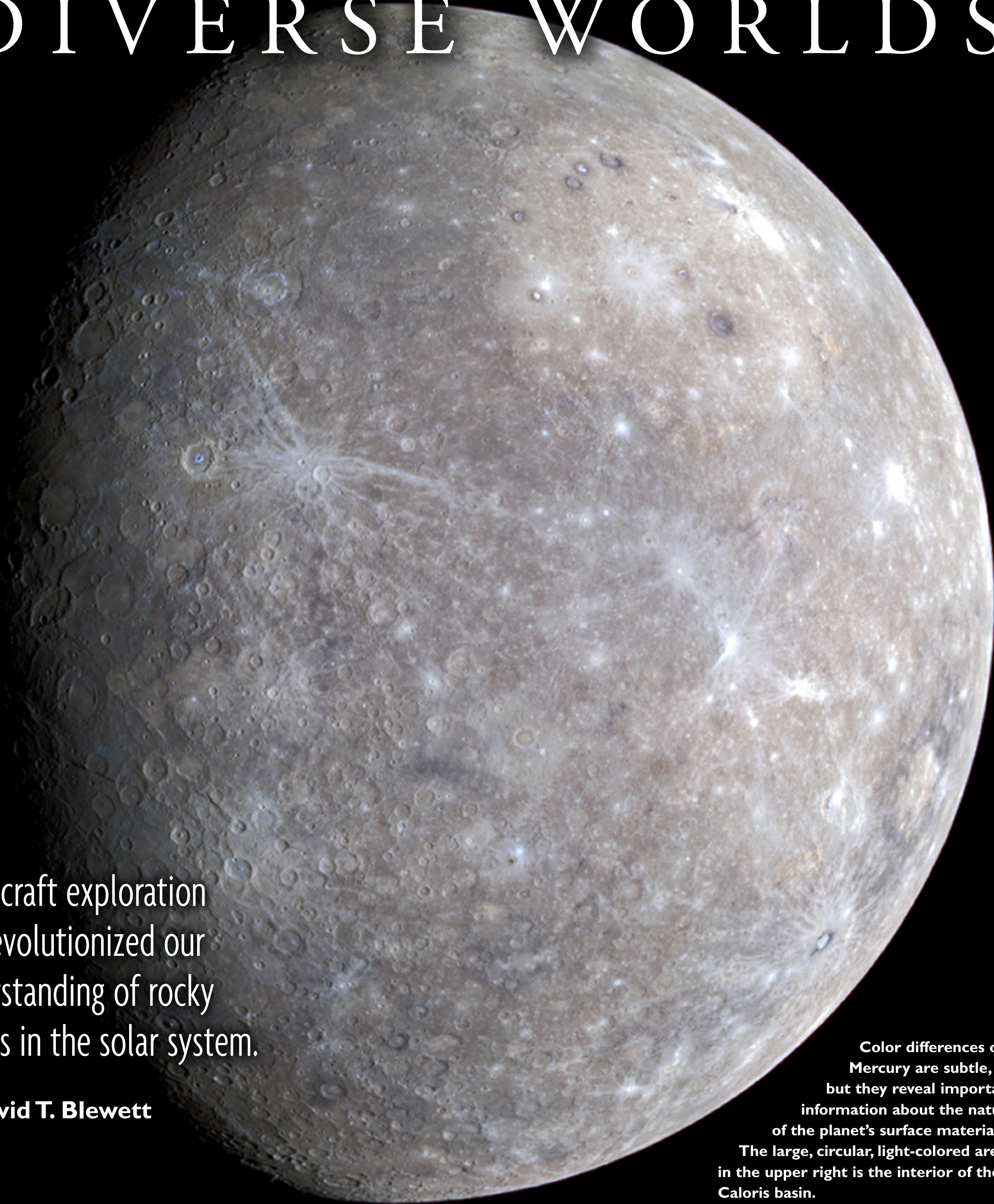
NEW VIEWS OF DIVERSE WORLDS



Spacecraft exploration has revolutionized our understanding of rocky bodies in the solar system.

by David T. Blewett

Color differences on Mercury are subtle, but they reveal important information about the nature of the planet's surface material. The large, circular, light-colored area in the upper right is the interior of the Caloris basin.

Unless otherwise noted, all images are courtesy NASA / Johns Hopkins University Applied Physics Laboratory / Carnegie Institution of Washington.

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Courtesy Astronomical Society of the Pacific

[Editor's Note: This is the first two-thirds of a plenary talk presented at the 2011 ASP meeting in Baltimore. David's complete talk included discussions of the Moon and Vesta, but this abbreviated version focuses solely on Mercury.]

The objects I'm going to be talking about today are Mercury, the Moon, and Vesta. The reason that these worlds are of great interest is that they allow us to investigate the fundamental forces that shaped all the solid-surface planets. On larger planets like Mars, Venus, and Earth, the surfaces have been greatly modified by water and wind, obscuring much of their history. But with these smaller rocky bodies, we have a chance to investigate the most basic geological processes.

Four Basic Geological Processes

What are those processes? First is accretion out of the solar nebula. Dust particles clumped together, growing and colliding to form larger and larger objects, until they reached the size of protoplanets. Some of those protoplanets melted from the heat of accretion and the energy released by radioactive nuclides, and consequently differentiated (or separated) into a core, mantle, and crust, with dense iron metal sinking to form the core.

Impact cratering is certainly another process that has profoundly affected all planetary surfaces. Two others are tectonism, the deformation of the surfaces of the planets due to horizontal or vertical stresses within the crust, and volcanism — whether it's explosive volcanism of the kind that produced the cinder cones found at Haleakala in Hawaii, or effusive volcanism that resulted in the big basalt flows in places like Iceland, Hawaii, or Mare Imbrium on the Moon.

So we will embark on a tour of the inner solar system to see some examples of what scientists are learning about these forces and the ways they interact to produce the worlds that we see today. Let's start with Mercury.

An Introduction to the Smallest Planet

Mercury is truly a planetary oddball. It's the smallest planet, but it has the highest density. It has a huge iron core and a very thin mantle. The relative size of its core is much larger than those of Venus, Mars, or the Moon. Mercury is in the most eccentric orbit. It's the only planet that's in a spin-orbit resonance — Mercury's globe turns on its axis three times for every two times it goes around the Sun.

Mercury has an actively generated internal magnetic field, even though two of its larger cousins (Venus and Mars) do not. It's the closest planet to the Sun, and yet there is evidence that ice could be lurking in dark polar craters. This is quite counter-intuitive given Mercury's scorching surface temperatures. Mercury has an enigmatic surface composition. We don't yet know what type of rock forms the surface, though MESSENGER is providing us with an assortment of clues. Further, the innermost planet has very complicated interactions between the surface, the magnetosphere, the exosphere, the solar wind, and interplanetary space — it's a dynamic and complicated system.

NASA

In this shot of Hadley Rille from Apollo 15, two geological process are evident — volcanism (the Mare Imbrium lava flow) and impact cratering.

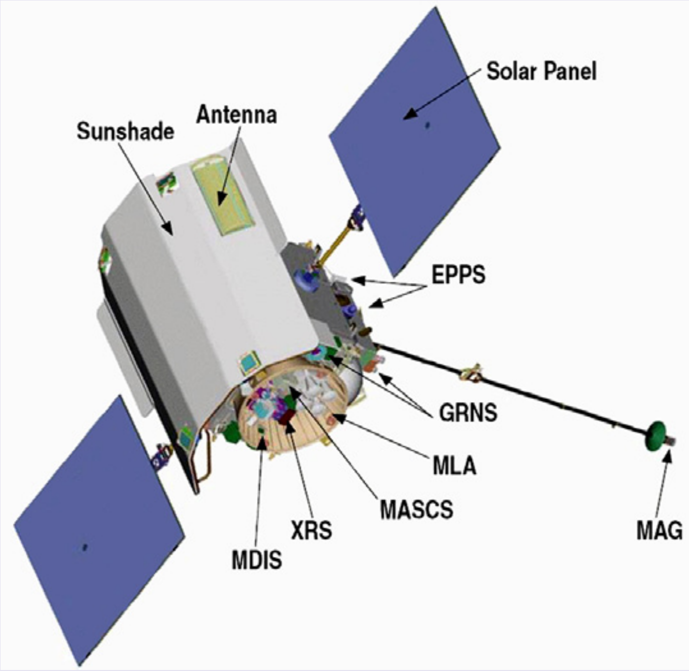
And of course, for a long time Mercury was quite lonely and neglected. Until 2008, it had been visited by only one spacecraft — Mariner 10 with three flybys back in the mid-70s. I don't have enough fingers and toes to count the number of missions that went to Mars during the same time period!

MESSENGER

MESSENGER is a somewhat contrived acronym. It stands for (MErcury Surface, Space ENvironment, GEochemistry and Ranging), which is why we always put MESSENGER in capital letters.

MESSENGER is a NASA "Discovery" mission — NASA's small size of planetary mission. (Cassini, currently exploring Saturn, is one of the large ones, called "Flagship" missions; New Horizons, on its way to Pluto, is a medium-sized "New Frontiers" mission). At the time MESSENGER was selected, the cost for a Discovery mission was capped at about $300 million. That's for the entire mission: design, development, the spacecraft, the instruments, launch, mission operations for eight years, and the data-analysis program. For Discovery, the time from start to launch can be no more than three years. MESSENGER was built and is operated by the Johns Hopkins University Applied Physics Lab (JHUAPL) in Laurel, Maryland.

One thing about traveling close to the Sun is that the solar panels for generating electric power don't have to be very big. The intensity of sunlight at Mercury is about 10 or 11 times greater than it is at Earth, and going close to the Sun means the spacecraft could get very hot. Thus MESSENGER has a sunshade made of woven ceramic

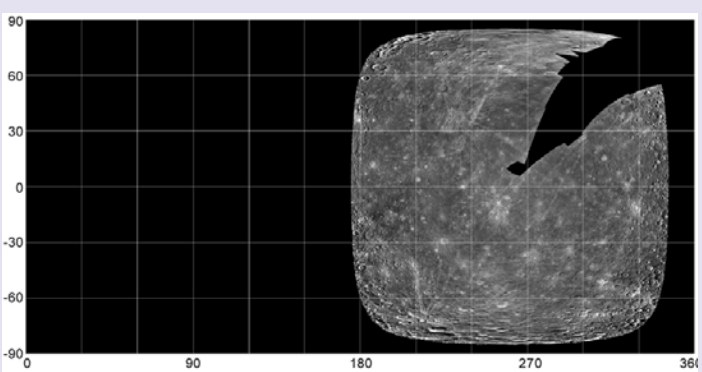


MESSENGER's sunshade covers the main body of the spacecraft, including all the instruments that look down at the planet. The magnetometer, which is mounted on a boom to keep it away from the magnetic fields generated on the spacecraft, has its own little sunshade.

cloth. The computers that control the orientation of the spacecraft (and everything else it does) have, reinforced in their electronic brains, a very important Rule Number One: *Always keep the sunshade pointed at the Sun!* If the spacecraft were to roll or pitch or yaw too far in the wrong direction, allowing sunlight to strike parts of the spacecraft that it's not supposed to, bad things would happen!

Also notice that MESSENGER does not carry the type of dish antenna found on many spacecraft. Instead, it has an electronically steerable phased array antenna. The solar panels are about 50% covered with mirrors to help maintain them in the proper temperature range. The other half of the panel's surface consists of photovoltaic cells.

After launch on August 3, 2004, the spacecraft did a bit of interplanetary pinball, using several planetary gravity assists to get to its destination. It went by Earth once, Venus twice, and Mercury three times (in 2008 and 2009) before finally entering orbit around Mercury in March of 2011. The flybys were very important for testing out the instrument sequences, affording the opportunity to practice for the challenge of being in orbit and having the equivalent of two flybys per day.



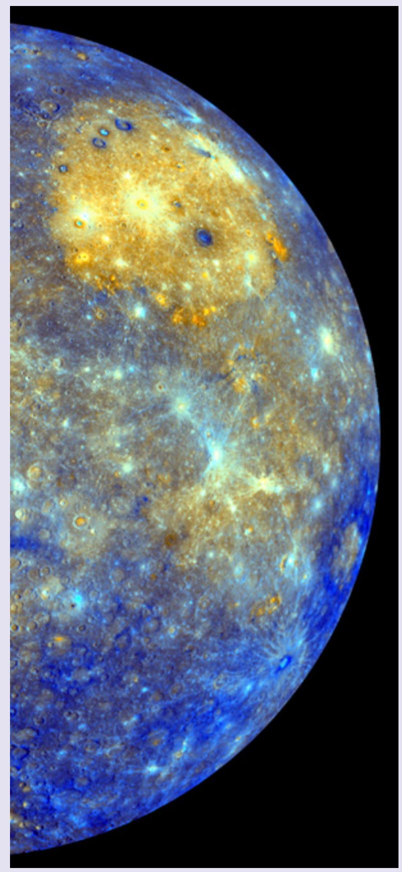
NASA / JPL

This chart shows what we had seen of Mercury before MESSENGER. Mariner 10 collected images of only about 40% of Mercury's surface, and not all of those were obtained at lighting conditions favorable for image analysis.

A Visual Overview of Mercury

On the first MESSENGER flyby, the spacecraft returned a fabulous image [see the opening photo on page 28] — it's a composite of images taken through three different color filters and is roughly what your eye would see if you were there. We saw for the first time the whole of the large impact structure called the Caloris basin (only the eastern third of the basin was sunlit during the Mariner 10 flybys).

The colors are subtle, but can be enhanced to bring out the differences. A digital image consists of a matrix of numbers, which can be manipulated mathematically, including via a statistical technique called principal components analysis (PCA). What PCA does is boil down all the color variation in a scene to a few factors that contain most of the variation. It does a really good job of highlighting the main sources of color variation. This is the enhanced color view *(right)*, which is really quite beautiful.



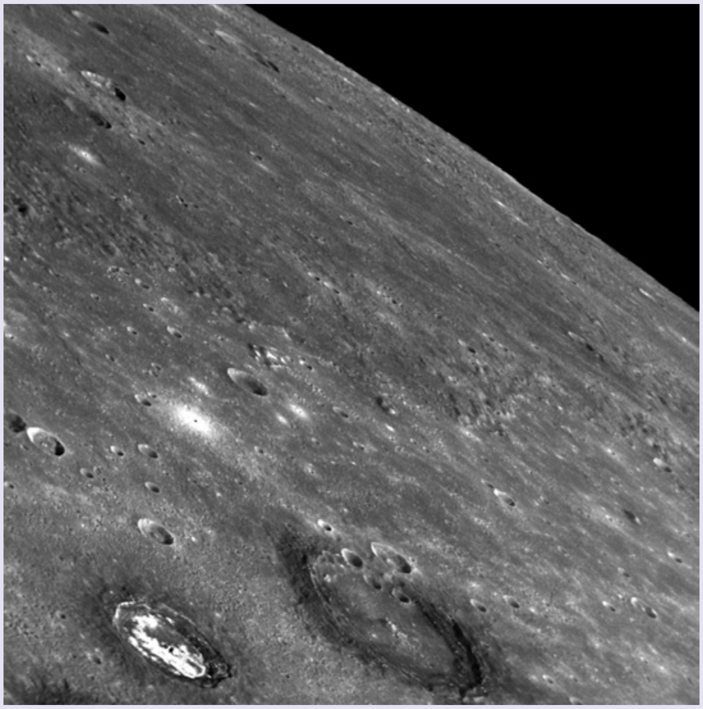
What we see on the surface are relatively bright, smooth plains (colored yellow) that fill the interior of the Caloris basin. There is a terrain with color properties like that of the "average" Mercury surface. Then there is dark material that has a bluish color, compared to the global average, in certain parts of the southern hemisphere and surrounding the exterior of the Caloris basin. Fresh impact craters dot the surface with their bright interiors and rays.

Strange Sights

A lot of strange sights have been seen on Mercury, things that the MESSENGER team is still trying to understand. For instance, the images reveal certain craters that have dark rims; several are found within the Caloris basin. This rather surprising. The dark rim indicates that the impact dug up dark material from beneath the surrounding smooth plains, which have a higher albedo.

Another class of crater on Mercury (including Sander; see the image on the next page) has highly unusual bright stuff on their floors. Mariner 10 spotted a number of them, though at fairly poor spatial resolution, and few scientists at the time really thought much about the bright material. But now we've seen many more with MESSENGER — I'll have more to say about them later on, but they're turning out to be amazing.

There is clear evidence for volcanic vents on Mercury. The prime example is in the southwest corner of the Caloris basin, where there



At the bottom of this image are the craters Sander (left) and 77-km-diameter Poe (right). The MESSENGER team proposed the name Poe (for Edgar Alan Poe) for two reasons. First, because the dark crater is in keeping with Poe's Gothic literary style, and second, because the Applied Physics Lab is located near Baltimore, a city where Poe lived and died.

is an irregular depression that appears to be on a gentle rise. It's surrounded by a velvet-textured, smooth, bright deposit that becomes more diffuse with distance away from the depression.

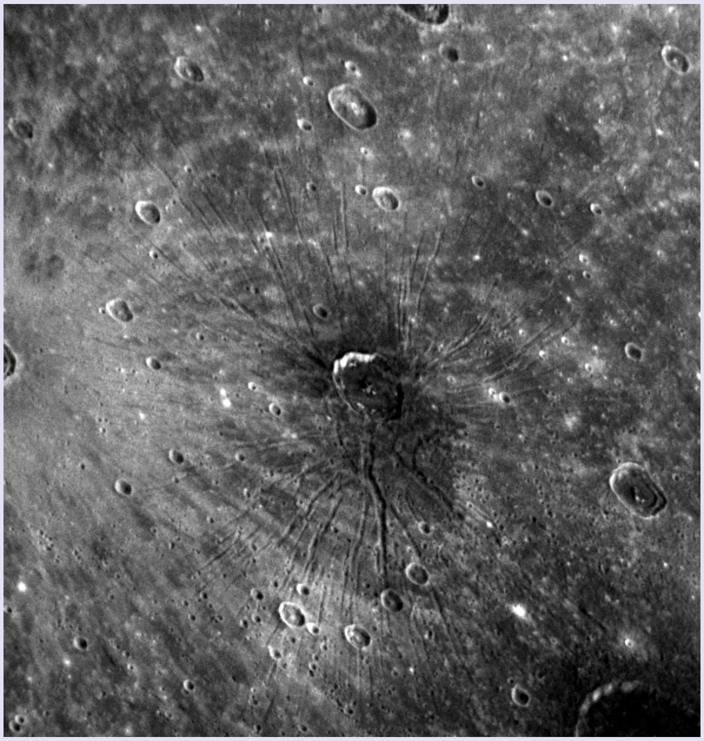
Features such as this are found on the Moon, and it is probable that they are pyroclastic deposits formed by explosive eruptions. On the Moon these deposits all appear dark, because the erupted material is rich in ferrous iron, causing it to appear dark against the lower-iron lunar highlands. But Mercury defies expectations, because its pyroclastic deposits are, instead, bright compared to the background surface.

Troughs and Scarps

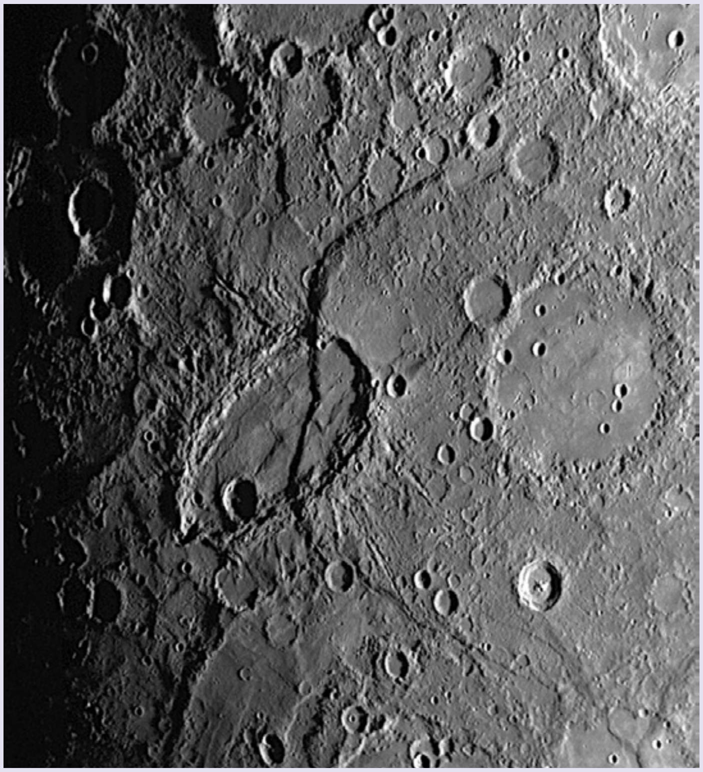
With Mercury, the surprises just keep coming. For instance, Pantheon Fossae *(upper right)* is right in the middle of the Caloris basin. The Fossae consists of a collection of hundreds of troughs radiating out from a central point. The central impact crater is probably unrelated — it appears that the impact post-dates the formation of the troughs. It was a big surprise to discover such a group of troughs on Mercury. There's nothing like Pantheon Fossae on the Moon or on the part of Mercury seen by Mariner 10.

Troughs are produced by tension in the crust when the surface is pulled apart and a valley opens up. Most everywhere else on Mercury the crust is dominated not by tension but by contraction — squeezing together. Contraction produces a type of landform called a scarp (cliff), in which one block of crust is pushed or thrust up over another along a fault.

It appears that Mercury's diameter shrunk by several kilometers (a result of cooling of the interior), producing contraction on a global scale. With all that contraction going on, it's curious to find evidence of tension in the form of troughs — forces working in the opposite direction. The timing and cause of the troughs are real puzzles that the structural geologists and geophysicists are working

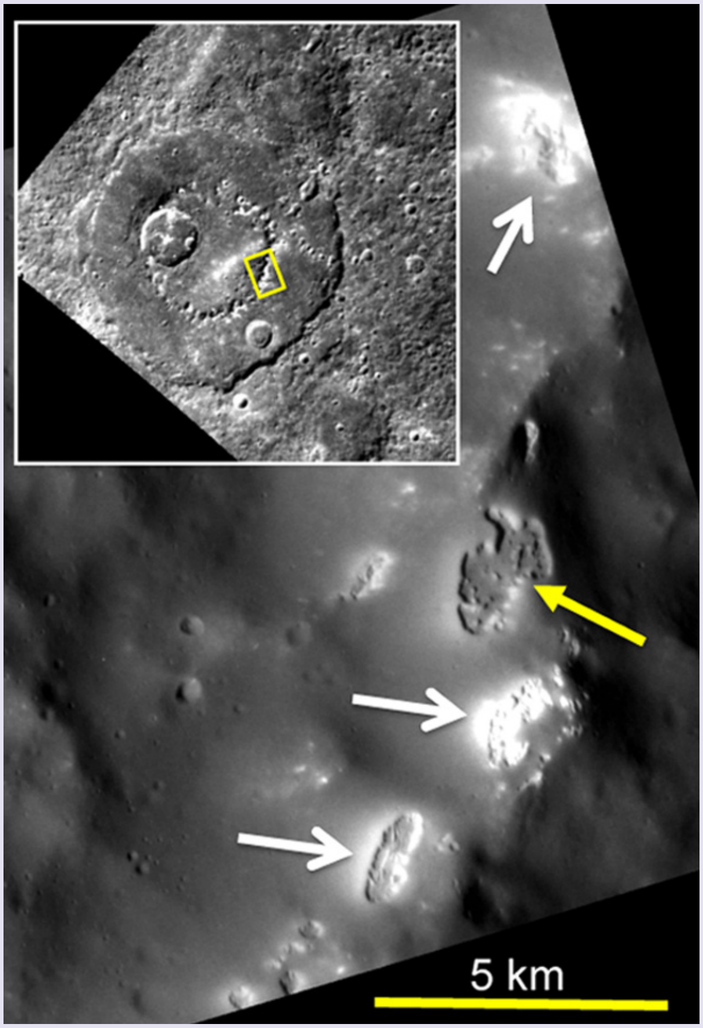


Pantheon Fossae consists of a collection of hundreds of troughs radiating out from a central point. The central impact crater (41 km in diameter) is likely unrelated to the formation of the troughs.



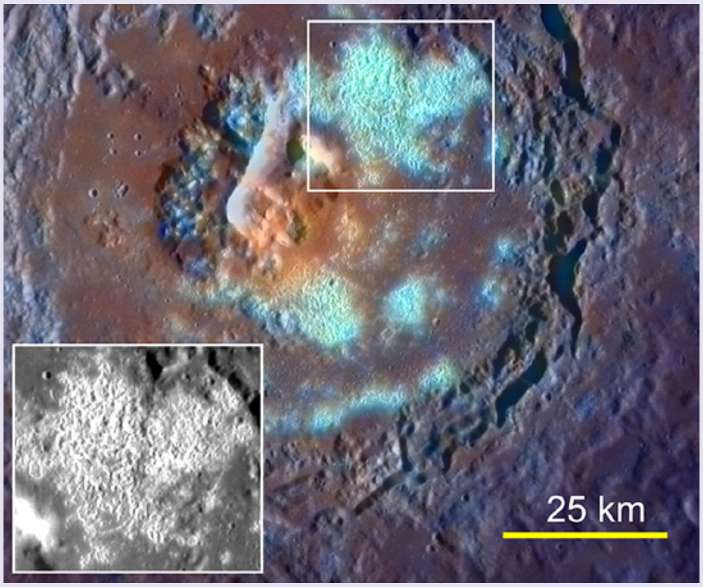
Beagle Rupes is more than 600 km long and one of the largest fault scarps on the planet. It crosscuts Sveinsdóttir crater and has uplifted the easternmost (right side) portion of the crater floor by almost a kilometer.

to solve. It also turns out there are many more scarps *(above)* than was originally thought, and some of them are huge. The presence of more scarps means that Mercury's global contraction was probably even more extensive than initially suspected.



AAAS / Science

High-resolution images by MESSENGER revealed a new landform now known as "hollows." White arrows indicate hollows with bright halos and interiors; the example at the yellow arrow has reflectance similar to the surroundings. It may be that the bright hollows are actively forming.



AAAS / Science

In this enhanced-color view of Tyagaraja, the enlargement shows a gathering of hollows as terrain with an odd, etched appearance. The reddish area in the crater's center is likely a pyroclastic deposit, so in some cases, there could be a relationship between the hollows and volcanism.

Hollows

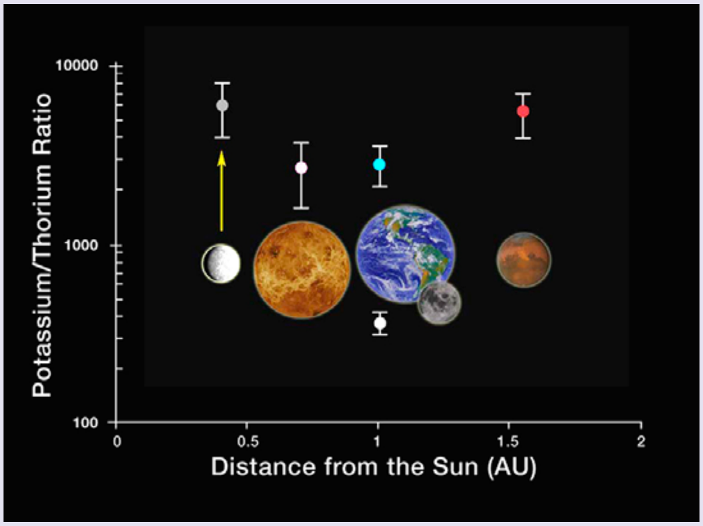
Mercury's surprises just keep on coming. From Mariner 10 and MESSENGER flyby images, we knew that certain craters and basins had unusually high-reflectance material in their floors, such as the crater Sander, mentioned earlier. The bright, bluish material is not limited to the floors of craters — it is also sometimes found in crater walls or on the peak rings of basins. Such deposits are unique to Mercury, with no counterpart on the Moon or any of the asteroids that have been imaged at close range.

Once the spacecraft entered orbit and was able to make high-resolution targeted observations, we found that that the bright stuff consists of very weird, irregular, shallow rimless depressions. Many of the depressions, which we have dubbed "hollows," have bright interiors and bright halos. The hollows are tens of meters to a few kilometers in size. They have a fresh appearance and few if any small impacts have formed on the hollows — indicating a very young age compared to the majority of the planet's surface. The hollows are unlikely to be volcanic, because their locations don't make sense for volcanism and the colors are different (hollows tend to be bluish whereas Mercury's pyroclastic deposits tend to be reddish).

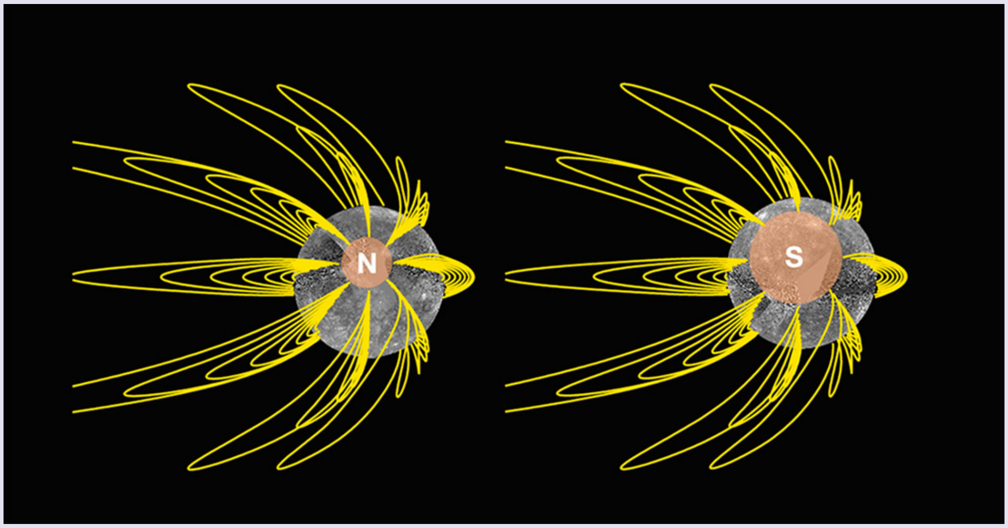
The MESSENGER team has had only a few months to think about this, but one hypothesis for the origin of the hollows is that sublimation or some other loss of volatile material is taking place. That is, a component of the rocks is unstable once it arrives at the surface of Mercury after being exposed by an impact, and is eroding (sublimating) because of high temperatures or as a result of the intense bombardment by micrometeoroids and solar wind particles to which the planet's surface is subjected.

The "Swiss-cheese" terrain that occurs on the south polar cap of Mars, formed by sublimation of carbon dioxide ice, has depressions that are very similar in appearance to some of Mercury's hollows. No one would ever have predicted that a Martian polar cap could be an analog for anything on Mercury!

In Tyagaraja crater *(lower left),* as in Sander, a large number of hollows have coalesced to form terrain with an odd, etched appearance. The hollows are a major puzzle, and the composition of the bright material and the process that forms them will be engaging planetary scientists for quite a while.



MESSENGER's sensors found that Mercury is not as depleted in potassium relative to thorium as expected. This reverses a trend (illustrated above) that shows potassium abundance decreasing the closer a planet is to the Sun.



As a result of the north-south asymmetry in Mercury's internal magnetic field, the magnetic "polar cusps," where field lines are open to the interplanetary medium, is much larger near the south pole than the north. Hence the south polar region is much more exposed than the north to charged particles heated and accelerated by solar wind–magnetosphere interactions.

Volatile Elements

MESSENGER carries a set of geochemical sensors. The gamma-ray spectrometer can measure the abundance of naturally occurring radioactive elements (chiefly potassium and thorium). Potassium is a volatile element, meaning that it has a relatively low boiling point. For Mars, Earth, and Venus, the trend is for decreasing potassium the closer the planet is to the Sun.

It was expected that during Mercury's formation close to the Sun, potassium would have been driven off, and thus the planet would continue the trend and be depleted in potassium. But it turns out that Mercury has a high level of potassium — similar to the average value of Mars. This rules out some of the high-temperature models for

Ron Dantowitz and Copland Crater

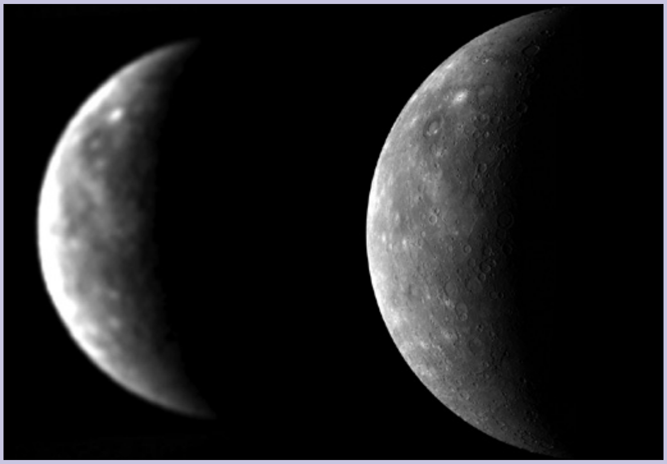
Some 10 years before MESSENGER arrived at Mercury, amateur astronomers Ron Dantowitz, Scott Teare, and Marek Kozubal got time on the 60-inch telescope on Mount Wilson. They observed Mercury and used an image-stacking technique to combine 40 near-infrared images that were taken during the instances of best seeing. They produced an image of Mercury and published a paper about their observations in the *Astronomical Journal* in 2000.

The image showed a part of Mercury that had not been viewed by Mariner 10 and so represented newly seen territory. They identified what they thought was a dark impact basin and a bright crater. In 2008, Ron approached the International Astronomical Union (IAU, the organization in charge of naming features on the planets), because he wanted to name that crater for a composer whose music he enjoys: Aaron Copland. The IAU liked the idea but felt it was a bit premature to assign a name to something seen at such low resolution.

In 2009 MESSENGER flew by on its third pass and imaged that part of the planet. Indeed, the dark basin that Ron and his collaborators saw is present, and beside it is a bright spot. But it turns out that the bright spot is not a crater. Instead it is a pyroclastic vent surrounded by a bright deposit similar to the vent in southwest Caloris.

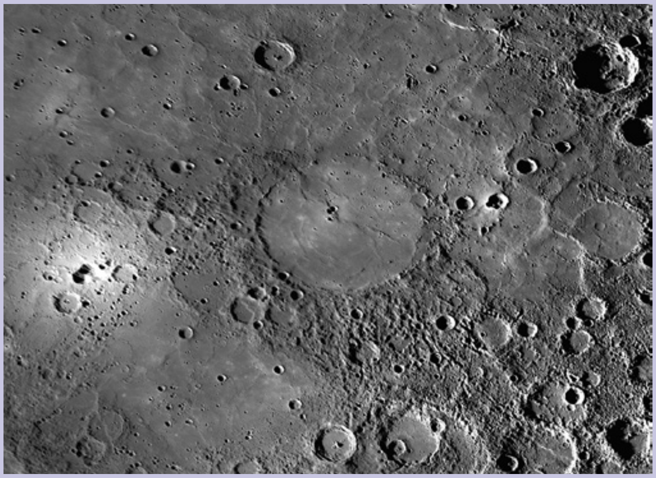
There are as yet no rules established for the naming of volcanoes on Mercury, but whatever it turns out to be, it won't be the same convention that is used for naming craters. On Mercury, craters are named for artists, musicians, authors, and painters. Therefore I contacted Mr. Dantowitz and suggested that the name Copland be proposed for a large flooded large crater adjacent to the bright spot. He was agreeable to that and the IAU accepted the name. So that's the backstory to how Copland got its name.

— *D. T. B.*

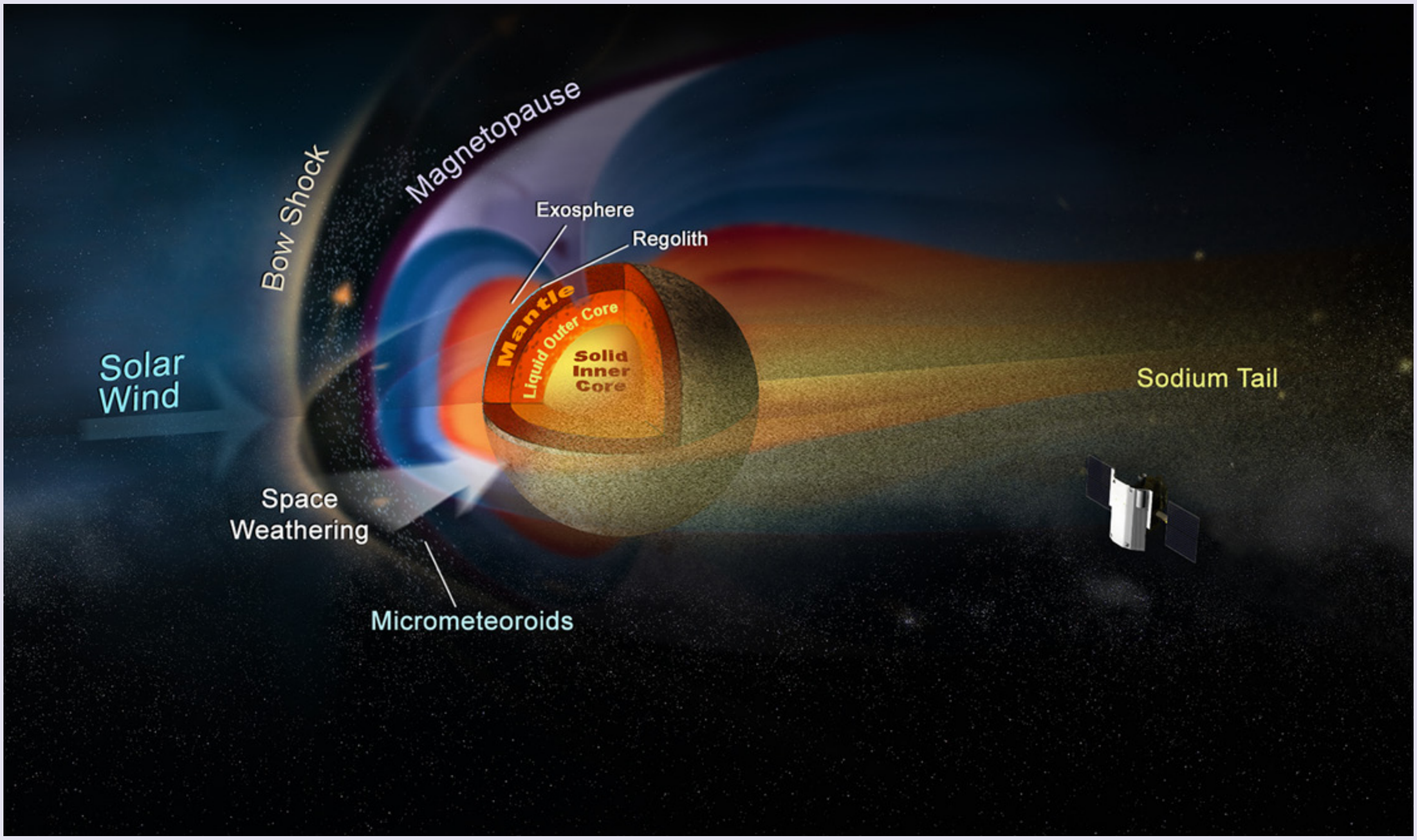


Left: Ron Dantowitz / Scott Teare / Marek Kozubal. *Right:* NASA / JHUAPL / Carnegie Institution.

***Left:* A composite of Mercury images taken in 1998 with the 60-inch on Mount Wilson. *Right:* A nearly identical view acquired in 2009 as MESSENGER approached Mercury for the mission's third flyby.**



The 200-kilometer-diameter crater Copland is centered in this view. The bright feature to its left, first imaged by Dantowitz and his colleagues in 1998, is likely a volcanic vent.



This illustration tries to summarize some of the complex interactions between the solar wind, the magnetic fields generated in a liquid outer core, the magnetosphere, the exosphere, and micrometeoroids bombarding the surface. It's a complex, dynamic system, and there is much yet to be learned.

Mercury's formation and suggests that the material from which Mercury formed may have come from a wider swath of the inner solar system than was previously suspected.

Fitting with the gamma-ray spectrometer result for potassium, the x-ray spectrometer has found higher-than-expected sulfur content on the Mercurian surface. Sulfur is another volatile element. Sulfur compounds may be involved in the formation of the hollows described earlier. Thus there is growing evidence that, contrary to the old prevailing wisdom, Mercury is not depleted in volatile elements, and thus models for the formation of Mercury need to be revised.

Magnetic Field

Mariner 10 discovered the planet's magnetic field. MESSENGER has confirmed that the intrinsic field has a dipole configuration, which wasn't quite clear from the Mariner 10 data. It looks like the strength of the field hasn't changed since Mariner 10 flew past, and we don't yet see any magnetized sections of crust (areas of magnetized crust are found on Mars and the Moon).

It has been determined that there is a shift in the magnetic equator relative to the geographic equator (see the illustration on the previous page). This offset, about 500 kilometers toward the north, is related to the nature of the internal dynamo that generates Mercury's magnetic field. An interesting consequence of the northward offset is that more solar wind and magnetospheric particles are able to get in and bombard the area of the surface around the south pole. This has implications for generating Mercury's thin atmosphere and also has implications for some of the processes that have happened to the rocks on the surface.

A Strange World

So the summary for Mercury is that it's a strange planet, and it is radically different from the Moon. Even some planetary scientists say: "Ah, Mercury looks just like the Moon."

At a cursory glance, yes. But in nearly every characteristic, Mercury and the Moon contrast sharply. Many aspects of this little planet are poorly understood, and MESSENGER is revealing numerous fundamental features about the planet that we don't yet comprehend. Among other things, models for its formation need to be reconsidered.

Mercury is a planetary endmember, an "anchor" for the process of planetary formation close to the Sun. In order to fully comprehend how the Sun's family of planets formed, we need to understand Mercury. Since many of the planets being discovered around other stars are "close-in," Mercury likely has much to teach us about planet formation in general.

MESSENGER's primary mission runs through March 2012. An extended mission proposal has been submitted to NASA, and we have enough fuel to maintain orbit for another Earth year. So hopefully, many more discoveries about Mercury are in store.

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