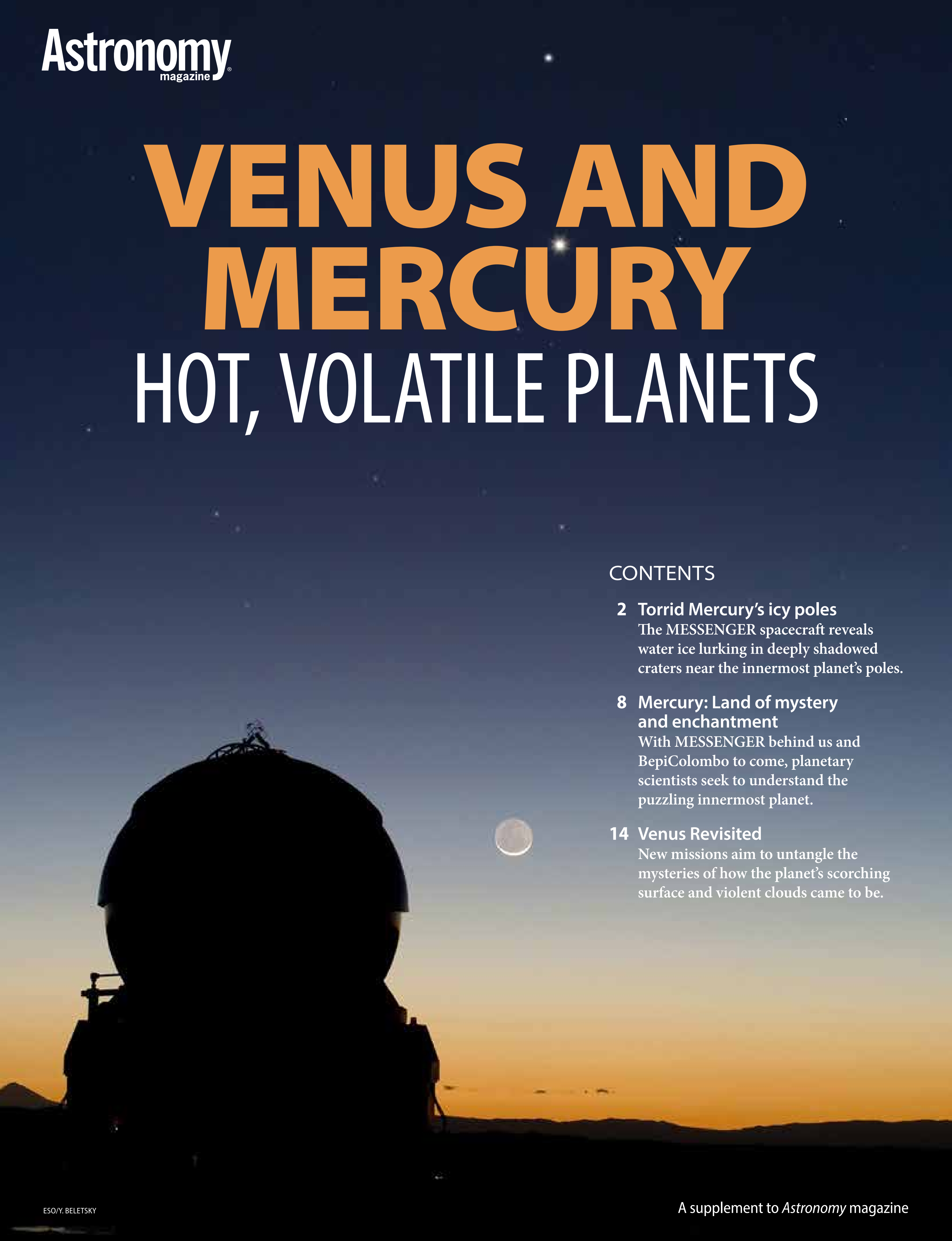
Astronomy magazine

VENUS AND MERCURY

HOT, VOLATILE PLANETS



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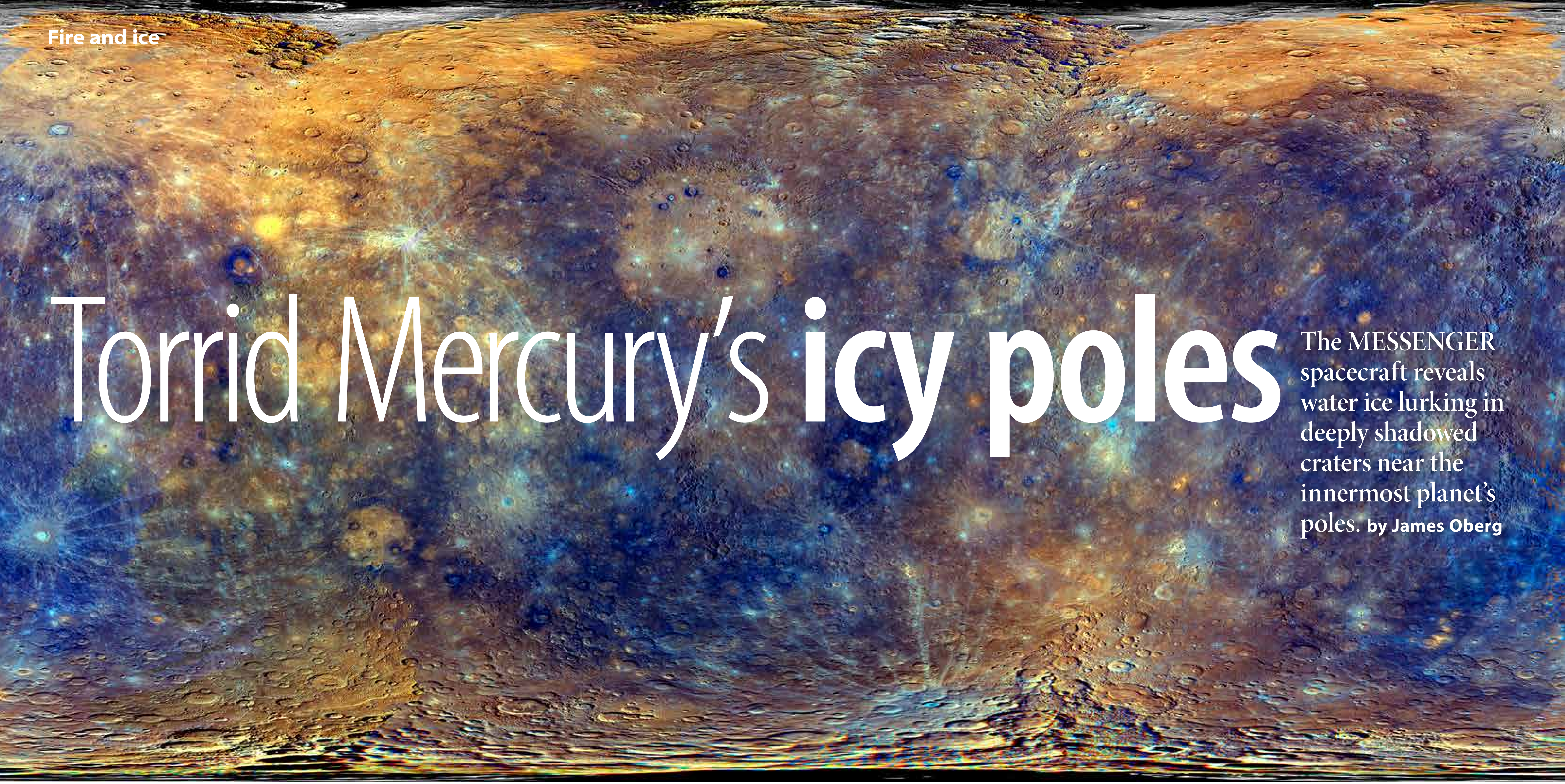
ESO/Y. BELETSKY

A supplement to *Astronomy* magazine



Torrid Mercury's **icy poles**

The MESSENGER spacecraft reveals water ice lurking in deeply shadowed craters near the innermost planet's poles. by James Oberg

Color explodes from Mercury's surface in this enhanced-color mosaic. The yellow and orange hues signify relatively young volcanic plains, while blue represents older terrain. The planet's equator runs horizontally through the center of this image; the poles lie at top and bottom. NASA/JHUAPL/CIW

The saga of water ice hiding in the shadows on Mercury ranks among the most fascinating chapters in the history of planetary exploration. And the story didn't end a year ago when scientists using NASA's MESSENGER spacecraft confirmed the existence of ice in craters near the planet's poles. MESSENGER — short for MErcury Surface, Space ENvironment, GEochemistry, and Ranging — started orbiting Mercury in March 2011 and has been returning reams of data ever since. The discovery of ice contains its own surprises and new mysteries.

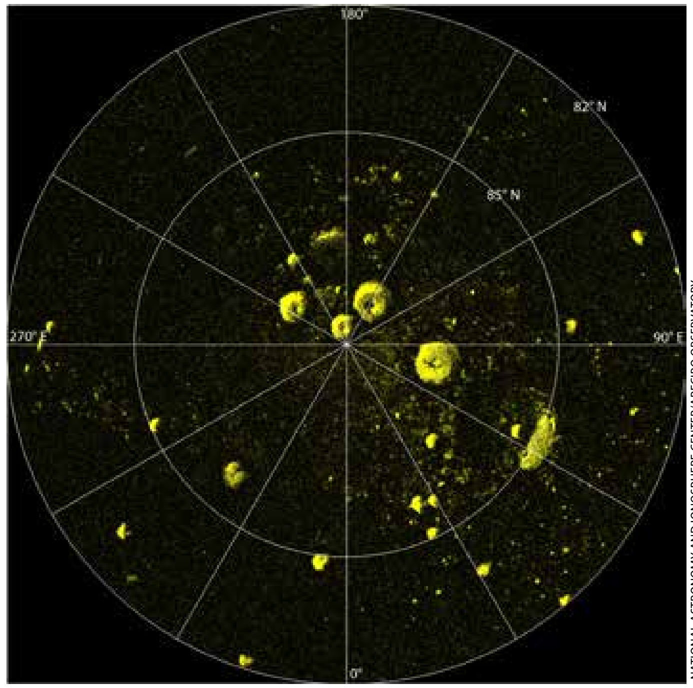
Scientists had suspected for decades that water ice might survive in corners of the solar system's innermost world. Theorists realized that cold regions could exist in certain areas, and observers seemingly backed up these theoretical computations.

Planetary scientist David Paige of the University of California, Los Angeles, a participating scientist on the MESSENGER project, stresses the wider significance of the ice story. "The Mercury discoveries demonstrate the power of theory and imagination in astronomy and planetary science," he says. "However, just because something might be there doesn't necessarily mean that it is. Careful observations and analysis are required as proof. Science works best when good observations are guided by theory."

During the past several decades, scientists have come to realize that a conspiracy of freak accidents involving Mercury's motion and orientation had created small regions on the planet's surface where it ought to be cold enough for ice to form and survive for billions of years. Unfortunately, instruments on NASA's Mariner 10 spacecraft, which made the only previous visits to the planet nearly 40 years ago, could not make the observations necessary to prove the case. Still, radar observations from Earth did detect unusually reflective regions in Mercury's polar regions that seemed to overlap the supercold regions theorists had calculated. This match provided a tentative hint of what might be.

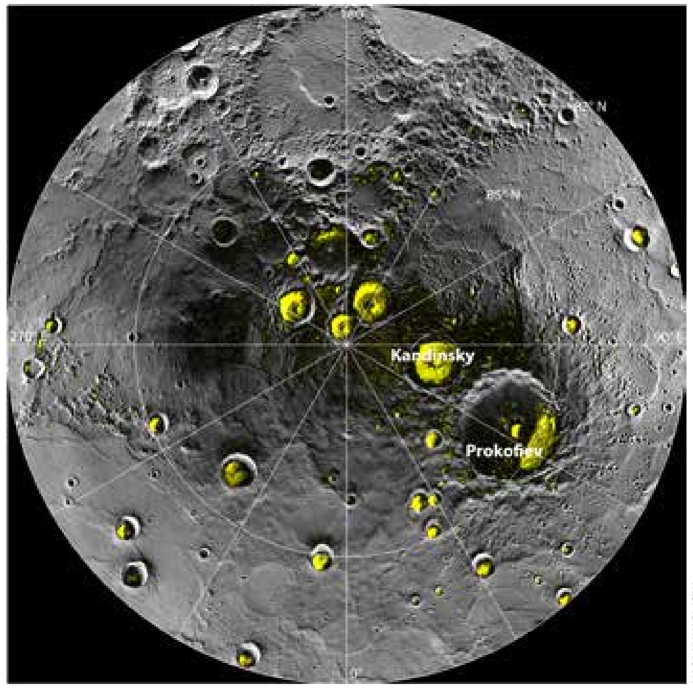
Untangling Mercury's web

It took centuries for astronomers to decipher Mercury's physical and dynamic characteristics and to understand their implications. Although the planet lies reasonably close to Earth, it is a difficult world to observe in detail. As the closest planet to the Sun, Mercury never strays far from our



NATIONAL ASTRONOMY AND IONOSPHERE CENTER/ARECIBO OBSERVATORY

Deep craters near Mercury's north pole harbor water ice. The first evidence for these deposits came from Earth-based radar observations in the early 1990s, which revealed bright patches that reflected most of the incoming signal.



NASA/JHUAPL/CIW

A mosaic of MESSENGER images of Mercury's north polar region appears beneath radar data of the same area seen at left. All of the large deposits sit on the floors or walls of impact craters, including Kandinsky and Prokofiev.

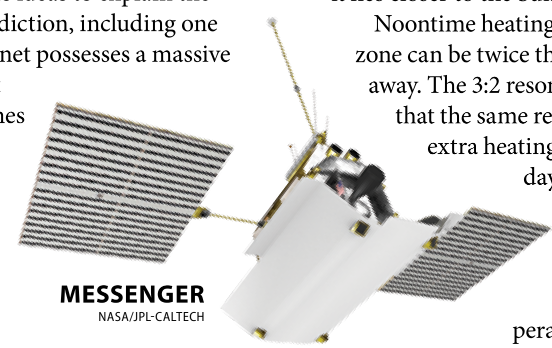
star's glare. The best observing conditions occur when it lies near one of its greatest elongations, which create brief periods when the planet climbs well above our earthly horizon and appears approximately half-lit.

It wasn't until the late 19th and early 20th centuries that astronomers, most notably Giovanni Schiaparelli in Italy and Greek-born Eugène Antoniadi in France, consistently observed the same markings on the planet's illuminated side. These features did not move over short periods and reappeared in the same locations at successive greatest elongations.

These observations implied that Mercury likely is tidally locked with the Sun and always keeps the same face pointed toward our star. The Moon suffers a similar fate, in which Earth's gravity locks the Moon so that it rotates in the same period it takes to revolve around our planet. The observations of Mercury also suggested that its rotation axis lines up nearly perpendicular to its orbital plane.

In Mercury's case, being tidally locked would create a scorchingly hot Sun-facing hemisphere, a perpetually dark and frigid region on the opposite side, and a fairly broad twilight zone where the Sun would rise and set periodically in response to the planet's varying orbital speed as it follows an elliptical orbit. (For the same reason, we see slightly more than half of the Moon's surface during a lunar month.) Astronomers accepted Mercury as another example of rotational lock well into the 20th century.

But further Earth-based observations suggested that Mercury's "dark side" was far warmer than it should be. Theorists proposed various ideas to explain the apparent contradiction, including one in which the planet possesses a massive atmosphere that spawns hurricanes to carry superheated air into the permanently shadowed regions. But none of the theories seemed to fit the observations.



MESSENGER
NASA/JPL-CALTECH

Then, in 1965, researchers bounced powerful radar beams off Mercury. A subtle shift in the wavelengths of the signals returned from the planet's edges didn't match an object rotating at the same rate as it revolved around the Sun — Mercury spins faster than anyone had suspected.

Even so, the planet is tidally locked, just not in a 1-to-1 ratio. Mercury rotates three times on its axis for every two revolutions it makes around the Sun. Although this so-called 3:2 resonance is stable over long periods, it has some bizarre implications.

First, each Mercury day, from one sunrise to the next, lasts two Mercury years. Long phases of heating and cooling are the rule across the planet's surface.

Second, despite these long cycles, not all longitudes experience the same share of heating. Because the planet has a fairly eccentric orbit, it travels much faster when it lies closer to the Sun.

Noontime heating in one longitudinal zone can be twice that in another 90° away. The 3:2 resonance also means that the same regions experience extra heating day after day after day. The two hottest zones lie along the equator on opposite sides of the planet. Temperatures there soar as high as 845° Fahrenheit (725 kelvins).

Third, Mercury's true rotation period relative to the stars (58.8 days) coincidentally turns out to be approximately half of Mercury's 116-day synodic period, the time it takes the planet to return to the same orbital configuration as seen from our planet.

This means that successive observation periods from Earth occur when the same side of Mercury faces the Sun. This dynamical accident is just bad luck for earthbound astronomers, who noticed — and misinterpreted — the repeated appearances of the same surface features.

James Oberg, *a former NASA "rocket scientist," now works as a space consultant for NBC News.*

A chill at the poles

But not all coincidences are bad news. With better observations in following years, scientists realized that Mercury's axis tilts 89.99° to its orbital plane — almost precisely perpendicular. Theory suggests that this near-perfect match of axis and orbit is a long-term effect of the planet's gravitational coupling with the Sun, which would mean that Mercury's rotation axis adjusts to changes in its orbital inclination over time. As a consequence, deep craters near the planet's poles can remain in permanent shadow and serve as ice traps for a billion years or more.

In 1991, researchers beamed radar signals at Mercury. Using the Goldstone radio telescope in California and the Very Large Array in New Mexico, they detected unusually strong radar returns from the planet's polar regions. These areas come into view because Mercury's orbit tilts 7° to Earth's, which allows astronomers to peek over the inner world's poles. The giant 1,000-foot (305 meters) radio dish at Arecibo Observatory in Puerto Rico later observed these same regions with similar results.

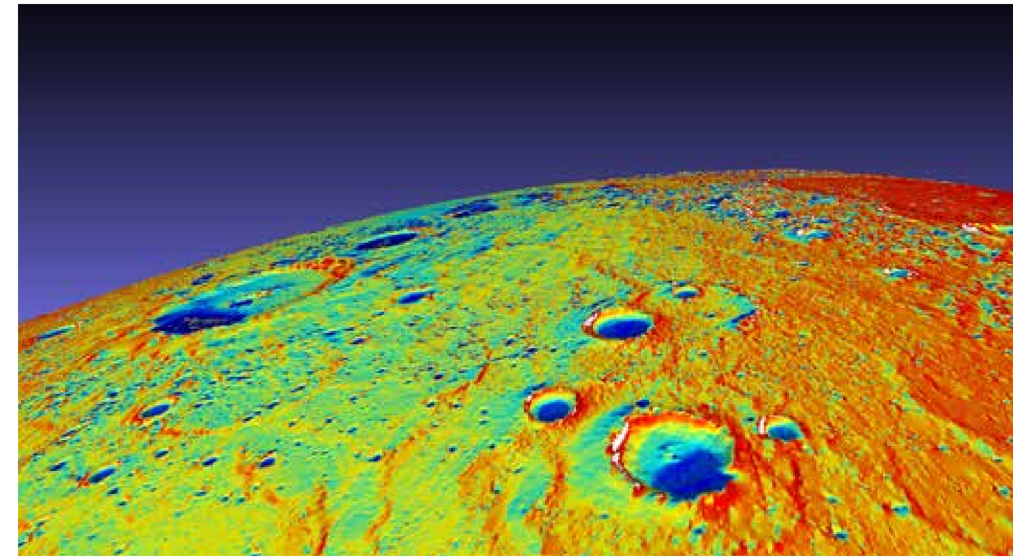
Photographs taken during the three Mariner 10 flybys in the mid-1970s showed that, in some cases, the high-return regions seemed to coincide with deep polar craters. Although water ice seemed the most likely cause, theorists developed several even more exotic explanations, including sulfur snow, sodium ions, or an unknown feature of the supercold surface. (After all, this was the coldest surface radar scientists had ever explored.)

MESSENGER to the rescue

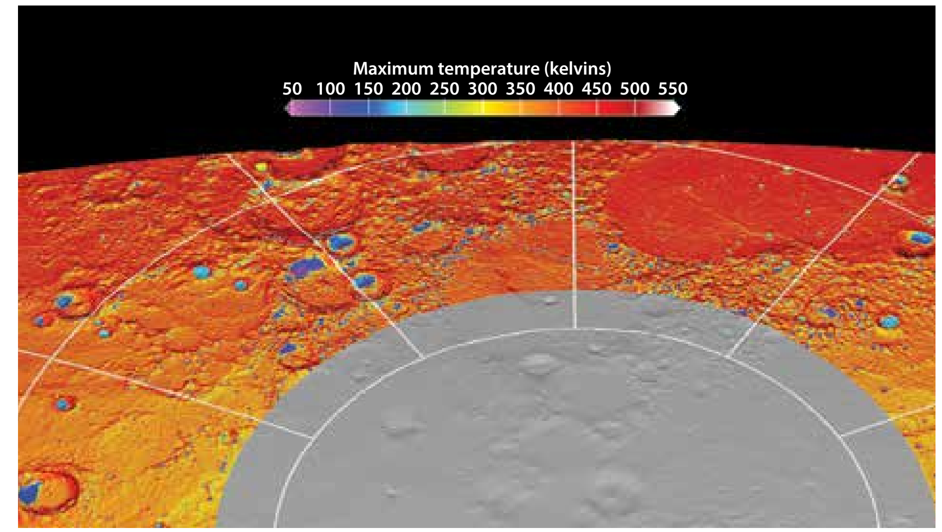
Into this uncertainty and mystery, NASA launched the MESSENGER probe in 2004. It was a challenge to get a spacecraft to Mercury with a speed slow enough that the biggest propulsion module possible could decelerate the craft into a stable orbit. After a seven-year voyage that included three flybys of the inner world, the probe arrived in its planned orbit March 17, 2011.

After a year of observations and analysis, NASA announced the results in November 2012. The ice is real, but it isn't what scientists expected. If anything, it proved even more interesting.

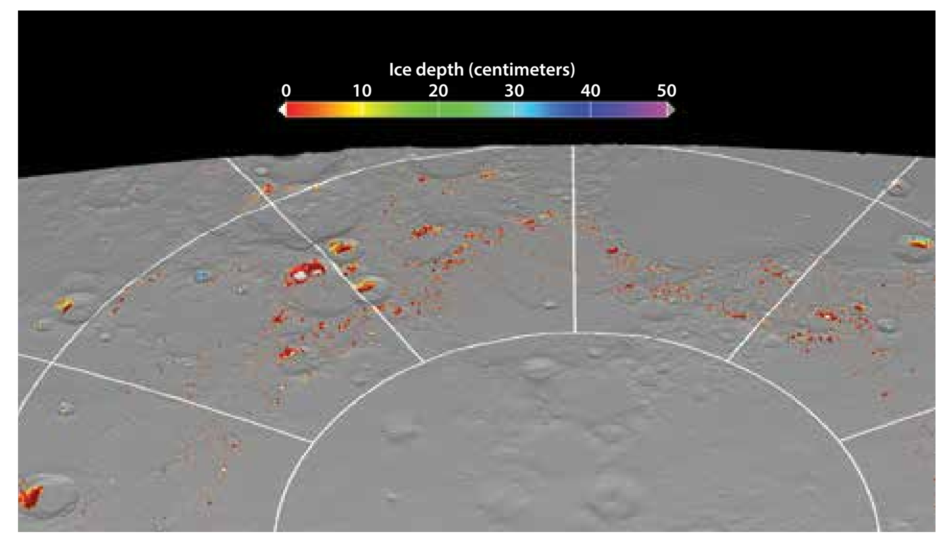
MESSENGER Principal Investigator Sean Solomon, director of Columbia University's Lamont-Doherty Earth Observatory, described how the science team painstakingly developed its case for ice at the poles. First, the researchers tested the hypothesis that the areas where scientists



This oblique view of the inner world's north polar region shows the surface temperature averaged over two Mercury years. Blue and purple represent the coldest areas, where ice can persist. NASA/UCLA/JHUAPL/CIW

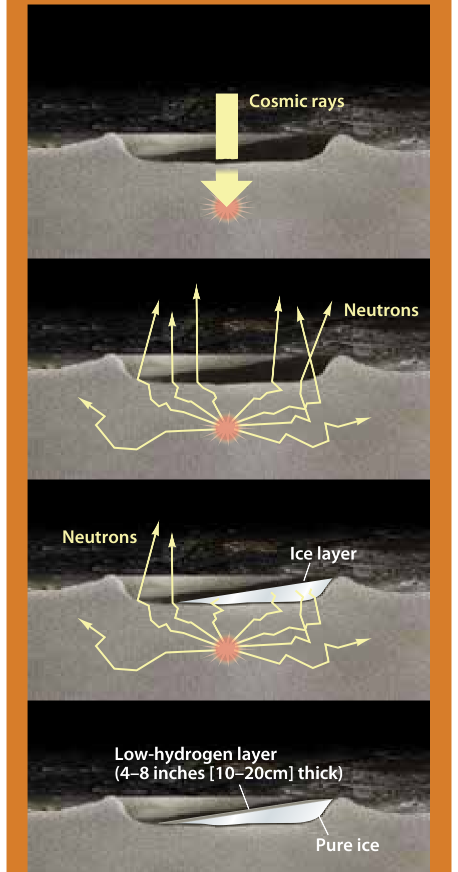


The highest temperature observed over two Mercury years gives a better idea of where ice can survive. The coldest spots in permanently shadowed craters only reached –370° Fahrenheit (50 kelvins). NASA/UCLA/JHUAPL/CIW



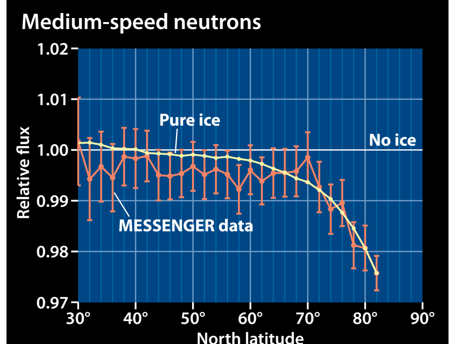
This map of "permafrost" shows the same area as above and indicates the depths below Mercury's surface where water ice should be stable. Gray denotes regions that are too warm for any ice, color reveals areas where subsurface ice can exist, and white shows spots cold enough for surface ice. NASA/UCLA/JHUAPL/CIW

How neutrons point to ice



When high-energy cosmic rays strike Mercury's surface, they liberate neutrons from subsurface atoms. Although these particles normally escape into space after traveling through the surface, hydrogen atoms in water ice block their route. An insulating layer low in hydrogen protects the ice. *ASTRONOMY*: RICK JOHNSON

Neutrons tell the tale



MESSENGER's neutron spectrometer surveys the entire planet looking for neutrons. If no ice existed on Mercury, the number of neutrons would remain constant with latitude. If the radar-bright deposits were pure ice, the plot would follow the yellow curve. The MESSENGER data closely match the pure-ice scenario. *ASTRONOMY*: RICK JOHNSON, AFTER NASA/JHUAPL/CIW

had observed bright radar returns were positioned inside craters having the right shape and in locations where ice could survive. "Imaging of both poles over multiple solar days on Mercury confirmed that all polar deposits are located in areas of permanent shadow," says Solomon. And the craters are big enough so that light reflecting from the Sun-facing rims does not flood the shadows with too much heat.

Second, the scientists used the craft's neutron spectrometer, an instrument that already had proved its worth during ice searches on the Moon, to seek evidence of hydrogen, two-thirds of the building blocks for water molecules. "Neutron spectrometer measurements [in the northern hemisphere] showed that the polar deposits have a hydrogen abundance consistent with a composition dominated by water ice," says Solomon, "but only if most ice deposits are buried beneath several tens of centimeters [at least several inches] of a low-hydrogen material."

The spacecraft's laser altimeter provided the third line of evidence. This instrument, developed to measure the precise shape and elevation of the planet's surface, also paid dividends in the hunt for ice. "Reflectance measurements showed that most polar deposits are dark at near-infrared wavelengths [1,064 nanometers in this case], but some of the polar deposits at the highest latitudes are much brighter than average for Mercury," says Solomon.

Finally, the team matched the newly imaged candidate regions to actual cold areas. "Thermal models derived with topographic maps constructed from altimeter profiles showed that water ice is thermally stable at the surface in those areas with bright reflectance, but is stable only if buried by several tens of centimeters of another still-volatile material for most [other] polar deposit areas," says Solomon. This unidentified material appears to be less volatile than water ice, which means it remains stable at higher temperatures.

A dark cover-up

MESSENGER scientists didn't anticipate discovering such a dark overcoat: "Finding unusually dark material in association with the ice deposits was definitely unexpected," says Paige. "We hypothesized that these may be dark organic-rich deposits like we find in comets and primitive outer solar system bodies. If this stuff really exists on Mercury, that would be pretty amazing."

Solomon agrees: "The surprise was that the material covering most of those [ice] deposits is not typical soil from Mercury's regolith [the layer of loose rock and soil found on the surfaces of most solar system bodies] but is instead material with a reflectance half that of Mercury's average. The specific reflectance and limiting temperature are best matched by organic-rich material found in comets and volatile-rich meteorites, and on the surfaces of outer solar system objects." Solomon adds that these properties strongly suggest that the water ice and the organic material found their way to Mercury's polar craters by a common process.

The researchers found the dark protective layer over ice in craters at some distance from both poles. Its distribution clearly avoids the longitudes of the "hot spots" created by Mercury's peculiar 3:2 resonance. The volatile deposits extend farther from both poles along the coldest longitudes — those 90° off the hot spot locations — providing further proof of their icy nature.

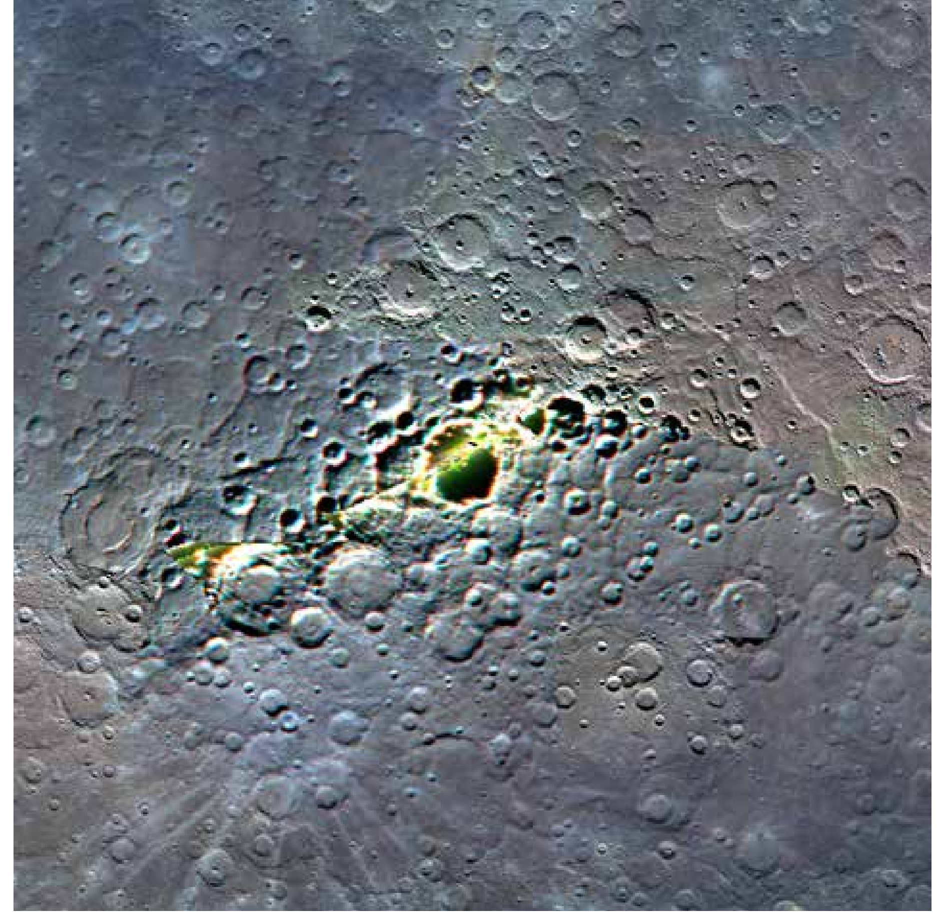
But closer to both the north and south poles, the temperatures drop even lower. In these regions, ice can remain stable without any protection. The water ice is pure, and it is naked to space. "We had expected to find evidence of ice, but bright ice on the surface and right where the thermal models predicted it was a surprise," says Paige. "Bright surface ice requires ongoing processes to deliver water to the polar regions faster than it can be buried by impact debris and [ultraviolet] radiation."

Taking a bath

Considering NASA's exobiology imperative to "follow the water" in search of extraterrestrial life, the question arises whether water ice on Mercury opens a potential new habitat for biology. The answer, so far at least, appears to be no.

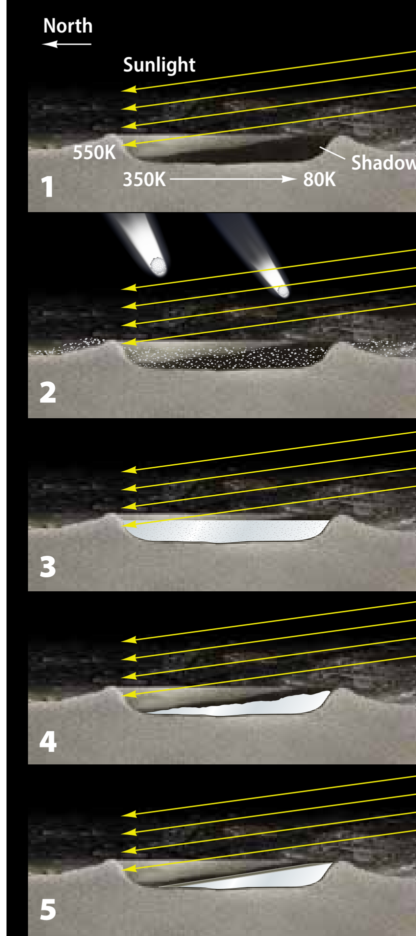
"The likelihood of persistent liquid water is remote," says Solomon. Water in Mercury's polar craters either will be a stable solid or in vapor form. "There may be brief intervals where water ice may be melted by sunlight or subsurface heat," he continues, "but there is no evidence that water has modified the surface or near-surface in ways detectable from orbit."

"We don't think there's any possibility for liquid water in association with these deposits," adds Paige. "They are way too cold. While surface and subsurface temperatures in the soil surrounding the ice deposits can be in the habitable zone [where conditions allow liquid water to exist], Mercury has no atmosphere, so any liquid water in these warmer regions would quickly boil away into space."



This enhanced-color mosaic reveals Mercury's south polar region. MESSENGER's most detailed observations show the planet's northern half because the probe flies closer to that hemisphere. But images of the south pole show craters that lie in permanent shadow, just like those in the north. NASA/JHUAPL/CIW

How ice forms and survives



Sunlight hits an impact crater near Mercury's north pole at a shallow angle. Although the sunlit rim grows hot, the opposite side remains in shadow (1). When comets strike the planet (2), they spread water and organic compounds over a wide area, and some migrate to the poles and get trapped in craters (3). Water ice in the warmer areas vaporizes over time (4) but stays stable in the coldest spots, protected by a layer of organic material (5). *ASTRONOMY*: RICK JOHNSON

But where it is cold, water ice is stable for a long time. "There could definitely be billion-year-old ice on Mercury because the cold traps [have remained frigid for a major fraction of the solar system's history]," says Paige. Still, he remains cautious: "We don't know enough about the sources and destruction rates of the ice to say how old any given piece of ice might be."

Could the ice exist in successive layers, with the oldest at the bottom? If so, it could provide future explorers with a time-lapse history of Mercury and, perhaps, solar activity. In much the same way, terrestrial geologists use ice cores from Antarctica and Greenland to study Earth's climate history.

"This is one possibility, but, unfortunately, we just don't know the answer," Paige admits. He does speculate that the apparently well-organized nature of Mercury's deposits suggests that they might have migrated, mixed, and reformed as the planet's orbit evolved over millions of years. This could jumble any time history.

To the next stage

The MESSENGER spacecraft continues to orbit Mercury, dipping closer to the surface to gather more precise measurements of particularly interesting regions. During the probe's final year of operation, mission planners intend to have it descend within 15 miles (25 kilometers) of the surface at specific points, where it will be able to make the most detailed observations yet.

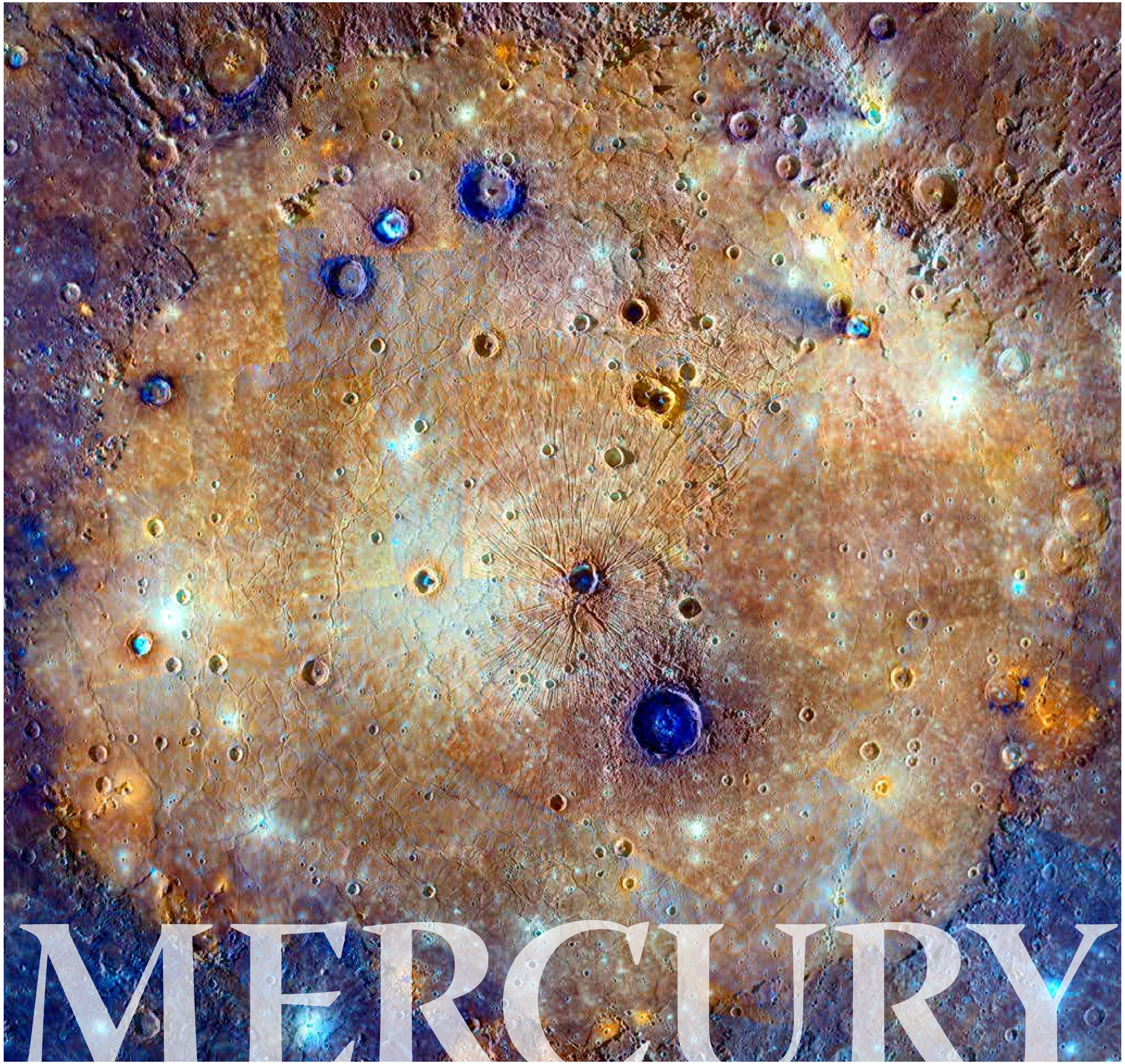
Until then, scientists will have to be content with what the orbiter already has delivered. For Solomon, the water ice detection ranks high for two reasons. "First, the required measurements were difficult, given that our spacecraft was far from the planet's polar regions and the polar deposits filled only a small fraction of the field of view of key remote sensing instruments," he says. "Second, the confirmation of water ice required that multiple lines of evidence all pointed in the same direction. The results came in one at a time, like plot developments in a mystery novel, and the solution came only on the final page."

Paige echoes those sentiments: "Scientists have been studying polar ice on the Moon and Mercury since the 1960s. The MESSENGER observations are like a satisfying end to a good story — or at least one chapter in a longer story."

David Lawrence of the Johns Hopkins University Applied Physics Laboratory, who led the design team for the neutron spectrometer that detected the hydrogen, stresses that polar ice on the Moon and Mercury reflect different phenomena. Mercury's poles are warmer than the lunar poles, he points out, but the planet has a lot more water in much purer form. "It's a continuing mystery, the differences in the ice between the Moon and Mercury," he says. "We'll need to go down and sample the surface."

Actually reaching and analyzing Mercury's polar ice is a challenge at the current limits of technological speculation. Perhaps a lander could do the job, or an impactor paired with an orbiting collector made of aerogel that captures the collision's debris.

In other words, it's an ideal goal for young planetary scientists to consider. After all, the next chapter on Mercury's polar ice remains to be written.



Land of mystery AND enchantment

With MESSENGER behind us and BepiColombo to come, planetary scientists seek to understand the puzzling innermost planet.

by Jesse Emspak

The giant Caloris Basin spans about 960 miles (1,550 kilometers). In this enhanced-color mosaic, yellow and orange represent relatively young volcanic plains while blue signifies older terrain. ALL IMAGES: NASA/JHUAPL/CIW

It ended with a bang, not a whimper. On April 30, 2015, NASA's MESSENGER spacecraft hurtled into Mercury's surface at around 8,750 mph (14,100 km/h). MESSENGER — short for MErcury Surface, Space ENvironment, GEochemistry, and Ranging — had orbited the planet 4,104 times over 4 years, 1 month, and 12 days, giving humans their first complete reconnaissance of the innermost planet. (Mariner 10 flew past Mercury three times in 1974–5 and MESSENGER followed with three more flybys in 2008–9.) The probe revealed a planet stranger than anyone expected. Luckily, scientists are planning another trip to Mercury. In 2017, the European Space Agency and the Japan Aerospace Exploration Agency will launch BepiColombo, which should arrive at Mercury in 2024.

"BepiColombo will do more planetary physics and probe deeper," says Wolfgang Baumjohann, principal investigator for the magnetometer instrument on BepiColombo's Mercury Magnetospheric Orbiter (MMO). MESSENGER, in a way, was just a taste, says David Rothery, a planetary geoscientist at the Open University in England and lead co-investigator on BepiColombo's Mercury Imaging X-ray Spectrometer instrument. "We know what questions to ask now."

BepiColombo will be able to do a lot of things MESSENGER could not. First, the mission boasts two spacecraft. One is the Mercury Planetary Orbiter (MPO), which will focus on the planet's surface chemistry and geology. The other is the MMO, which will concentrate on the inner world's magnetic and solar wind environment. Both will

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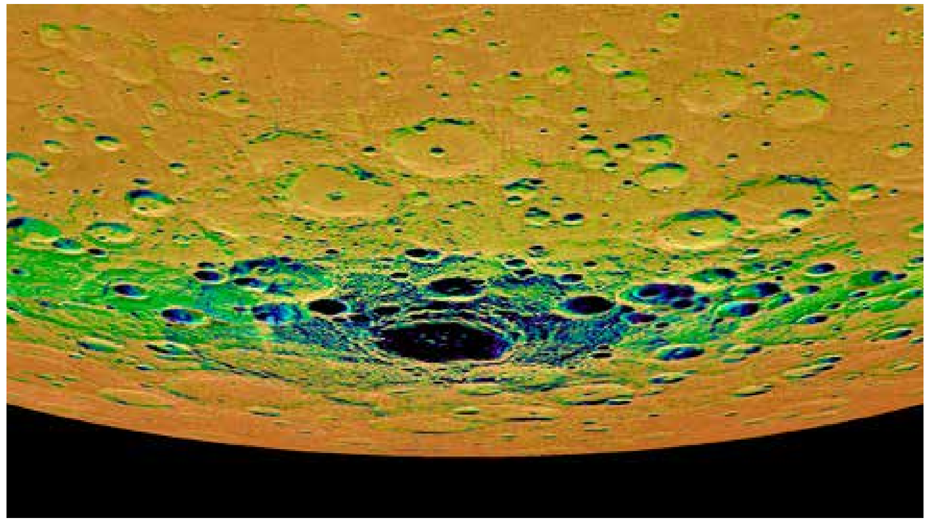


The colors in this view of Mercury's south pole reveal how much sunlight various regions receive. The black areas represent those in permanent shadow, the largest of which is the crater Chao Meng-Fu. Unfortunately, MESSENGER did not view the planet's southern hemisphere in as much detail as the northern, a situation BepiColombo should correct.

carry instruments to measure Mercury's magnetic field, allowing for simultaneous readings from different positions.

Orbital dynamics also plays a role in improving BepiColombo's science. MESSENGER's closest approach to the planet (periapsis) was above the northern hemisphere at an initial altitude of about 125 miles (200 kilometers). Its farthest point (apoapsis) was some 9,440 miles (15,193km) above the southern hemisphere. This orbit meant that observations of the southern hemisphere came from much farther away, reducing the probe's resolution. Although this arrangement allowed scientists to investigate the solar wind environment, it prevented them from getting a close look at the magnetosphere near Mercury and reduced the clarity needed for geological studies.

BepiColombo's two orbiters, on the other hand, will take up symmetrical paths. Once they get to Mercury, they will separate and enter polar orbits. The MPO will be close in, with a periapsis of 300 miles (480km) and an apoapsis of 930 miles (1,500km). The MMO's track will be more eccentric, with a minimum altitude of 365 miles (590km) and a maximum of 7,230 miles (11,640km). Mission planners designed both orbits so the probes will examine the northern and southern hemispheres in equal detail. Although BepiColombo's best visual resolution won't be quite as good as MESSENGER's was, the coverage will be more comprehensive.

MAGNETIC PERSONALITY

Mercury's magnetic field is about 1⁄100 the strength of Earth's. MESSENGER showed that the field doesn't align with Mercury's equator. Instead, it is offset some 300 miles (480km) toward the planet's north pole. That's about 20 percent of the planet's 1,516-mile (2,440km) radius. This makes the field more than three times stronger in the northern hemisphere than in the southern.

The center of Earth's magnetic field roughly coincides with our planet's center, though the magnetic axis tilts some 11° to the rotational axis. Mercury's field tilts only 4.5° to the rotational axis, but the offset is a major puzzle. "There are other planets that have magnetic fields not centered on the center of the planet, and other planets that have magnetic fields sort of aligned [with the rotational axis],"says Steven Hauck, a planetary scientist at Case Western Reserve University in Cleveland and a member of the MESSENGER team. "Mercury has both."

The magnetic field likely arises from a dynamo — the movement of electric currents in the core's liquid outer part — just like the one that surrounds Earth. "MESSENGER confirmed that field predominantly comes from the core," says Hauck.

The question is what kind of dynamo it is. On Earth, convection drives the process. Heavy elements sink to the core and lighter ones float to the top. The movement creates a dynamo that generates the magnetic field.

Mercury is probably different, says Catherine Johnson, a planetary scientist at the University of British Columbia in Vancouver. One of the odd things about Mercury's magnetic field is its strength, or lack thereof. If a planet rotates above a certain critical rate and has a liquid layer inside it, a dynamo is pretty much inevitable. But Mercury's is a lot smaller than scientists expected.

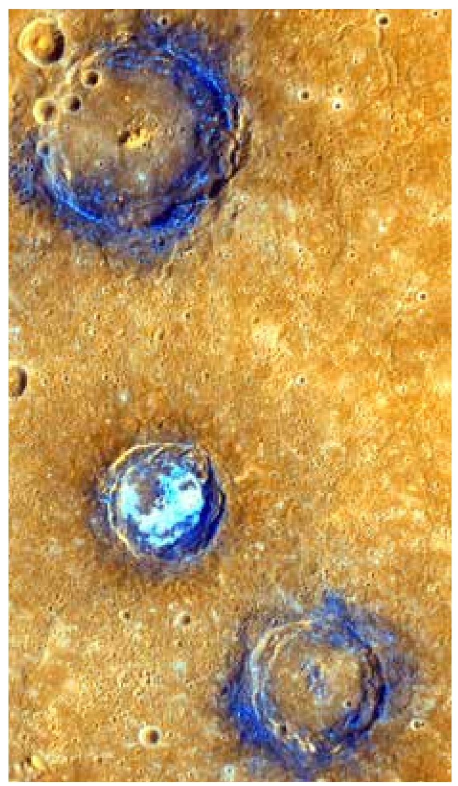
Johnson says there are several hypotheses to explain this, most centering on the fact that Mercury is less massive so its core exerts less pressure on the material inside it. That alters the way iron "freezes out" as the planet cools.

And Mercury clearly had a stronger magnetic field in the past, says Johnson. As MESSENGER made close passes to the surface before its final impact, it found magnetic anomalies in the crust — areas that had been magnetized previously. This means any field Mercury had needed to be strong enough to magnetize the rock and needed to last for 3 to 4 billion years.

MESSENGER could not pin down whether the magnetic field is symmetric around its axis. "The important thing about the measurements BepiColombo will be getting is not just verifying MESSENGER, but to see if there is smaller scale structure in the field — and can you see it over the southern hemisphere," says Johnson.

A STATIC FIELD

Mercury's magnetic field seems remarkably stable. Mariner 10 didn't get enough data to tell if the field's overall structure changed with time. Ordinarily, you would expect it to — Earth's field changes quickly enough that navigational charts must be updated every few years. Yet there was little evidence that Mercury's field structure changed at all. Although MESSENGER got more data, it might not have been able to see changes because the onboard instruments weren't sensitive enough, says Johnson. The reason: Mercury's internal field is only about four times stronger than the external one generated by the solar wind — 200 nanotesla compared with 50 nanotesla. So, on Mercury, changes in the external field can drown out signals from the internal one. That's not a problem on Earth, where the internal field registers 30,000 nanotesla and the external one just 10 nanotesla.



The large craters Poe, Sander, and Munch (top to bottom) lie in the northwestern part of the Caloris Basin. The impacts that created these features excavated darker material from beneath the surface, which appears blue in this enhanced-color mosaic.

"Separating these field contributions from these two sources is a very tricky problem," says Karl-Heinz Glassmeier, head of the Space Physics and Space Sensorics group at the Technical University of Braunschweig in Germany and principal investigator of BepiColombo's Mercury Magnetometer experiment. He adds that the relative strengths of the internal and external fields leave open the possibility that the external one affects the dynamo process, or at least has an outsized effect on the fields themselves.

Another consequence of the relatively small internal field is that events happen quickly, in mere seconds. This means that whenever MESSENGER took readings of the field during a solar flare, it didn't have enough time to get to a different location to measure what the effect might have been. In contrast, earthly magnetic events unfold over many minutes or even hours. With BepiColombo's two spacecraft, one can take measurements close to the planet's surface while the other does so farther out in the magnetosphere.

MESSENGER also studied Mercury's atmosphere. It contains atoms of sodium, calcium, and several other elements. On the side of the planet where the Sun is rising, calcium atoms appear in abundance, while on the dusk side there seem to be far fewer. Magnesium behaves similarly, though it's not as pronounced. Matthew Burger, a research associate at NASA's Goddard Space Flight Center, says the degree of asymmetry was unexpected based on observations from Earth. The amount of sodium atoms appears to stay relatively constant between the dawn and dusk hemispheres.

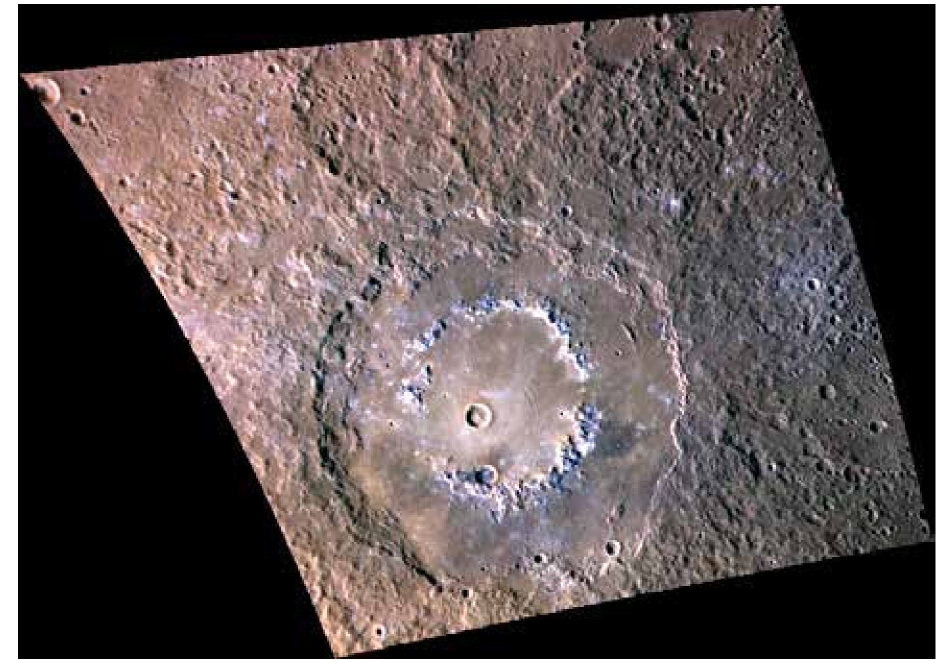
The mechanism driving the abundance of sodium might be impacts from tiny dust grains in that part of the solar system. But there's a mystery here, too. Sean Solomon of Columbia University's Lamont-Doherty Earth Observatory notes that Earth-based observations detected rapid changes in the amount of sodium in Mercury's atmosphere but MESSENGER didn't see the same thing. The difference might arise because of the way earthly telescopes view the innermost planet — from our home, you can't see all of Mercury. BepiColombo's consistent, whole-world coverage should help solve this problem.

A CHEMICAL MISFIT

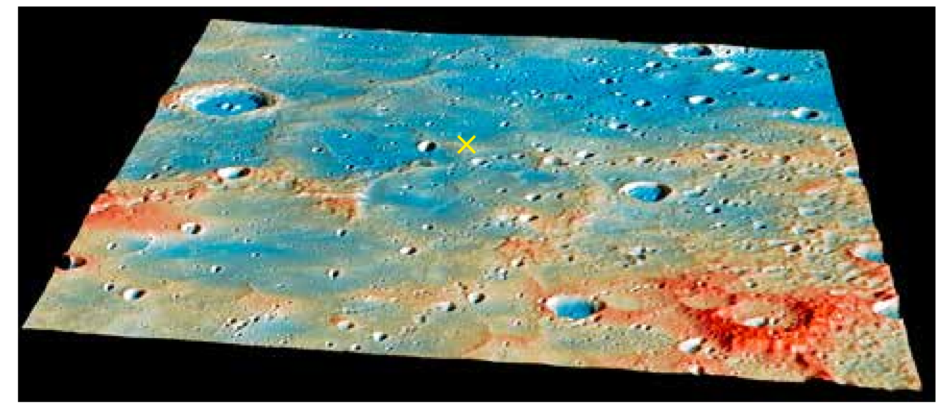
Which brings us to another weird thing about Mercury: Its chemistry is simply wrong. Before MESSENGER, planetary scientists knew the planet had a density second only to Earth, and it lagged behind our planet only because our greater mass compacts its material. Given the planet's proximity to the Sun and high temperature, most scientists anticipated that Mercury's surface would be rich in metals, with lots of compounds containing iron. There would be few volatile elements, those that vaporize at relatively low temperatures.

MESSENGER found the reverse. There are lots of volatiles on the surface and less iron than anyone expected. The abundance of iron in surface rocks hovers at around 2 percent. The amount of other metals also differs from the Moon and the other inner planets. For example, Mercury possesses more magnesium and less aluminum than Earth, the Moon, or Mars. Meanwhile, the planet's potassium and chlorine abundances are similar to volatile-rich Mars.

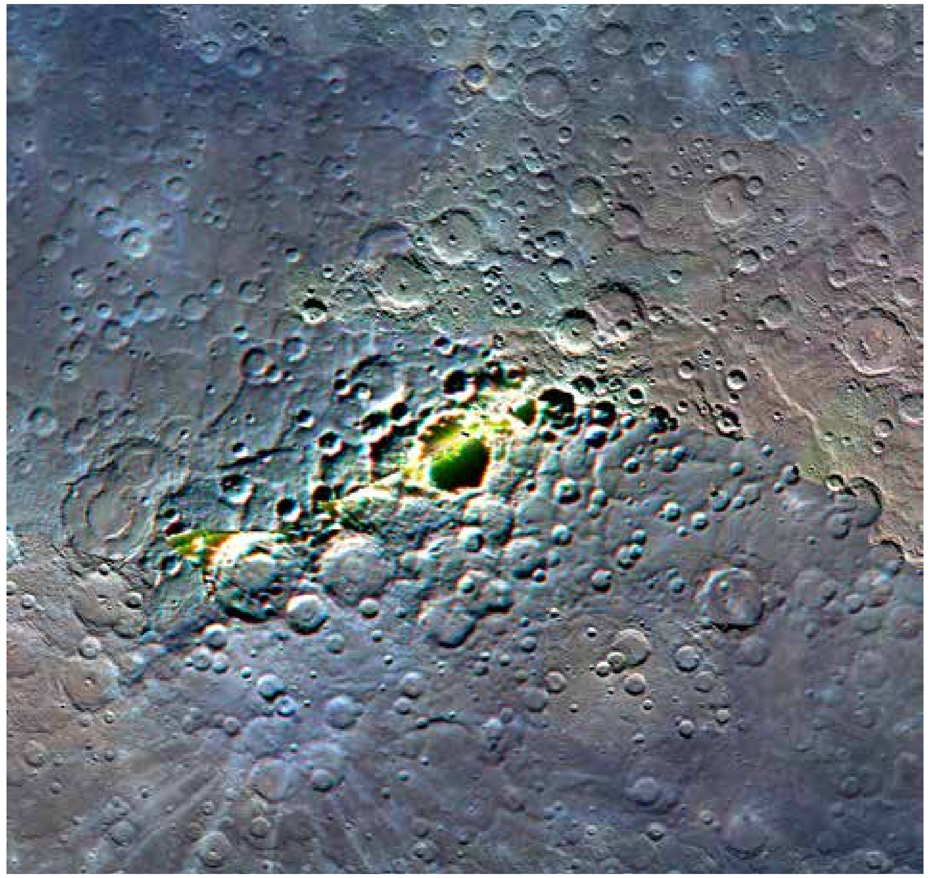
Most surprising, however, is the presence of sulfur. Sulfur turns to gas at



The two-ringed crater Raditladi stands out for the many bright hollows that line the peaks along the crater's inner ring. Scientists think hollows are features from Mercury's recent past, and that they likely are still forming today.



"X" marks the spot in Mercury's northern hemisphere where the MESSENGER spacecraft crashed April 30, 2015. The impact likely formed a crater 52 feet (16 meters) in diameter.



This enhanced-color view shows Mercury's south polar region. Ice likely lurks at the bottom of these permanently shadowed craters, where temperatures can plunge to –370° F (–223° C).

Mercury's temperature, so what existed there initially should have boiled away long ago. At the same time, there's almost no oxygen bound up in the surface rocks.

These elemental abundances fly in the face of the models planetary scientists worked with before MESSENGER. Previously, many researchers assumed that Mercury was a planet whose mantle got stripped off by a giant impact. It was the most logical way, it seemed, to explain why the planet has a core that starts a mere 250 miles (400km) below the surface. In such an impact, Mercury would have lost most of its volatile substances.

MESSENGER also found regions with unique geochemical compositions, called "terranes." The spacecraft's spectrometers mapped the elemental abundances at Mercury's surface. They found a magnesium-rich area in the northern part of the planet and an aluminum-rich region in the southern hemisphere as well as one in the area around the giant Caloris Basin. Earth's Moon has areas where the surface composition differs dramatically from the average, such as in the maria. But on Mercury, the terranes don't always seem to match up with visible surface features.

Shoshana Weider of the Carnegie Institution for Science in Washington, D.C., says that it's possible the magnesium-rich region is an ancient impact crater, a spot hit so forcefully that the crust cracked and mantle material bubbled up. Just as important to the process could be the mantle itself. Some researchers think it could be heterogeneous, unlike Earth's mantle, because it is relatively thin. "Even on Earth, you have places that are different," says Weider. Mercury's thin mantle would be even more likely to have spots that differed from others. The composition of the terranes also would depend on the amount of heating and cooling the mantle experienced.

Because MESSENGER couldn't achieve the same resolution in the southern hemisphere, however, BepiColombo will play an important role. The upcoming mission will be able to see the chemical "map" of both north and south with equal accuracy.

That two-hemisphere precision also can address the question of the surface distribution of volatiles. MESSENGER picked up high concentrations of volatiles near the north pole — most famously in its discovery of water ice in permanently shadowed craters. Since BepiColombo will look at both hemispheres, it should be able to tell if the distribution comes from thermal processes. Volatiles heat up near the equator, especially at so-called hot poles where the Sun stays directly overhead for longer periods. They then get deposited in cooler polar regions. "We'd expect a symmetrical distribution," says Weider. "That would be a nice answer."

Another notable feature MESSENGER revealed is that Mercury's surface appears dark. On the Moon, dark areas often contain lots of iron-bearing compounds, which undergo space weathering — the gradual darkening of the surface as micrometeorites and solar wind particles bombard it. Other compounds, such as those containing titanium, also darken under the onslaught. But Mercury doesn't have much iron or titanium in its crust and soil, so there must be another answer.

Carbon could be one solution, and models indicate that the early Mercury might have had a carbon-rich outer layer. One scenario suggests that the molten rock covering the young Mercury was less dense than the otherwise similar magma that existed on the early Moon and Earth because it contained much less iron in the material that eventually formed the mantle and crust. As a result, only the low-density carbon compound graphite would be light enough to float on it and make a crust.

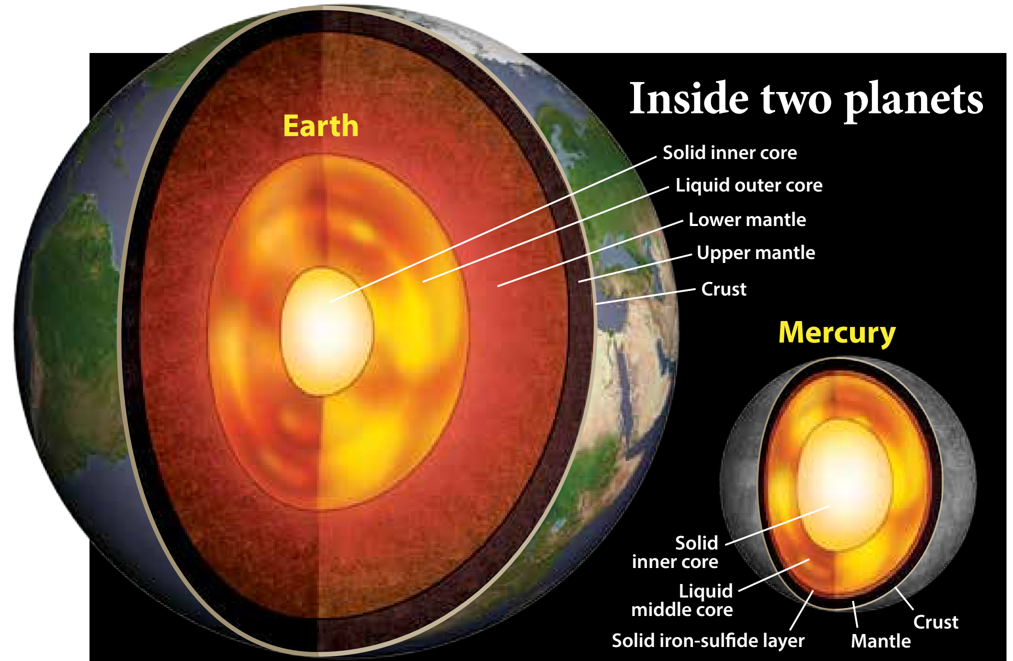
NOT-SO-SLEEPY HOLLOWS

But perhaps the most surprising MESSENGER discovery are hollows — features akin to sinkholes that have sharp edges but were not formed by impacts. No similar structures have yet been found elsewhere in the solar system. MESSENGER scientist David Blewitt of Johns Hopkins University notes that the hollows are extremely young and probably still actively forming. "The big surprise was that there was some sort of modification of the surface," he says. The hollows likely form when volatile elements sublimate. The surrounding soil can't hold the structure and it caves in.

A field of bright hollows lurks in the western portion of the Zeami impact basin. Although an individual hollow may be only a few hundred feet across, fields like this can extend for several miles. Even bigger populations of these enigmatic features exist in the northern and northeastern parts of Zeami.

Scientists want to know exactly what is sublimating. "There's some component that is unstable at the surface," says Blewitt. "Between solar heating and space weathering, you have these fresh-appearing features." While the culprit is likely some volatile-bearing compound, MESSENGER wasn't able to determine which one.

BepiColombo will be able to explore these questions with a wider range of spectroscopic instruments. The MPO will carry both an infrared and X-ray spectrometer. The first measures the amount of radiation at specific infrared wavelengths to see which elements are present. The second uses fluorescence, the same process that causes a black-light poster to glow when illuminated by ultraviolet light, to measure X-rays given off by various elements at the planet's surface when they are exposed to solar X-rays. Because the orbiter will be able to examine both hemispheres close-up, these maps will be more complete. MESSENGER couldn't match the magnesium-rich area in the north to a geological feature, but BepiColombo might be able to find other elements that do correspond and determine, for example, what makes Mercury dark.



The interiors of Mercury and Earth are quite different. Mercury's gigantic core starts just 250 miles (400 kilometers) below the surface, and it has a relatively thin crust and mantle. A majority of Earth's volume resides in its mantle. The liquid parts of the cores of both planets help generate their magnetic fields. *ASTRONOMY: ROEN KELLY*

Scientists designed the infrared spectrometer on the assumption that iron would be abundant, says Rothery, and it is tuned to a narrow range of wavelengths near iron's signature. But the lack of iron turned up by MESSENGER might be a blessing — a number of other elements radiate at nearby wavelengths. The absence of a strong iron signal will make it easier to detect minerals such as plagioclase, which forms much of the lunar highlands. That would reveal a lot about Mercury's early crust because it will tell scientists what was floating on the top of the magma ocean early in the planet's history.

A GIANT IMPACT?

In the face of Mercury's strange geology, some planetary scientists have proposed ideas for the planet's origin that don't require a giant impact. Erik Asphaug of Arizona State University in Tempe hypothesizes that Mercury itself is a "hit-and-run" impactor. If that's the case, the planet could have held on to its core and lost a lot of mantle material while still retaining volatile compounds.

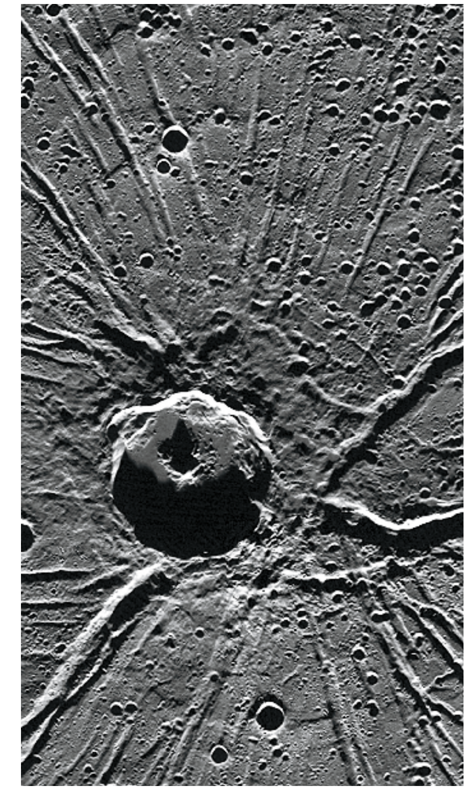
"The main problem for Mercury wasn't the volatiles, but the problem of getting rid of all that mantle rock after the giant impact," he says. "Modelers had made valiant attempts, but nothing worked."

Ordinarily, you might expect the volatiles to disappear in that kind of impact — if you're looking at the target body. Asphaug imagines a situation where Mercury and Venus hit each other and then, on further passes, the two bodies compete for the now-stripped mantle material. In this scenario, Venus would win out, leaving Mercury with a crust, a thin mantle, and a large core.

He notes that the simulations he has run didn't need to involve wildly improbable collisions or configurations. Most had about a one-in-ten chance of occurring. While that doesn't sound like much, in the context of an early solar system with lots of large bodies flying around, it can work.

"Mercury surviving after a couple of hit and runs turns out to be exactly the luck you expect when you start with 20 Mars-like planets to accrete Venus and Earth, and have two unaccreted survivors [Mars and Mercury]. The other kind of one-in-ten luck is to be left alone, which Mars was," he says.

Solomon likes this idea. "I think he's on the right track — it's not too big a stretch of the imagination."



The aptly named "spider" lurks near the center of the mammoth Caloris impact basin. It comprises the sharp-rimmed crater Apollodorus surrounded by the radiating channels of Pantheon Fossae. Despite the proximity of the crater and troughs, scientists don't think their formation is at all related.

New missions aim to untangle the mysteries of how the planet's scorching surface and violent clouds came to be. **by Jesse Emspak**

VENUS REVISITED

THE FIRST SPACECRAFT TO PULL into Venus' orbit in nearly a decade arrived in December 2015, hailing from Japan. Akatsuki was five years late for its rendezvous, but Venus has gotten used to waiting. The European Space Agency's (ESA) Venus Express visited the thickly shrouded world in April 2006, and that was the first mission to Venus since NASA's Magellan arrived in 1990. Named for the Roman goddess of love, Venus wasn't feeling much of that from space agencies on Earth. Our planet's more favored neighbor, Mars, had hosted roughly a dozen visitors in the same period.

"Venus exploration is behind schedule," says David Grinspoon, senior scientist at the Planetary Science Institute in Washington, D.C., and author of the book *Venus Revealed*. "Our understanding of Venus is about the same as it was with Mars in the 1970s."

Some planetary scientists are trying to change that. For years, Venus lost out to Mars because of the tantalizing possibility of finding life on the Red Planet. Yet in some respects, Venus is more similar to Earth than Mars is, and our inner neighbor might have much to tell us about our past, our future, and even current exoplanets.

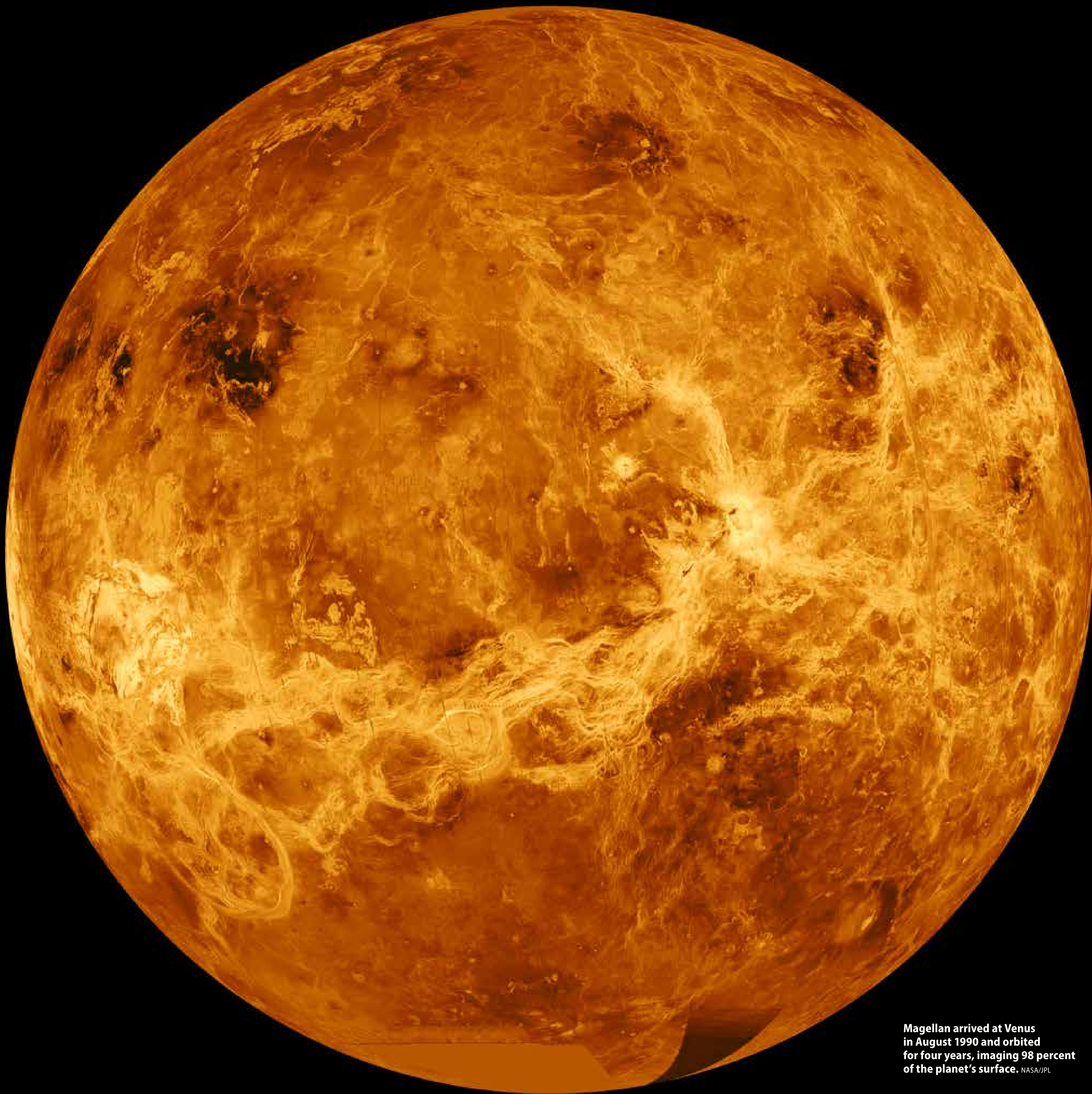
Venus wasn't always so unloved. From 1960 to 1984, more than 20 spacecraft investigated Venus — nearly as many as Mars up to that point. The USSR's Venera and Vega programs resulted in no less than 18 orbiters and landers (though not all missions were successful), and the U.S. added five spacecraft.

Two new NASA missions to Venus are in advanced planning stages, with their fates to be decided this year. Both ESA and the Russian Space Agency have designs on the drawing board. And of course, there's the current science from Akatsuki finally streaming to Earth. All in all, things are looking up for Venus exploration, and upcoming missions — mostly orbiters but some with plans for landers or craft that will dive into the atmosphere — could answer fundamental questions that planetary scientists still have about Venus, and provide hard evidence to nail down their current theories.

The twin paradox

Venus is often referred to as Earth's twin for a reason: The two planets' most basic physical properties are nearly identical. "If we found Venus around a sunlike star,

Jesse Emspak *is a science writer who lives in New York.*



Magellan arrived at Venus in August 1990 and orbited for four years, imaging 98 percent of the planet's surface. NASA/JPL

▲ **The VERITAS spacecraft, if selected by NASA for approval, would fly in the early 2020s. Like the previous Magellan mission, VERITAS would orbit Venus, but it would study the planet in much greater detail.** NASA/JPL-CALTECH

► **The proposed DAVINCI spacecraft would parachute to Venus' surface, taking data during an hourlong descent.** NASA/GSFC

[astronomers would] be jumping up and down saying we found another Earth," says Colin Wilson, deputy project scientist on Venus Express.

How similar are they? Venus has a radius of 3,760 miles (6,050 kilometers), and Earth's radius is 3,960 miles (6,370km). Venus' mass is 82 percent that of Earth, and its surface gravity is 91 percent of the terrestrial norm. The two planets' densities are also almost identical. That means their bulk composition should be about the same, especially since both planets formed in the same region of the solar nebula. Their evolution also should have been similar.

But thanks to subtle differences, that didn't happen. Present-day Earth has liquid water and an atmosphere dominated by nitrogen and oxygen. Argon accounts for nearly 1 percent, but carbon dioxide and other gases exist only in trace amounts. The Venus of today is covered by a dense atmosphere — 90 times more massive than Earth's — consisting of 97 percent carbon dioxide, with the rest as nitrogen and trace gases. Carbon dioxide is a powerful greenhouse gas that keeps Venus' surface temperature at an average of 864° F (462° C). A visitor to Venus could pour a glass of liquid zinc or lead.

Unlike Earth, Venus' surface is invisible from above — at least in visible light. It's covered with highly reflective sulfuric acid clouds that never break. On Venus, the Sun is a diffuse splotch of brightness, appearing as it does on an overcast day on Earth. That bright patch takes 117 Earth-days to cross the sky. Venus takes 243 Earth-days to make a complete rotation — longer than the planet's year, which is 225 Earth-days. The daylight period is shortened slightly because the planet has a retrograde rotation — the Sun rises in the west. The slow rotation also means Venus lacks a magnetic field of any significance.

When it rains on Venus, the droplets evaporate before they reach the ground. Besides a forecast of "cloudy with a chance of sulfuric acid rain," there doesn't seem to be much in the way of weather at ground level. Surface pressures are so high — 90-plus atmospheres — that it's like being underneath more than half a mile (900m) of ocean, and the carbon dioxide there begins to behave as a supercritical fluid, a strange hybrid of liquid and gas.

Previous missions found that Venus' terrain is as varied as Earth's. Highland regions called tesserae consist of ridges and folds in the crust that extend for miles and form tile-like patterns. The lowlands seem to be basalts, cut with what might be lava channels. Some mountains appear peaked with a kind of metallic "frost," and even features that look like dune fields exist. Some areas have coronae — pancake-like structures that can spread over 100 miles (160km).

Venus also is bone-dry. If the planet did form with similar amounts of water as Earth, as seems likely, it's clear that water isn't there anymore.

How did Venus become a toxic hellscape while Earth stayed relatively cool? The prevailing model is that Venus' water turned into vapor as the Sun, which was much dimmer billions of years ago, brightened and warmed the planet. While there's some debate as to whether Venus ever shared Earth's vast oceans, it seems likely the planet was cool enough for substantial liquid water in its early days. But as the temperature climbed, any water evaporated, and once it reached the upper atmosphere, the Sun's ultraviolet light broke apart water (H_2O), and it quickly reformed into hydrogen (H_2), hydroxide (OH), and oxygen (O_2). Much of the oxygen stayed aloft because it is less dense than carbon dioxide, but some descended and reacted with surface rocks. Absent any biology to take the carbon dioxide out of the air and replace it with oxygen, as on Earth, the water and carbon dioxide — powerful heat-trapping gases — caused a runaway greenhouse effect.

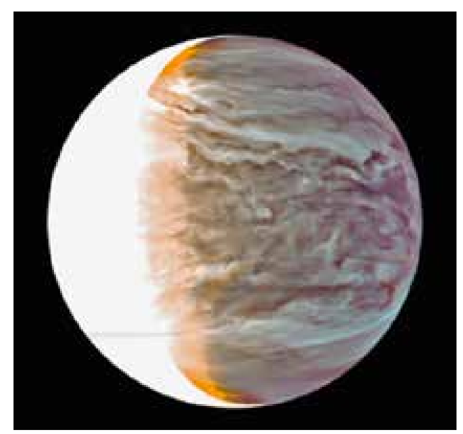
The situation wasn't helped by the planet's slow rotation. On Earth, our relatively rapid spin creates a dynamo effect in our planet's iron core. This in turn generates a magnetic field that protects our home world from the solar wind, the stream of energetic particles the Sun flings in all directions. As the wind whipped by unprotected Venus, it stripped the hydrogen from the atmosphere, leaving fewer ingredients for the planet to have any hope of reforming its water, even if conditions were to miraculously become more temperate.

Yet the data from Venus Express and the Magellan probe don't seem to tell the whole story — and that's where the new missions come in.

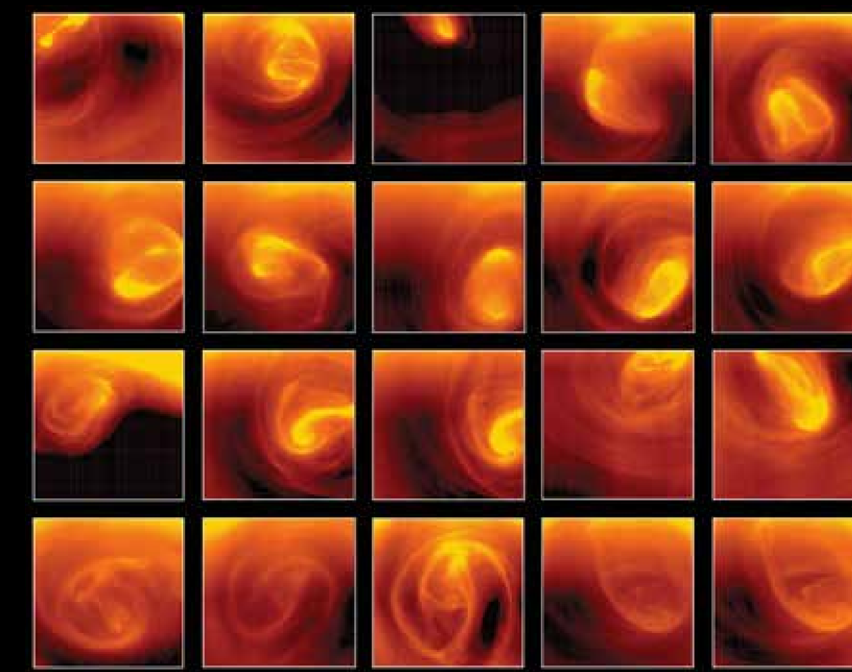
Many mission options

NASA is considering two missions this year. The Deep Atmosphere Venus Investigation of Noble gases, Chemistry, and Imaging (DAVINCI) will focus on atmospheric chemistry. It involves an atmospheric probe — "Huygens for Venus," quips Lori Glaze, a scientist at NASA's Goddard Space Flight Center and the mission's principal investigator — that will measure the atmosphere's makeup at different layers during an hourlong descent to the venusian surface.

"It doesn't need to survive hitting the surface," Glaze says. She notes that the Pioneer Venus and Vega missions looked at the atmosphere, but they couldn't give scientists a good handle on the composition with respect to altitude, and that's what's needed to understand the kinds of reactions that occur in Venus' cloudy skies.



The Akatsuki space probe, launched by Japan's space agency, entered venusian orbit in December 2015. By March, the spacecraft was sending images back to Earth from its infrared cameras, and in April it officially assumed full science observations. This image shows Venus' night side from one of Akatsuki's two near-infrared cameras. JAXA



The Venus Express mission imaged clouds swirling above Venus' south pole at dizzying speeds. The high-altitude clouds, like those seen here, can travel 60 times faster than the planet rotates, contributing to the polar vortex Venus Express studied in detail during its eight-year stay. ESA/VIRTIS-VENUS EXPRESS/INAF-IAPS/LESIA-OBS. PARIS/G. PICCIONI

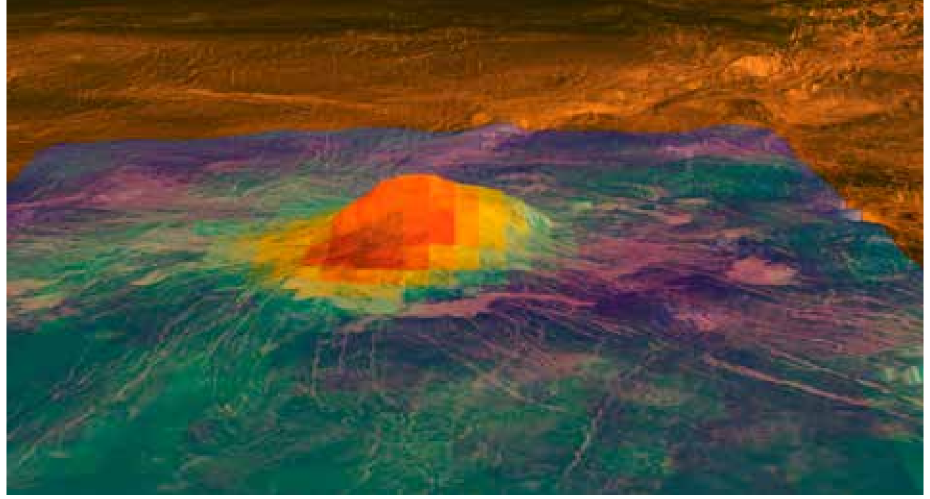
NASA's other option is the Venus Emissivity, Radio Science, InSAR, Topography, and Spectroscopy (VERITAS) mission. The VERITAS orbiter would operate similar to Magellan, but the big difference would be that its radars will have much better resolution, able to spot features as small as about 100 feet (30m) across compared with Magellan's more than 300 feet (100m). It also will measure the planet's gravity and how the surface emits heat, which means it can see "inside" some geological formations and discover, for example, whether the coronae are filled with magma. VERITAS also will be able to measure how the composition of surface rocks differs.

"We'll be looking for surface mineralogy variations," says Suzanne Smrekar of the Jet Propulsion Laboratory, the principal investigator on VERITAS. "We're trying to understand chemical variation, if there are continents like on Earth, active volcanism … also to see if there are tectonic features, and to try to understand thermal evolution — temperature variations in the lithosphere." NASA will decide in September 2016 whether DAVINCI, VERITAS, or both will fly.

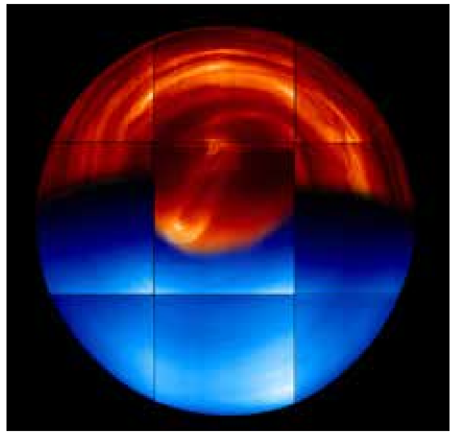
From ESA, there's EnVision, an orbiter also equipped with advanced radar, and it likely won't launch until 2029, says Richard Ghail, a lecturer in engineering geology at Imperial College London, who proposed the mission. Aside from a more advanced set of radars than Magellan, EnVision will be able to "spotlight" small areas to image them in greater detail. "Instead of 100-meter [300 feet] resolution, we can get down to 6 meters [20 feet]," Ghail says. That is enough to see day-to-day changes on the surface. Spotlighting can get that resolution down to 10 feet (3m).

While there is some overlap with a craft like VERITAS, Ghail says having the VERITAS mission go actually would free up EnVision to do more spotlighting of specific areas and less global-scale mapping, since VERITAS will have accomplished that already.

The Russian proposal is called Venera D. This spacecraft would bear some resemblance to the Vega missions because it involves a combined orbiter and lander. It might even include a balloon probe, also like the Vega missions. Like many missions before it, Venera D would focus on Venus' atmosphere and investigate the origins of the planet's unusual atmospheric rotation



Venus' Idunn Mons is likely an active volcano, with infrared imaging revealing hot spots along the peak's summit and cascading over the side in flows. ESA/NASA/JPL



Venus Express' cameras sent back many views of Venus, revealing different layers of the planet's clouds. Here, the spacecraft imaged the night side in infrared (upper, red layer), showing clouds lower in the atmosphere, about 28 miles (45 kilometers) in altitude. Clouds closer to 40 miles (60km) appear in ultraviolet imaging (lower, blue) on the planet's day side. ESA/VIRTIS-VENUSX IASF-INAF, OBSERVATOIRE DE PARIS (R. HUESO, UNIV. BILBAO)

as well as its chemistry. The lander would allow for soil analysis, provided it survives long enough. The longest any lander has lasted on Venus was barely two hours — a record held by the Soviet Venera 13 mission, so history is on Russia's side. The Russian Space Agency hasn't made any firm commitments to the mission, but if it did, it would be the first post-Soviet planetary mission of its kind. Launch wouldn't happen any earlier than 2024.

Venus now

Current Venus research is already on a delayed schedule. Japan's Akatsuki probe was supposed to arrive at Venus in 2010, but it missed its orbital insertion. Instead, it took a cruise around the Sun for five years until engineers could steer it into an alternate orbit, more elliptical than originally planned. Recovering the spacecraft at all was a major achievement. Akatsuki currently orbits Venus in a 13-day ellipse that takes it from closest approach at 260 miles (400km) out to 273,000 miles (440,000km). Sanjay Limaye, senior scientist at the Space Science and Engineering Center of the University of Wisconsin-Madison, says science goals actually will be enhanced by the improved orbit, which allows for longer periods of observation as Akatsuki swings out to its farthest position.

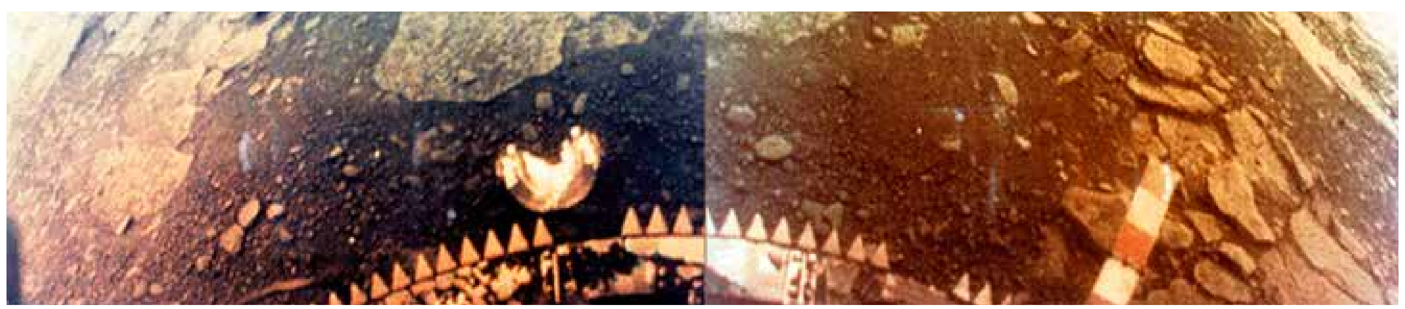
Two of Akatsuki's cameras work in the near-infrared and study the planet's surface, the motion of clouds, and the particles that comprise them. A long-wave infrared camera tracks the temperatures at the cloud tops, about 40 miles (65km) above the planet's surface. The other two instruments are an ultraviolet imager and a lightning and airglow camera. Venus Express showed tantalizing glimpses of what might have been lightning in Venus' clouds, so Akatsuki will try to clinch those observations.

One of the problems Akatsuki will study is the "superrotation" of the atmosphere. Venus' atmosphere zooms around the planet at hundreds of kilometers per hour in the upper regions. That's not unusual — other planets show the same thing from time to time. But why the superrotation should be orders of magnitude faster than the planet's rotation is unexplained. "We cannot yet accurately model superrotation numerically," Limaye says. Akatsuki can help tackle this question by creating a better picture of how the upper atmosphere differs from the lower and how the two interact.

A smoking gun for volcanism

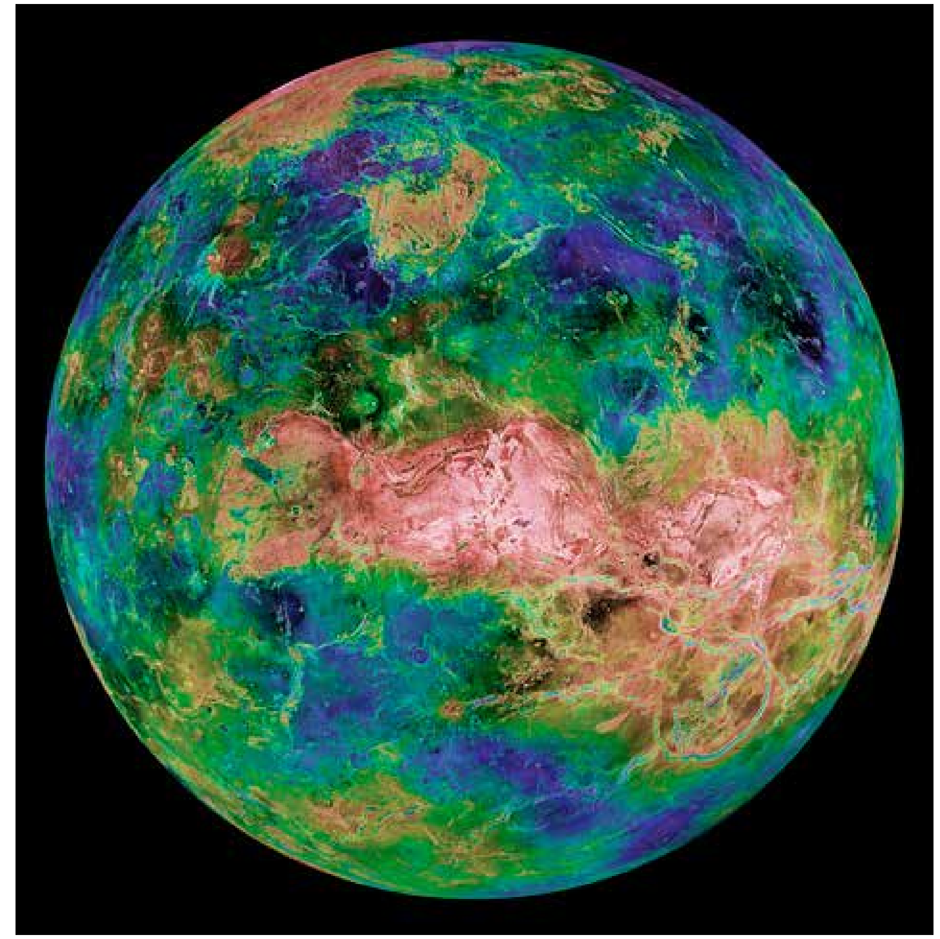
Venus Express and Pioneer Venus both found sulfur compounds — primarily sulfur dioxide, which must continually enter the atmosphere somehow in order to be observed, because sunlight breaks it up fairly quickly. "That provides pretty good evidence that Venus is volcanically active," Grinspoon says. "There's a lot of sulfur dioxide in the atmosphere, and that sulfur would not stay without a source." Volcanism on the surface would do it. But Venus Express hasn't provided the smoking gun, as it were. "We see a lot of volcanoes, but we don't know if they are still active," Grinspoon adds.

There are three strong lines of evidence of active volcanoes on Venus, Wilson says. First is the way the detected sulfur behaves. In the first year of Venus Express' observations, sulfur levels spiked and then decreased tenfold over five to six years. That points to a source that "burped" sulfur, as volcanoes do. A second clue is the infrared surface emission. Darker surfaces emit more heat as infrared radiation (think about asphalt on a hot day), and fresh unweathered basalts — such as from recently spewed and hardened volcanic material — are dark. Venus Express' cameras also caught some changes in surface temperature that looked like signs of recent lava flows. Finally, images from Magellan's radar maps show features that look pretty clearly like volcanoes, and even lava.



Venera 13 survived on Venus for 2 hours, 7 minutes, and took this picture of the venusian surface (and parts of itself) on March 1, 1982. The Vega missions in June 1985 also deployed landers, but Vega 1's instruments activated while it was still 12 miles (20km) above the surface, so it returned only limited data. Vega 2 successfully transmitted data from the surface, but lasted only 56 minutes. NASA HISTORY OFFICE

Venus Express captured this image of clouds in 2011, five years into its planned two-year investigation. It finally plunged to its end in 2014, after five mission extensions. ESA/MPS/DLR/IDA



Researchers constructed this elevation map of Venus using mosaicked data from Magellan. Blue represents lower elevations and red higher elevations. NASA/JPL/USGS

But none of these is absolute proof, Glaze says. What's needed is a picture from one day to the next, or one week to the next, showing the changes in topography. That could show that volcanoes are active today, as opposed to in the distant past.

Volcanic activity is a big piece of the overall Venus puzzle because it offers a way to resurface the planet periodically. Previous imaging missions showed Venus doesn't have many impact craters. Assuming the craters are randomly distributed, that means something made older ones disappear — the surface is getting rebuilt every so often, perhaps as little as every couple of hundred million years or as much as 750 million to 800 million years. And given that the craters are on average hundreds of miles apart, whatever is resurfacing the planet also must exist in the same well-distributed pattern, Ghail says.

If there are active volcanoes — and Ghail thinks there are — then this resurfacing is a constant, steady process. But if volcanoes aren't currently active, then the resurfacing is likely to be something big and sudden, covering huge chunks of the planet. VERITAS and EnVision could go a long way toward providing a clear answer.

Where's the water?

The other big question mark is water. Venus Express' atmospheric analyses showed the ratio of deuterium (hydrogen that carries an extra neutron) to ordinary hydrogen is quite large, and that hydroxide is in the atmosphere. Ordinary hydrogen is lighter than deuterium, and a high ratio of deuterium should mean the primordial hydrogen was stripped away somehow, probably by the solar wind. The hydroxide is a product of the dissociation, or chemical breakup, of water by ultraviolet light. But Venus surprised the scientists. "We'd expect it to lose water faster," says Wilson. "But the escape rate is less than on Earth. That came as a surprise." Further atmospheric and geological studies might shed some light on this by narrowing down the rate of outgassing water from the surface, for example.

Speaking of water, geological tests by VERITAS can help scientists understand better how much water Venus has now. Such tests also could reveal if Venus once had something like plate tectonics or formed a surface resembling that of early Earth. By looking closely at what kind of rock makes up some of the higher-altitude terrain, such as the tesserae, it will be possible to see if it is made of crust that looks like continents on Earth. "That is critical to answering the question," Smrekar says. "What you're measuring is surface temperature in relation to the composition of rock. Basalt is a dark rock, granite is a light rock, and they have different temperatures as a function of altitude."

To make granite, you need water. "If you don't have water, you end up with things that approach granite but never get that far," Ghail notes. Finding granite, therefore, would mean Venus once had oceans — or at least enough water to allow for the reactions that make granite.

Ghail says the way the higher terrain looks — such as Aphrodite, Lakshmi, and Ishtar Terra — is tantalizing. "Aphrodite looks like ancient, heavily formed continental-like material," he says. Furthermore, these regions seem to cover about the same area that geologists think was covered by continental crusts on Earth soon after it formed and the first oceans filled up.

Knowing what Venus was like in the distant past will offer a lot of insight into why Earth's twin grew up so different from its temperate sister. "Venus, in my mind, is an incredibly rich place to learn about Earth," Glaze says. "The planets are so similar — how did biology form here and not there?"