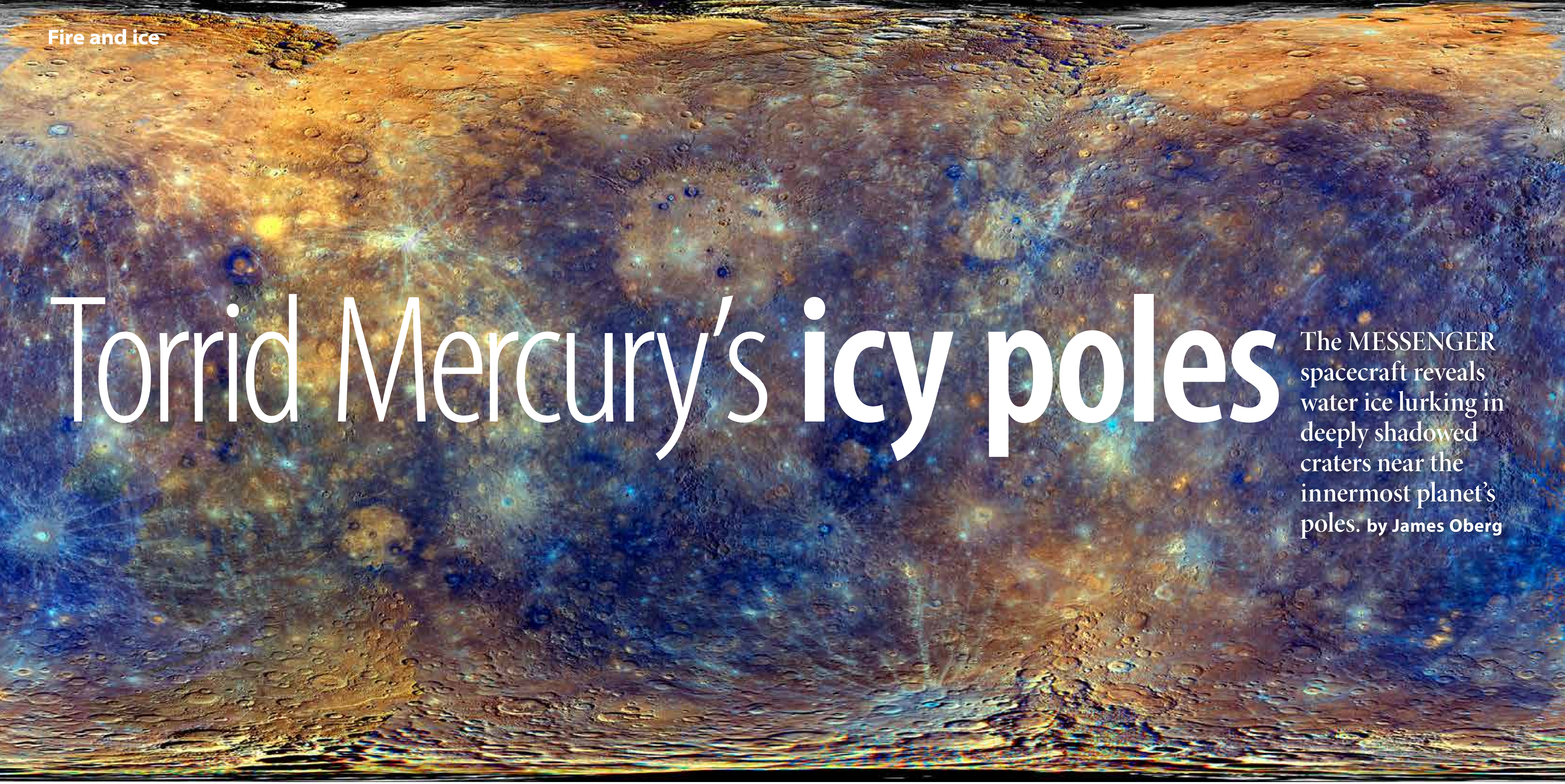


Torrid Mercury's **icy poles**

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.

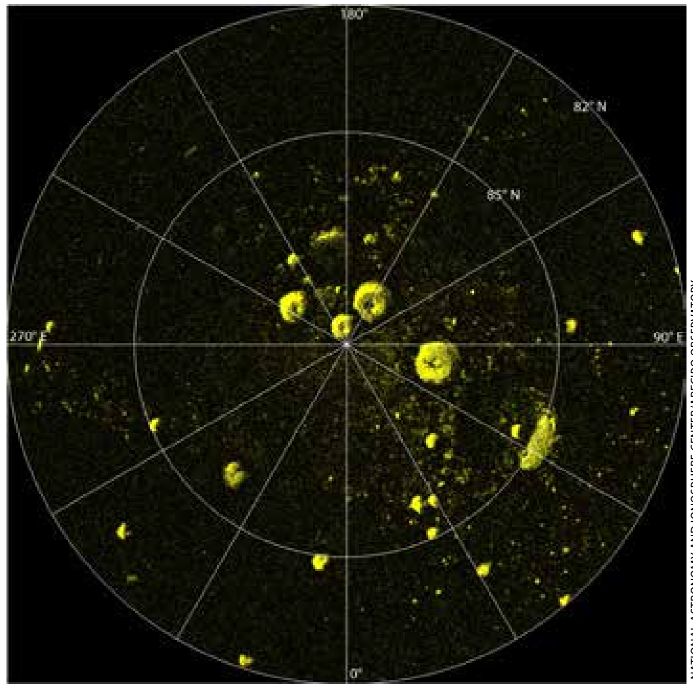
Scientists had suspected for decades that water ice might survive in corners of the solar system's innermost world. Theorists realized that cold regions could exist in certain areas, and observers seemingly backed up these theoretical computations.

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."

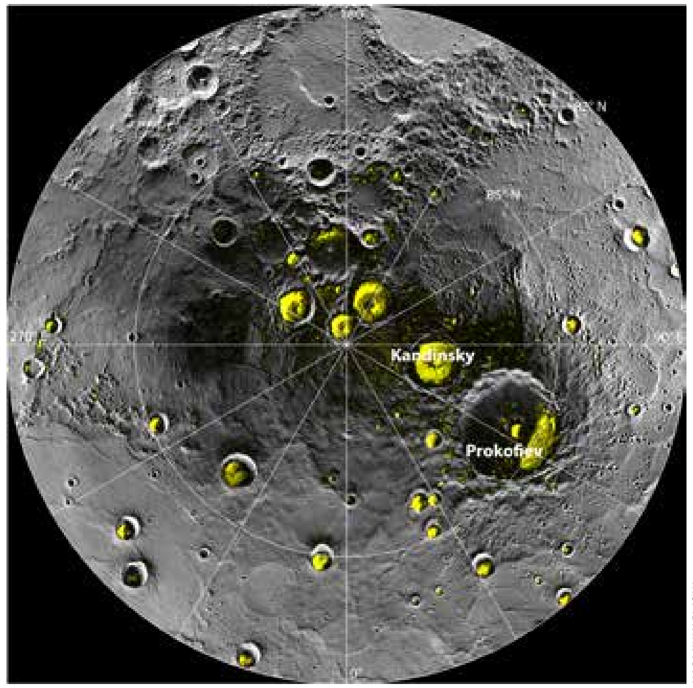
During the past several decades, scientists have come to realize that a conspiracy of freak accidents involving Mercury's motion and orientation had created small regions on the planet's surface where it ought to be cold enough for ice to form and survive for billions of years. Unfortunately, instruments 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



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. NATIONAL ASTRONOMY AND IONOSPHERE CENTER/ARECIBO OBSERVATORY



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. NASA/JHUAPL/CIW

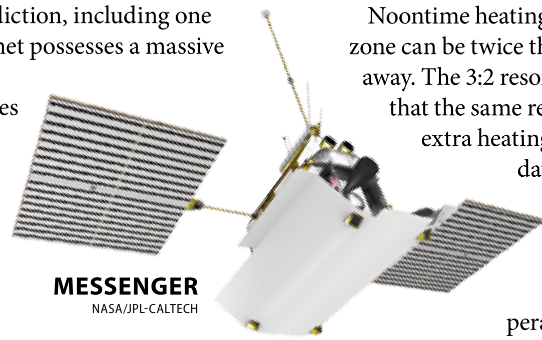
star's glare. The best observing conditions occur when it lies near one of its greatest elongations, which create brief periods when the planet climbs well above our earthly horizon and appears approximately half-lit.

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.

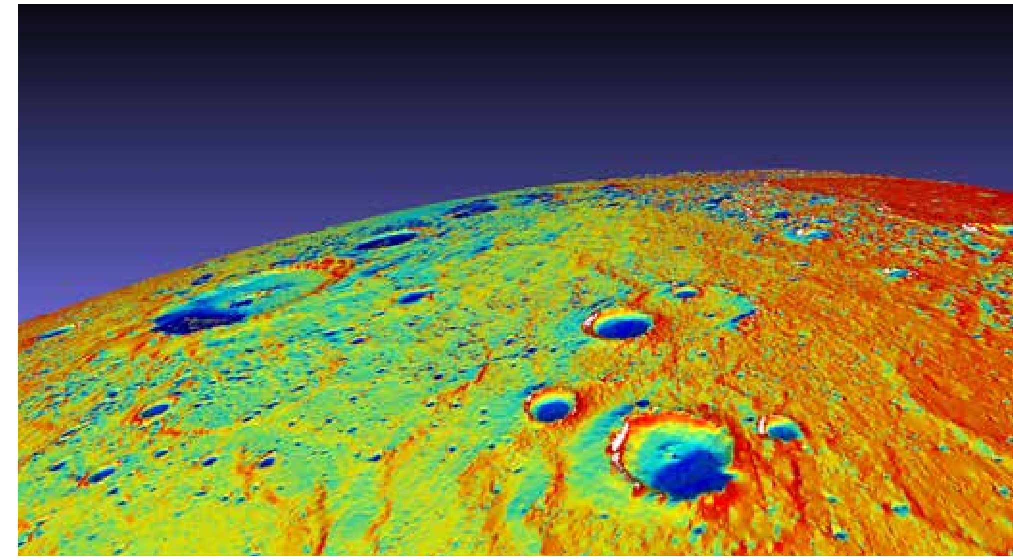
Photographs taken during the three Mariner 10 flybys in the mid-1970s showed that, in some cases, the high-return regions seemed to coincide with deep polar craters. Although water ice seemed the most likely cause, theorists developed several even more exotic explanations, including sulfur snow, sodium 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

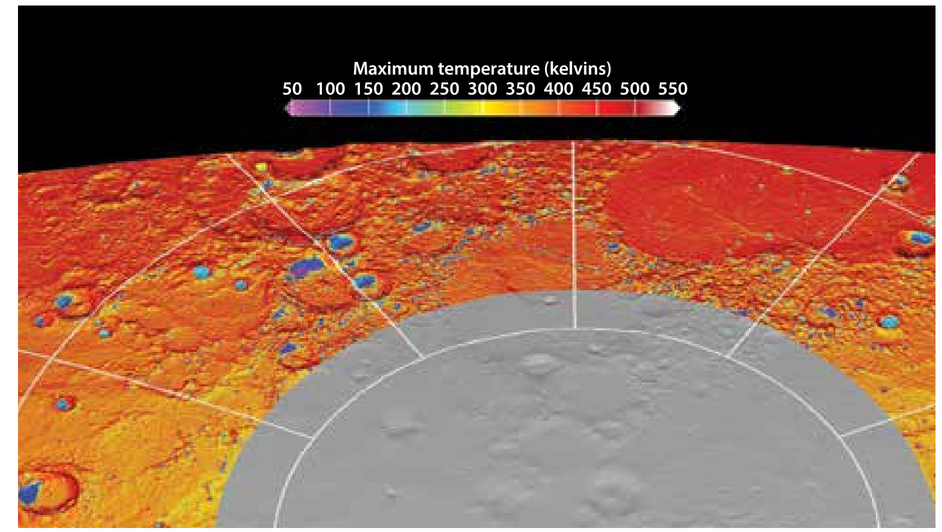
Into this uncertainty and mystery, NASA launched the MESSENGER probe in 2004. It was a challenge to get a spacecraft to Mercury with a speed slow enough that the biggest propulsion module possible could decelerate the craft into a stable orbit. After a seven-year voyage that included three flybys of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

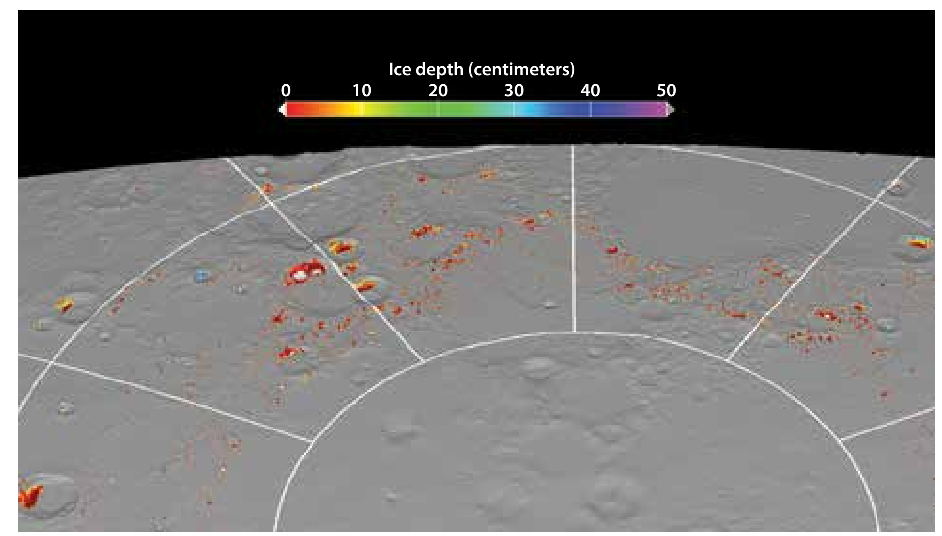
MESSENGER Principal Investigator Sean Solomon, director of Columbia University's Lamont-Doherty Earth Observatory, described how the science team painstakingly developed its case for ice at the poles. First, the researchers tested the hypothesis that the areas where scientists



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

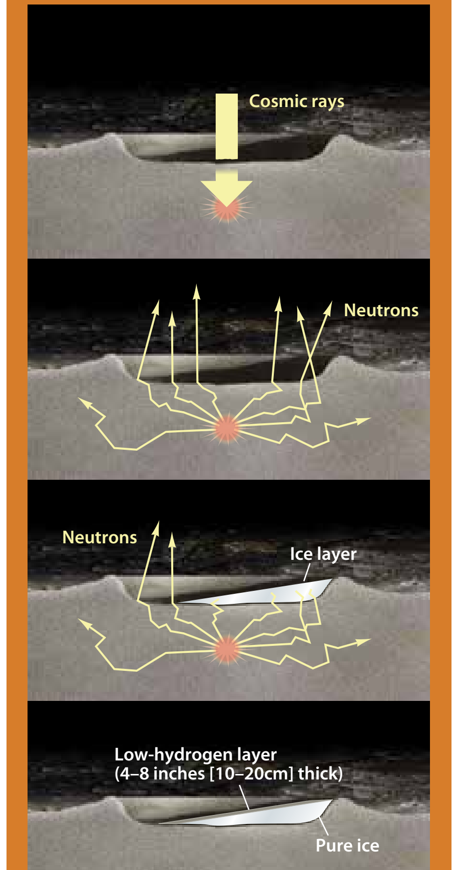


The highest temperature observed over two Mercury years gives a better idea of where ice can survive. The coldest spots in permanently shadowed craters only reached –370° Fahrenheit (50 kelvins). NASA/UCLA/JHUAPL/CIW



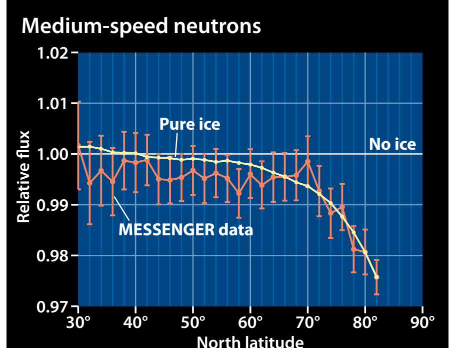
This map of "permafrost" shows the same area as above and indicates the depths below Mercury's surface where water ice should be stable. Gray denotes regions that are too warm for any ice, color reveals areas where subsurface ice can exist, and white shows spots cold enough for surface ice. NASA/UCLA/JHUAPL/CIW

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.

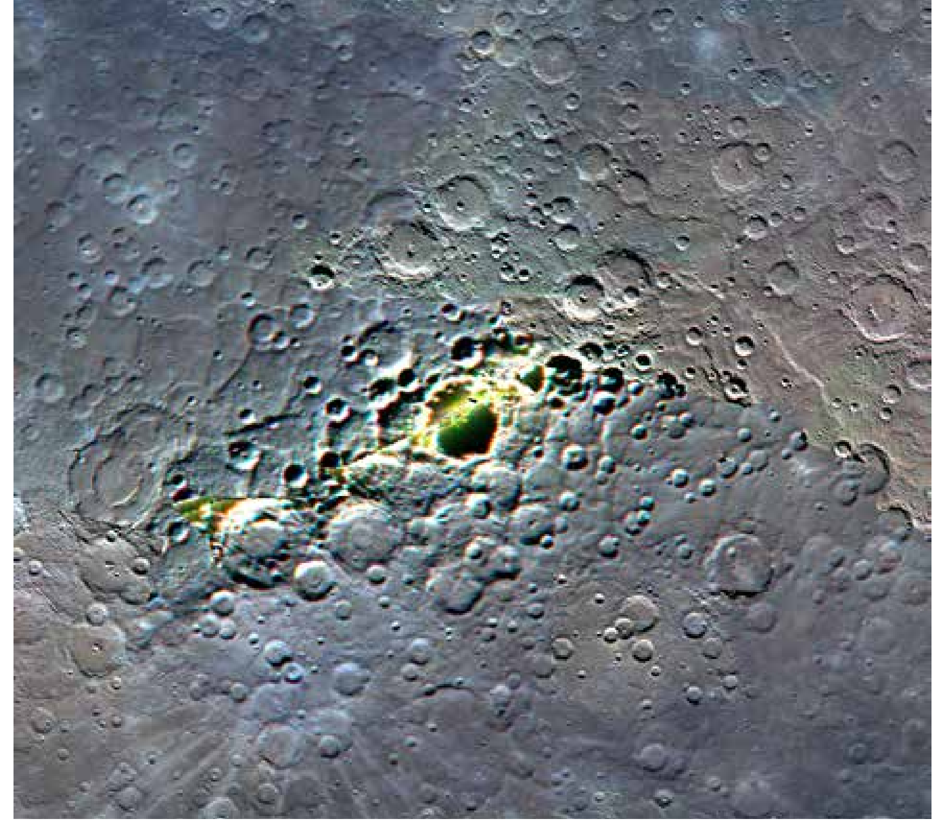
But closer to both the north and south poles, the temperatures drop even lower. In these regions, ice can remain stable without any protection. The water ice is pure, and it is naked to space. "We had expected to find evidence of ice, but bright ice on the surface and right where the thermal models predicted 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.

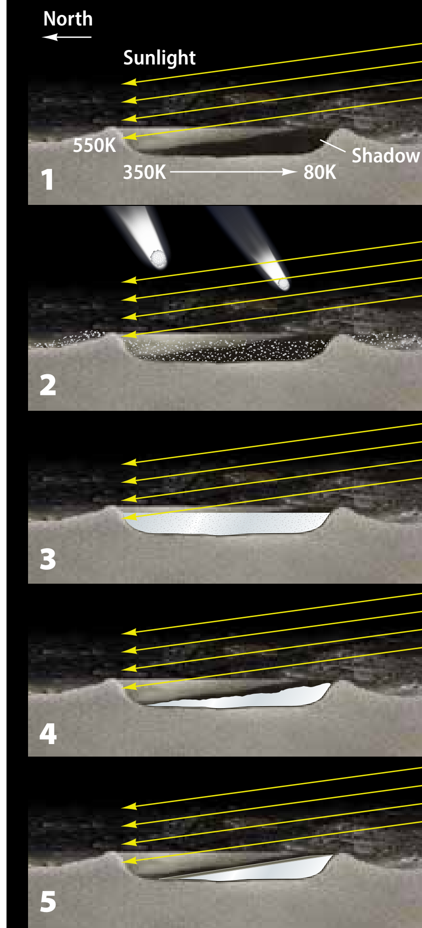
"The likelihood of persistent liquid water is remote," says Solomon. Water in Mercury's polar craters either will be a stable solid or in vapor form. "There may be brief intervals where water ice may be melted by sunlight or subsurface heat," he continues, "but there is no evidence that water has modified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

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.

READ MORE ABOUT THE MESSENGER SPACECRAFT'S DISCOVERIES AT MERCURY AT **www.Astronomy.com/toc.**