ASTRONOMY BEAT

The Discovery of Hollows on Mercury

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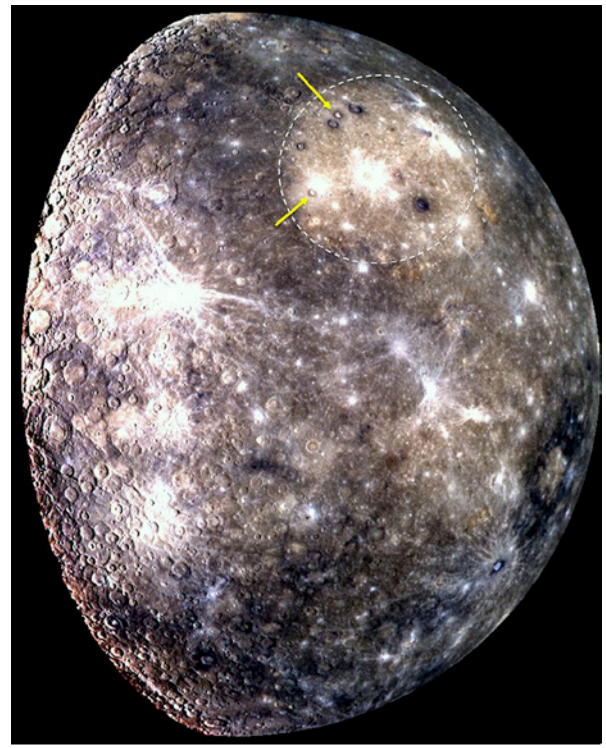
I was a graduate student in geology and geophysics at the University of Hawaii in the early and mid-1990s. At that time only one spacecraft had ever visited Mercury — Mariner 10 performed three flybys between 1974 and 1975. To me, Mercury had an air of mystery. The data for the planet, like telescopic spectra from the 1970s and early '80s and the Mariner 10 images, seemed really ancient.

For my dissertation, I worked mainly on compositional studies of the Moon using reflectance spectra obtained with telescopes at Mauna Kea observatory and multispectral images returned by the Clementine spacecraft. These studies focused on determining the rock types present at various locations on the lunar surface by analyzing the absorption of light in the near infrared, which is controlled by the presence of ferrous iron in the silicate minerals that compose the rock.

Mercury is a planet that superficially resembles the Moon, though thanks to MESSENGER, we now know that Mercury is radically different from the Moon in nearly every characteristic that we can measure, including internal structure, magnetic field, surface composition, and tectonic history. Of course we didn't know this at the time, and I was interested in trying to apply the lunar iron-determination technique devised by Paul Lucey, one of my dissertation committee members, to ground-based spectra of Mercury that had been collected by other workers. We were partly successful, and agreed with



It was amazing to finally acquire new views of Mercury, 33 years after Mariner 10. This color composite of MESSENGER images has a spatial resolution of about five kilometers per pixel. The dashed circle shows the approximate rim of the Caloris impact basin. Several dark-rimmed impact craters stand out from the brighter Caloris interior plains, and two (marked with arrows) have unusually bright floors. The crater Sander (upper arrow) is shown in closeup on pages 3 and 4. Unless otherwise stated, images are courtesy NASA/Johns Hopkins University Applied Physics Laboratory/Carnegie Institution of Washington.

prior conclusions that Mercury's surface must have a very low iron abundance compared to that of the Moon.

One of the Mariner 10 findings that stuck in the back of my mind came from a short paper published in 1977 by Daniel Dzurisin, who had done his PhD using Mariner 10 data. He noted that some impact craters have unusual bright patches on their floors. Color ratio images, made by dividing an image taken through an ultraviolet (UV) filter by one taken through an orange filter, showed that the bright patches had a high UV/orange ratio, a characteristic referred to as a "blue" spectral slope.

MESSENGER to Mercury

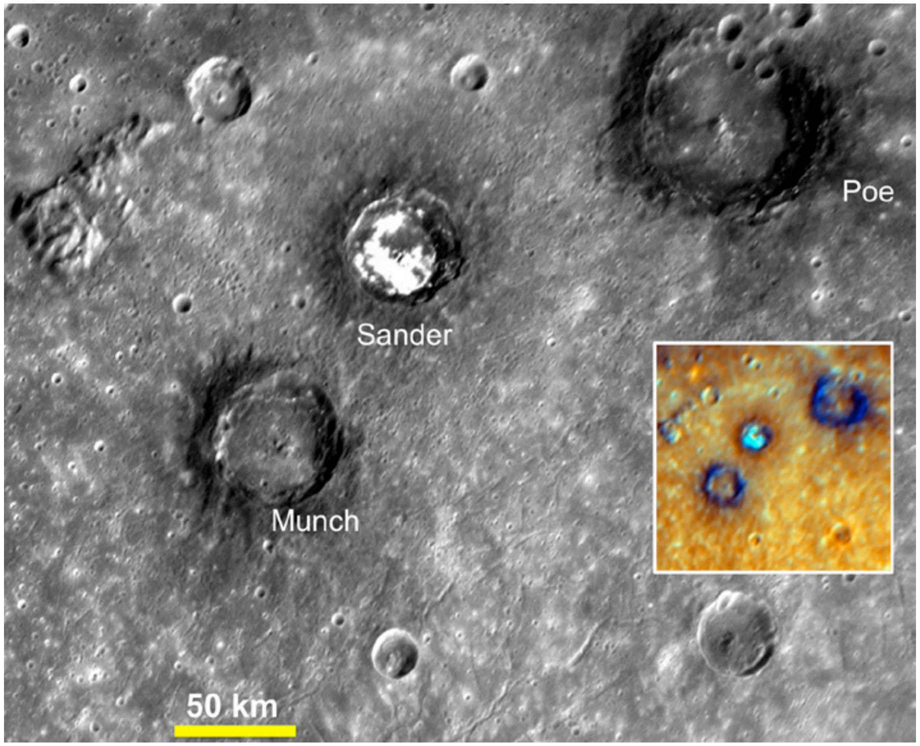
Fast-forward a few years. In 1999 a proposal for a Mercury orbiter called MESSENGER (MErcury Surface, Space ENviroment, GEochemistry, and Ranging) was selected by NASA as the seventh mission in the Discovery program. (Discovery is NASA's lowest-cost class of planetary mission.) The Principal Investigator for MESSENGER is Sean Solomon, then at the Carnegie Institution of Washington. The spacecraft was launched in 2004, and in 2006 NASA solicited research proposals for the MESSENGER Participating Scientist (PS) program. A PS program allows a project to keep costs low by having a smaller science team during a mission's years of development and cruise to the target, bringing on additional science help starting about a year before the major return of data begins. Thanks partly to the Mercury work that I had done in graduate school (during a time when few others were thinking about mercurian geology) my PS proposal was selected and I was very excited to be joining the MESSENGER team. The funny bright, blue crater patches first described by Dzurisin were a topic that I mentioned in my proposal.

MESSENGER sports a complement of seven scientific instruments designed to examine Mercury's magnetic field, its extremely thin atmosphere (exosphere), the solar wind and other charged particles

MESSENGER science team members and summer college intern students at the Johns Hopkins University Applied Physics Lab in early August 2011. The interns helped to search images and compile locations of hollows for a paper published in the Sept. 30, 2011, issue of *Science*.

in the vicinity, and to make compositional and topographic studies of the surface. The imaging system has two cameras: a wide-angle camera that can collect images through 11 different color filters from the blue to the near-infrared, and a narrow-angle camera to view the surface at high spatial resolution in monochrome (black and white). The CCD detectors in these cameras offer much better stability and signal-to-noise performance than did the relatively primitive Mariner 10 vidicon cameras.

MESSENGER employed an ingenious energy-saving "planetary pinball" trajectory to get to Mercury. By using gravitational assists, the spacecraft was able to reduce the amount of fuel needed to get there and to go into orbit. Carrying less fuel means a smaller



In the monochrome image of Sander, deposits of bright material can be seen on the crater floor. The inset is a false-color composite image of the same area, showing that Sander's floor materials have a characteristic cyan appearance — a result of high reflectance and relatively shallow ("blue") spectral slope. Sander is flanked by dark-rim craters Poe and Munch, which lack the bright floors. Mercury's bright-floored craters have no counterpart on the Moon.

spacecraft mass, and a smaller mass can be carried aloft on a smaller launch vehicle (rocket). Smaller rockets are cheaper than bigger ones, keeping costs down. In the three years after launch, the spacecraft made one flyby of Earth and two of Venus, each time using the planet's gravitational tug to bend its path toward Mercury. January 14, 2008, brought MESSENGER's historic first flyby of Mercury — becoming just the second spacecraft to reconnoiter the elusive innermost planet.

The science team awaited the arrival of the images with great anticipation. We knew that the spacecraft would view a part of Mercury that had not been seen by Mariner 10. What would we find on this terra incognita? It was amazing to see Caloris, a large impact basin. Mariner 10 had shown us the eastern third of it, but now we could appreciate the entire 1550-km-diameter structure (see page 1).

The lighting conditions during the MESSENGER flyby were optimal for color imaging of Caloris, and it proved to be dazzling. The interior is filled with high-reflectance, smooth volcanic lava plains, whereas the basin rim and exterior plains are dominated by darker material. "Red spots" that proved to be material deposited by explosive volcanic eruptions dot the margins of the basin. Inside the basin, a handful of impact craters have penetrated the plains and excavated dark material from the subsurface. These craters have distinctive dark rims, unlike any on the Moon. Two of the dark rim craters especially drew my attention because of their bright, bluish floors *(opposite)*. Here were new examples of the kind of material that Dzurisin had talked about. The enigmatic bright, bluish materials were dubbed "bright crater floor deposits (BCFDs)."

MESSENGER sped past Mercury, having set itself up for two more flybys: one in early October of 2008 and another in late September 2009. Images and other data were successfully collected during these two maneuvers, and the spacecraft was sent toward a March 2011 final approach to Mercury. The data from the flybys allowed nearly all the areas unseen by Mariner 10 to be mapped. More examples of the BCFDs were discovered, and it became clear that their color properties were quite anomalous compared with other surfaces on the planet.

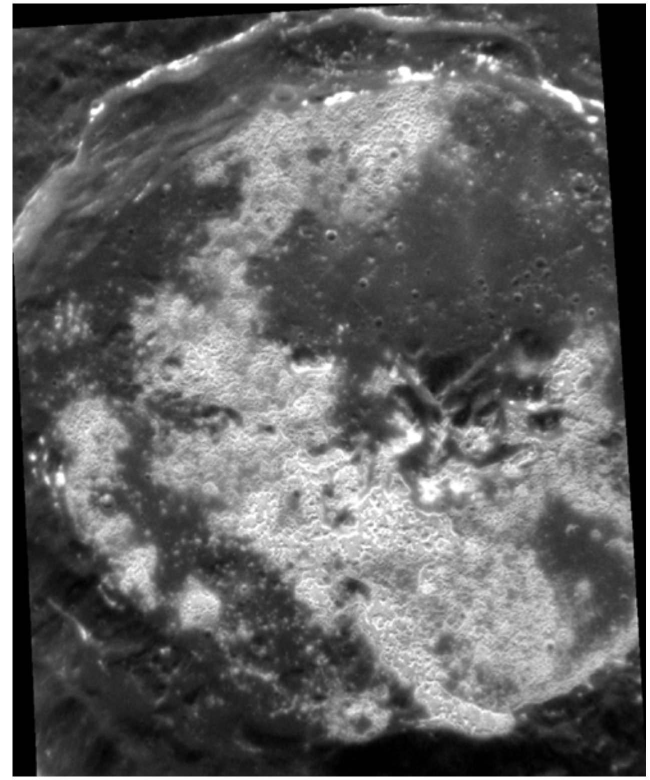
However, at the relatively low spatial resolution of the flyby images, it was very unclear what exactly these materials were. Speculation included a distinctive type of impact melt, perhaps produced in especially high-velocity collisions (Mercury gets hit by comets that can be traveling two or three times faster than the average speed at which asteroids strike the Moon). Or maybe the bright, blue materials were uplifted from depth in the "rebound" phase of crater formation and represent a rock type that has a patchy distribution in the subsurface. The images just didn't show enough detail to figure out what was going on.

Orbital Science

On March 18, 2011, MESSENGER fired its main engine for 15 minutes, consuming nearly one-third of the propellant that it carried at launch. This "burn" slowed the spacecraft enough so that it could be captured by Mercury's gravity and settle in to its mapping orbit. History was made again — the first spacecraft to orbit Mercury! (The four other planets known to the ancients, as well as the Moon and asteroid Eros, had orbiters before Mercury.)

After two weeks of "commissioning" during which the mission engineers verified that the spacecraft's systems were all operating correctly in the challenging thermal environment presented by the hot Sun and the hot planet, systematic science observations began. The plan was to collect a global multicolor image base map under illumination conditions with the Sun high in the sky. A complementary monochrome map would be built up by imaging with the Sun lower on the horizon, when shadows emphasize the texture and topography of the surface. In addition, targeted images of features of special interest would be collected when possible. The targeted images have very high spatial resolution, with pixel sizes as small as 15 meters, much better than the flyby images, which were typically several hundred meters per pixel.

Based on the flyby data, the team had targeted a number of BCFDs for the special high-resolution observations. As the first targeted images came down, we were surprised to find that all the BCFDs were actually composed of groups of shallow, rounded depressions that had bright interiors and halos *(opposite)*. On the floors of craters like Sander, a great many of these depressions had coalesced and covered large areas of the floors. It also became apparent that the things we had been calling BCFDs occurred in a variety of locations (including crater peaks, rims, walls, and ejecta deposits), not just on crater floors. Thus the term "bright crater floor deposits" was a bit of a misnomer.



This targeted image of Sander crater, obtained by MESSENGER while in Mercury orbit, is about 32 km (20 miles) across. The areas of high reflectance seen at low resolution in the image on the previous page are revealed to be composed of numerous flat-floored depressions that have irregular outlines and bright interiors and halos. The name "hollows" was adopted for features of this type.

A Problem of Nomenclature

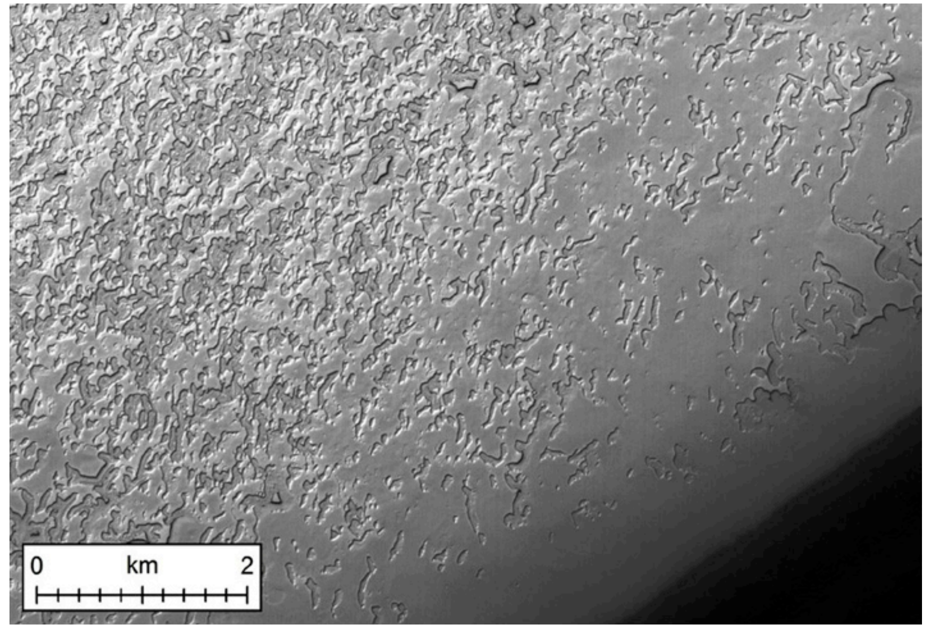
The science team's Geology Discipline Group discussed the problem of what to call these amazing features. The International Astronomical Union (IAU) is in charge of naming surface features on the planets and has a set of approved Latin names for various feature types (mare, catena, rupes, mons, etc.). Should we find an existing name to apply to these fascinating Mercury depressions? Should we invent a new one and propose it to the IAU for adoption? If the IAU were to approve use of a specific feature type for the "features formerly known as BCFDs," there would then be the matter of a naming scheme. For example, impact craters on Mercury are named for deceased writers, artists, and composers, and tectonic scarps (cliffs) are named after "ships of discovery." What naming scheme would be proposed for our odd bright blue depressions?

An alternative was to just use an informal name. This has precedent on the Moon. For example, "lunar swirls" are unusual wispy albedo markings (the Reiner Gamma formation is the most famous). The term "lunar swirl" is accepted and used in the lunar science community, but there is no special IAU feature term for them, and individual swirls are not given official IAU names according to a theme. The same is true of features like the lunar Mairan domes or the Rümker hills — no special feature type, no official names.

In the process of our research, we found that there is an IAU descriptor that would be a good fit for the Mercury features: "cavus" (plural "cavi") is used for "hollows, irregular steep-sided depressions usually in arrays or clusters." The term cavi is used on some icy satellites and in a few places on Mars. Hence it was tempting to ask the IAU to approve use of cavi for Mercury.

However, in the end we decided against it. The main reason was that the features we sought to describe are quite common, and are overwhelmingly associated with impact craters and basins. It would be quite a chore to write naming proposals for all of them (imagine if every crater central peak had to have an official mons designation). It seemed simpler just to refer to the features by the name of the impact structure with which they are associated.

The word "hollows" from the IAU definition of cavi caught our attention, though, and we began to use hollows as our shorthand for "irregular, flat-floored, shallow depressions with bright halos and interiors that have characteristic blue spectral slope." The term hollows is also useful for distinguishing them from other types of pits on Mercury that form by volcanic processes.



This Mars Reconnaissance Orbiter image shows the rounded depressions known as "Swiss-cheese terrain" on the south polar CO_2 cap of Mars. The depressions, which resemble Mercury's hollows, form by sublimation of the CO_2 ice. Courtesy NASA/JPL/Malin Space Science Systems.

Mercury's hollows remain a mystery. Their composition and the mechanism by which they form are active areas of research. The hollows resemble the "Swiss-cheese terrain" found on the south polar ice cap of Mars. The martian terrain is formed by sublimation of CO_2 ice. Obviously, Mercury's surface is composed of silicate rocks, not ice. But the consensus so far is that some kind of sublimation-like loss process is producing the hollows.

MESSENGER's X-ray spectrometer discovered a surprisingly high abundance of sulfur on the surface. Perhaps sulfide minerals in the rocks are susceptible to destruction under the broiling solar heat and intense bombardment by micrometeoroids and charged particles of the mercurian environment.

Although the rate at which the hollows are estimated to be forming is slow compared with erosion on the Earth or Mars, the hollows are among the freshest-looking features on Mercury. It is quite likely that they are actively forming today. Investigation of these beautiful and unexpected features, using data from MESSENGER and (someday) the European Bepi-Colombo orbiter, will lead to a better understanding of Mercury's composition and the forces that modify its surface. I count myself lucky to have been there for their discovery.

About the Author

David T. Blewett is a member of the Senior Professional Staff in the Planetary Exploration Group at the Johns Hopkins University Applied Physics Laboratory.

Resources

- You can browse the MESSENGER image gallery at http://messenger.jhuapl.edu/gallery/sciencePhotos. Click on "Release by Topic" to find more images of hollows.
- There is a good PDF article called "MESSENGER: Revealing Mercury's Secrets" (B. Denevi, and C. Ernst) in the December 2011 issue of the *Lunar and Planetary Information Bulletin*: www.lpi.usra.edu/publications/newsletters/lpib/lpib127.pdf.
- An atlas of Mariner 10 images (NASA Special Publication no. 423) is available on line: http://history.nasa.gov/SP-423/sp423.htm.
- For those wishing to delve into our current understanding of the hollows and Mercury's crust, here are three papers that have appeared in *Science:*
    - "Hollows on Mercury: MESSENGER evidence for geologically recent volatile-related activity," *Science, 333*, 1856–1859 (2011)
    - "The evolution of Mercury's crust: A global perspective from MESSENGER," *Science, 324*, 613–618 (2009)
    - "Reflectance and color variations on Mercury: Regolith processes and compositional heterogeneity," *Science, 321*, 66–69 (2008).

Requests for copies of these papers can be addressed to the author: david.blewett at jhuapl.edu. ✦

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