Shamali (University of Alberta) reported new calculations of convection and magnetic field generation in the core, which make specific predictions that will be tested by future missions. Their calculations specifically take into consideration the presence of a thin mantle of rock. This is quite different from calculations done for the Earth and its much larger rocky mantle.

Flying Atoms

Studying its very flimsy atmosphere is one of the most active fields of research about Mercury. (In reality, Mercury does not have an atmosphere because it is so tenuous that atoms do not hit each other often as they do in official atmospheres like on Venus, Earth, and Mars.) There are new observations of the atmosphere using Earth-based telescopes, experiments on the effects of the space environment on surface materials (the source of the gases in the atmosphere), and theoretical studies of how the gases are released, subsequently trapped again, and how much gas is lost to space.

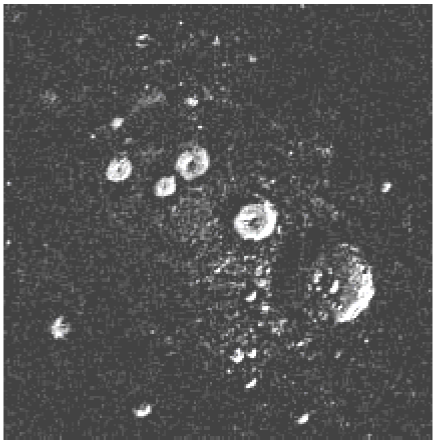
Ann Sprague (University of Arizona) reviewed what we know about the atmosphere. It is dominated by sodium and potassium atoms. These come from the surface of Mercury. There was a great hope in the past that we could use the concentrations in the atmosphere to deduce the concentrations in the surface, which would provide crucial information for understanding how Mercury formed. Unfortunately, much of the sodium and potassium is recycled--it is released from the surface, flies around in the atmosphere for a while, and gets redeposited on the surface. In addition, some of the sodium and potassium come from impacting meteoroids, not only from Mercury. The whole atmosphere-surface system is quite complicated and there was spirited debate among specialists in mecurian atmospheric composition and dynamics.

Ice at the Poles

Like the Moon, Mercury might have water ice in permanently-shadowed craters near its poles. This is where we expect water to concentrate because it is cold enough. Water added by a comet impact, for example, would be lifted into the atmosphere during the daytime. Some would be lost by a variety of processes, but some would condense out onto the surface at night. Eventually, some of the water might reach a crater near the poles where it is dark all the time. It then stays there more or less permanently.

John Harmon (Arecibo Observatory) reviewed the evidence for water ice from observations of Mercury using radar. The first evidence for water ice came from observations made in 1991 using the Goldstone radio telescope in California in conjunction with the Very-Large Array in New Mexico. Such observations have now been made from both the Goldstone-VLA system and the Arecibo Observatory in Puerto Rico.

The basic data for detecting water ice involves the nature of the polarization of radar waves by surface materials. This leads to a distinctive signature for water ice, though other possibilities cannot be completely ruled out. Harmon outlined the main evidence for water ice. First, the ice signature is almost entirely confined to permanently-shadowed craters. Second, this is where calculations suggest the water ice should be found. On the other hand, some of the apparent ice deposits are in craters too small and too far from the pole to be cold enough. So, the case is not closed.



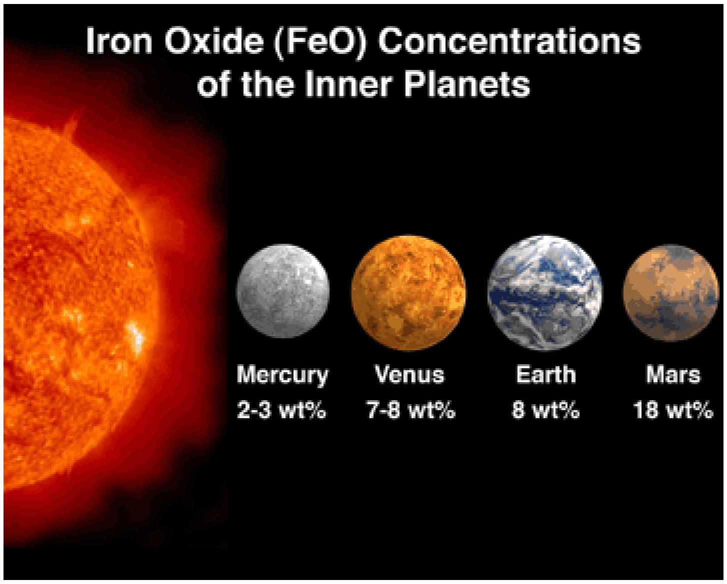
Raw delay-Doppler image of Mercury
Courtesy of John Harmon,
National Astronomy and Ionosphere Center,
Arecibo Observatory, Puerto Rico.

Radar reflectance shows polar impact craters with bright floors interpreted as ice deposits on Mercury. Click on image for a larger version.

Formation of Mercury

The chemical composition of Mercury is important in testing ideas for how the planets formed. We think we know two important chemical facts about the planet. One is that its metallic iron core makes up about 70 wt% to 80wt% of the planet, much more than the other rocky planets. The second is that it is low in oxidized iron (FeO). We know the surface contains little FeO, but how do we know that the interior also does? Mark Robinson and I suggested in a recently published paper that since lava flows do not have much FeO, the mantle must not have much, either. Our reasoning is that when rocks melt, the first magma to form has about the same amount of FeO as does the rock that is melting. Thus, if the surface of Mercury has 3 wt% FeO (as discussed above), and at least some smooth plains are volcanic, then the mantle has low FeO, too. Amazingly enough, nobody seems to disagree with this conclusion, though everybody, including Mark and me, recognize that we need independent measurements of the chemical composition of Mercury.

The compositions of lavas on the surface of Venus, which were measured by the Soviet Venera landers in the 1970s and 1980s, are a bit lower in FeO compared to Earth, so Venus probably has a bit less FeO than Earth. Numerous studies of the composition of the rocky portion of Earth (crust and mantle) suggest a FeO content of 8 wt%. Martian meteorites and other information about Mars indicate much more FeO, about 18 wt%. So, there appears to be a gradient in FeO in the inner Solar System: Low in Mercury, medium in Venus and Earth, and high in Mars.



Not shown to scale. Click on image for a higher resolution version.

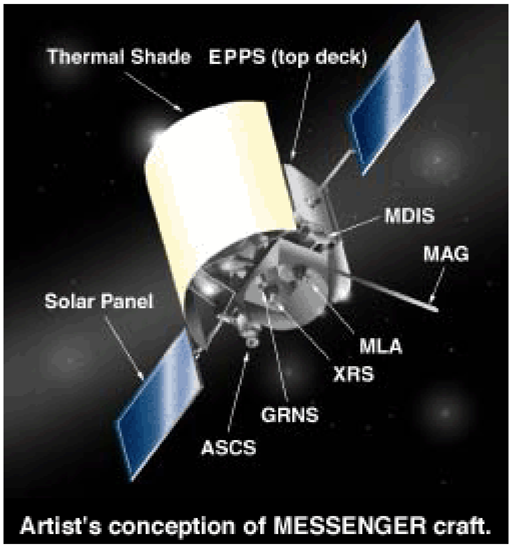
The apparent gradient in FeO might give important clues to the way the planets formed. The current view of planet formation is that there was a stage of rapid growth from hundreds of millions of asteroid-sized objects to tens of roughly lunar-sized objects, though millions of smaller bodies remained. These moon-sized objects have been nicknamed "planetary embryos." George Wetherill (Carnegie Institution) has done numerous computer calculations to follow collections of planetary embryos as they assembled into larger planets. He paid particular attention to the source locations of the embryos that ended up forming bodies at different distances from the Sun. The calculations suggest that the inner planets formed from embryos originally located at distances of 0.5 to 2.5 astronomical units (AU; the distance of the Earth from the Sun is 1 AU). In other words, the calculations predict that there should not be much of a chemical gradient in the inner Solar System. The apparent gradient in FeO suggests that the calculations overestimate the amount of mixing. On the other hand, we need much more data about Mercury, Venus, and Mars to be sure.

Several hypotheses have been proposed to explain why Mercury has such a humongous metallic core. For example, one calls on the differing physical properties of metallic iron and rock to separate them from each other during collisions between planetesimals, with more metal ending up in Mercury. Another suggests that a giant impact stripped away much of an originally much larger silicate mantle. Neither idea explains why Mercury is also low in FeO. However, an idea proposed by Al Cameron (Harvard-Smithsonian Center for Astrophysics) and studied in detail by Bruce Fegley (Washington University in St. Louis) and Cameron predicts that Mercury has low FeO. The idea is that early in its history, but after the inner planets formed, the Sun went through an extremely high-temperature phase. The temperature might have been so high that it vaporized much of the mantle of Mercury, leaving behind a thin shell of chemically-modified rock. They predict the necessary low FeO, but also enormous enrichments in aluminum, calcium, and magnesium, and very low amounts of sodium and potassium. These can be tested by instruments onboard the missions to Mercury.

My colleague Ed Scott and I suggest that a special class of meteorites might represent the type of rock that accreted to form Mercury. Called collectively metal-rich chondrites, they have lots of metallic iron and their silicate minerals are low in FeO (2-4 wt% FeO, just like Mercury). Other chemical features include low concentrations of sodium and potassium, but no enrichments in thorium or uranium. This suggestion will be tested by the missions to Mercury.

New Missions to Mercury

Mercury is difficult to get to. It is close to the Sun, so it requires a lot of energy to put on the gravitational brakes and go into orbit. As a result, most routes to Mercury involve close fly-bys of Venus to slow the spacecraft and allow it to approach Mercury. Once there, the spacecraft and its instruments have to operate in a very hot environment. Sunlight is strong and the planet's surface on the daylight side is very hot. This requires sunshades and special orbits that place the spacecraft far from the hottest part of the surface.



Artist's conception of MESSENGER craft.

Artist's conception of BepiColombo craft (ESA).

Click on either image to link to the mission website.

Two missions are planned for Mercury. One, already being built and funded by NASA's Discovery Program, is called the MErcury Surface, Space ENvironment, GEochemistry, and Ranging mission. Its nickname, MESSENGER, conjures up the role of the Roman god Mercury, who flew from Olympus on winged heels as the swift-footed messenger of the gods. It carries a payload that will allow us to address numerous fundamental problems. The key questions to be addressed are:

- What planetary formation processes led to the high metal/silicate ratio in Mercury?
- What is the geological history of Mercury?
- What is the nature and origin of Mercury's magnetic field?
- What is the structure and state of Mercury's core?
- What are the radar-reflective materials at Mercury's poles?
- What are the important volatile species and their sources and sinks on and near Mercury?

The other mission is named in honor of Giuseppe (Bepi) Columbo, an Italian scientist who explained Mercury's unusual rotation (three turns for every two trips around the Sun). He also suggested to NASA the way to make multiple fly-bys of Mercury during the Mariner 10 mission. The BepiColumbo mission, sponsored by the European Space Agency, is still in the planning stages. Preliminary plans call for one small lander and two orbiters (one orbiter contributed by the Institute of Space and Astronautical Science, ISAS, of Japan). The total payload is similar in many ways to that on MESSENGER, but the team will be able to design the spacecraft's orbits to obtain high-resolution coverage for different regions than those characterized by MESSENGER. The teams are in close communication to maximize the science returned by the two missions.

Additional Resources

BepiColumbo mission.

MESSENGER mission.

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