The Hitchhiker's Guide to Planets

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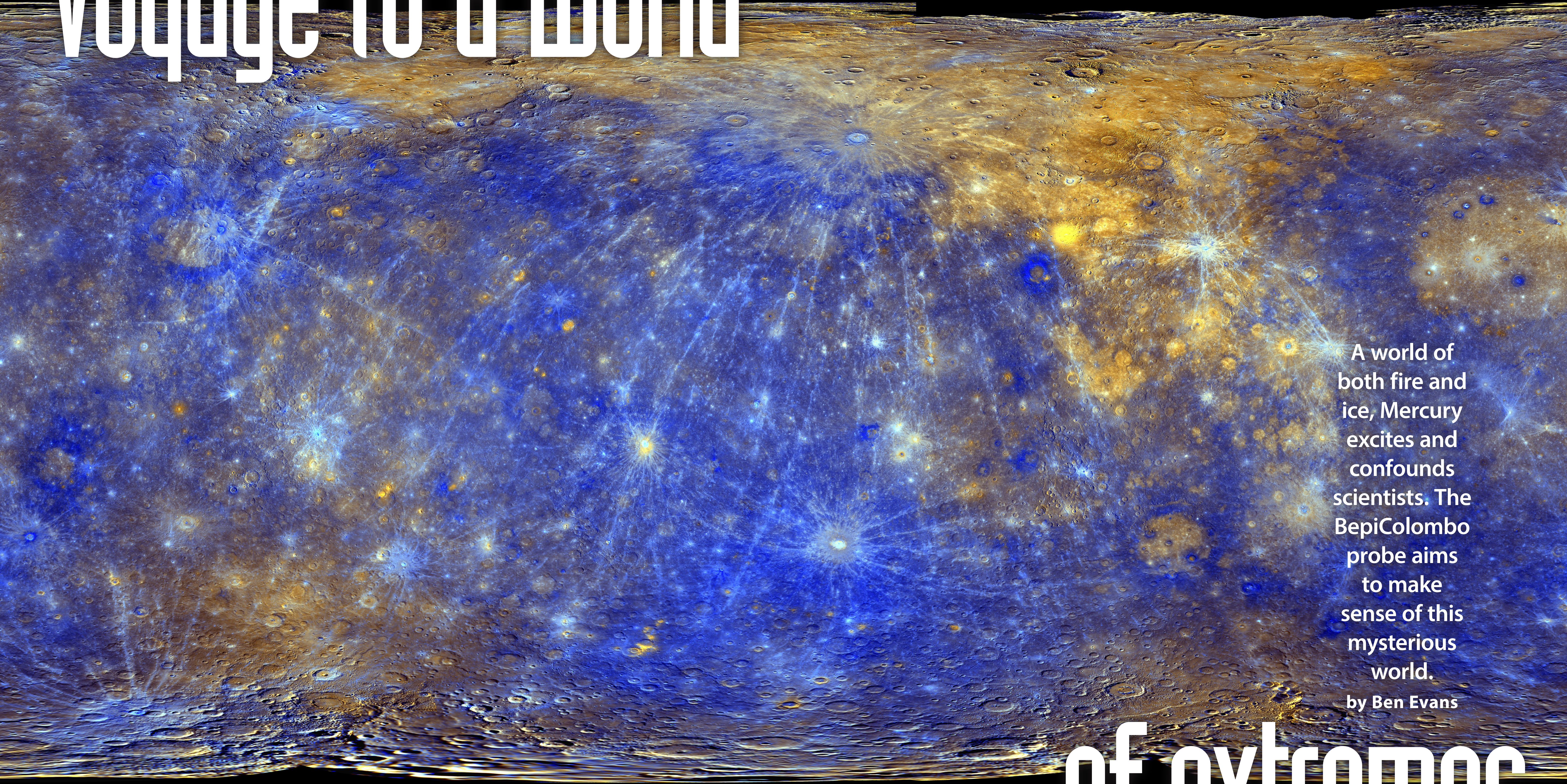
Astronomy®

Voyage to a world of extremes

A world of both fire and ice, Mercury excites and confounds scientists. The BepiColombo probe aims to make sense of this mysterious world.

by Ben Evans



Color explodes from Mercury's surface in this enhanced-color mosaic taken through several filters. The yellow and orange hues signify relatively young plains likely formed when fluid lavas erupted from volcanoes. Medium- and dark-blue regions are older terrain, while the light-blue and white streaks represent fresh material excavated from relatively recent impacts. ALL IMAGES, UNLESS OTHERWISE NOTED: NASA/JHUAPL/CIW

Mercury is a land of contrasts. The solar system's smallest planet boasts the largest core relative to its size. Temperatures at noon can soar as high as 800 degrees Fahrenheit (425 degrees Celsius) — hot enough to melt lead — but dip as low as –290 F (–180 C) before dawn. Mercury resides nearest the Sun, and it has the most eccentric orbit. At its closest, the planet lies only 29 million miles (46 million kilometers) from the Sun — less than one-third Earth's distance — but swings out as far as 43 million miles (70 million km). Its rapid movement across our sky earned it a reputation among ancient skywatchers as the fleet-footed messenger of the gods: Hermes to the Greeks and Mercury to the Romans.

Even though Mercury lies tantalizingly close to Earth, it is frustratingly hard to get to. Only two spacecraft have ever visited this barren world. But that is set to change October 19, when the international BepiColombo spacecraft begins a decade-long odyssey to unlock the secrets of a planet that seems to defy common sense.

The mission's namesake — Italian scientist, mathematician, and engineer Giuseppe "Bepi" Colombo (1920–1984) — was instrumental in devising a means to deliver a spacecraft from Earth, via Venus, to Mercury. Scientists already knew that a planet's gravitational field could bend the trajectory of a passing spacecraft and enable it to rendezvous with another celestial body. In the early 1970s, Colombo showed that if a spacecraft encountered Mercury, it would end up with a period almost twice that of the planet's orbital period. He suggested that a precisely targeted flyby would present a possibility for an economical second encounter.

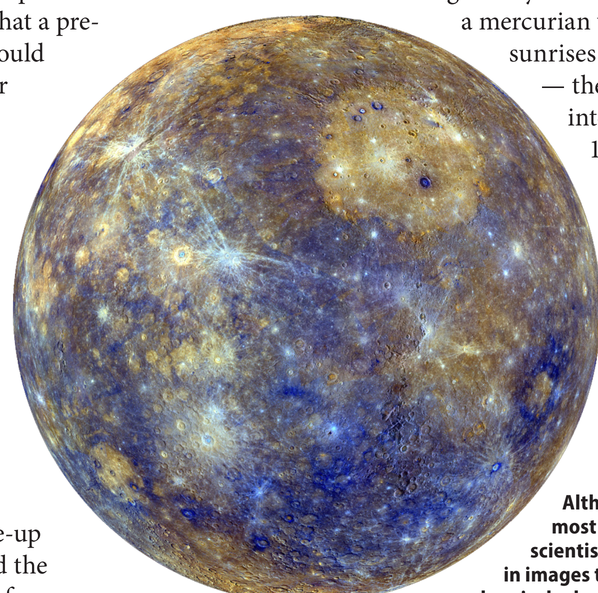
NASA confirmed the idea and used it to send the Mariner 10 spacecraft past the innermost planet three times. The probe encountered Mercury in March 1974, September 1974, and March 1975. Its photographs gave humanity its first close-up views of the world, and the last ones we would see for a generation.

Sadly, Mariner 10 provided only a partial view because of a quirk in Mercury's orbital parameters.

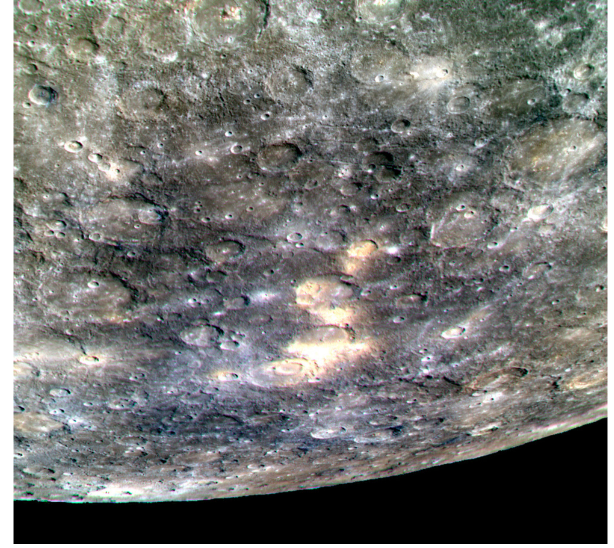
Italian scientist Giuseppe "Bepi" Colombo helped develop a technique for sending a space probe to Mercury and having it execute multiple flybys. The European Space Agency honored his contributions by naming the BepiColombo spacecraft after him. ESA

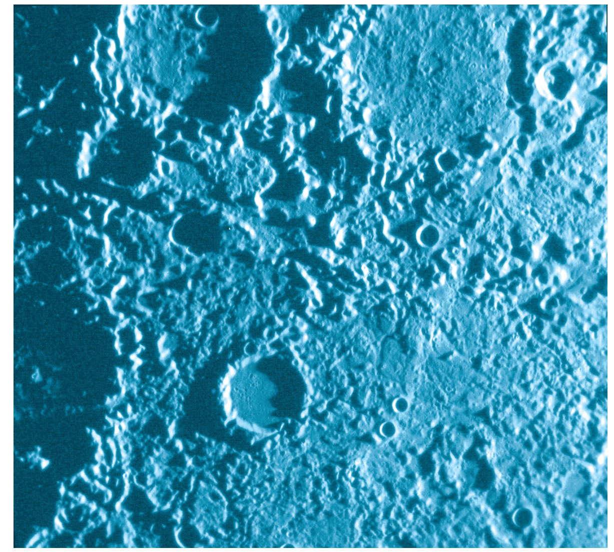
Before the Space Age, telescopic observations indicated that Mercury was tidally locked to the Sun, rotating once for each 88-day orbit and thus perpetually showing the same hemisphere to its parent star. But in the 1960s, radar measurements pegged its actual rotation at 58.6 days, two-thirds of its orbital period. In essence, the planet spins about its axis three times for every two solar orbits.

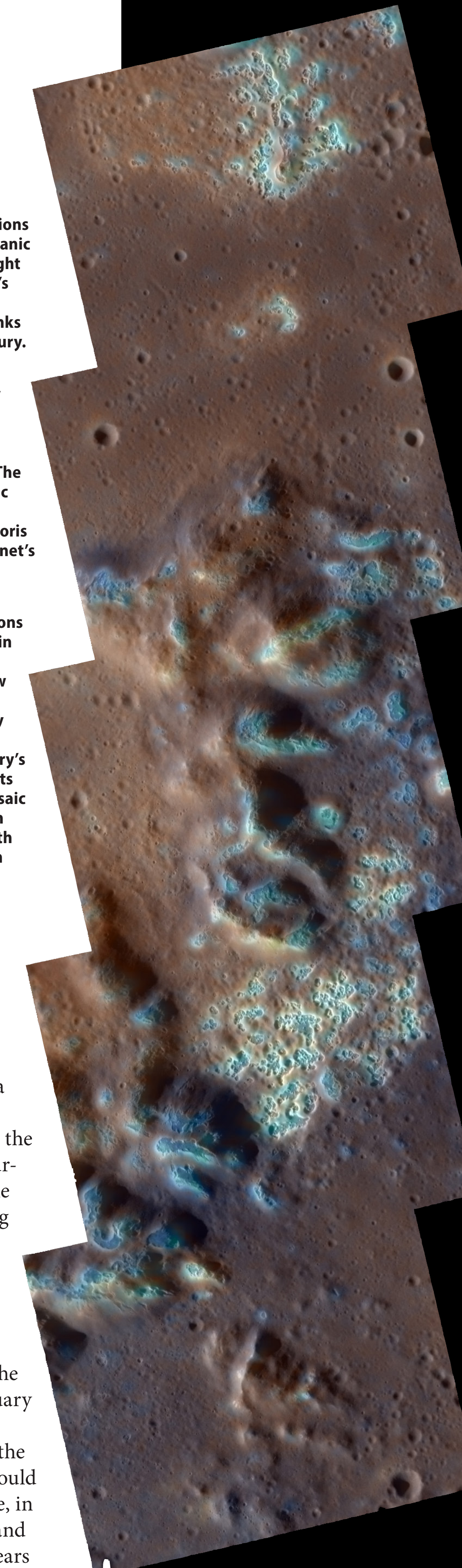
As Colombo first described, this means a day on Mercury lasts twice as long as its year. Day and night each last a mercurian year apiece, with new sunrises arriving every 176 days — the same as the six-month interval between Mariner 10 flybys. So, the Sun illuminated the same hemisphere of Mercury during all three encounters, and the spacecraft was able to map only about 45 percent of the planet's surface.



Although Mercury appears mostly gray to the human eye, scientists often enhance the colors in images to heighten differences in chemical, physical, and mineralogical properties among surface rocks. The circular tan feature at upper right is the giant Caloris Basin. The center of this hemispheric view lies at 0° latitude and 140° longitude.







Upper left: Explosive eruptions driven by superheated volcanic gases left behind these bright yellow deposits in Mercury's southern hemisphere. This cluster of volcanic vents ranks among the largest on Mercury.

Lower left: When planetary scientists first saw this oddly bumpy and grooved landscape, they informally dubbed it "weird terrain." The region formed when seismic waves from the mammoth impact that created the Caloris Basin converged on the planet's opposite side.

Right: Bright blue depressions litter the floor and mountain peaks in the Raditladi impact basin. These shallow "hollows" typically have smooth floors unmarked by impact craters, suggesting that they are among Mercury's youngest features. Scientists created this five-image mosaic by merging high-resolution black-and-white photos with a lower-resolution image in enhanced color.

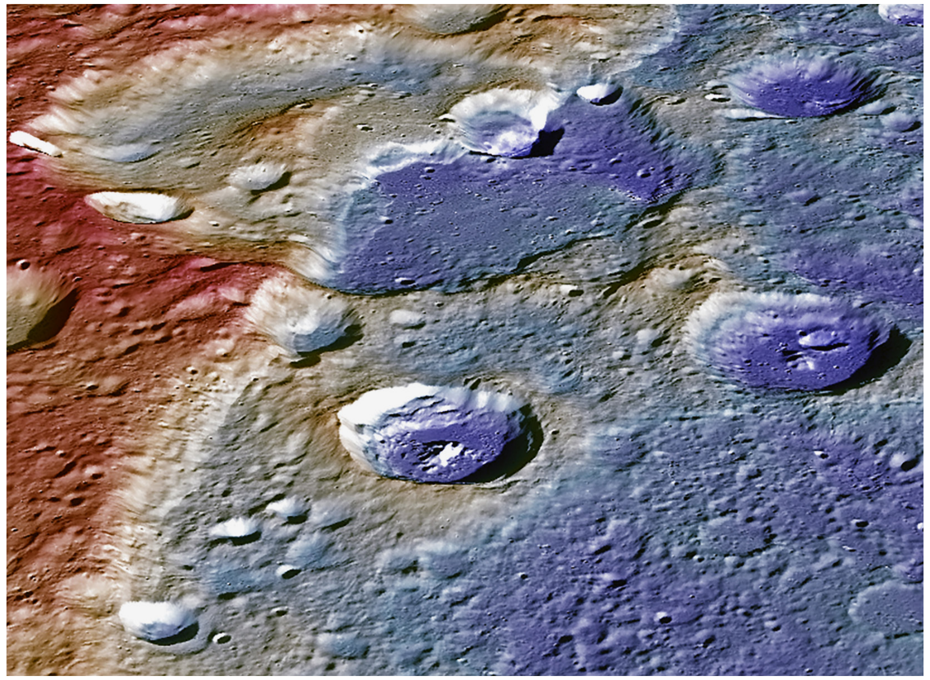
A STRANGE, OLD WORLD

Mariner 10 revealed an ancient terrain of rugged highlands and smooth lowlands, strikingly reminiscent of our Moon. Yet the similarities aren't even skin deep. Mercury's craters differ markedly from lunar ones, because their impact ejecta blankets a smaller area, partly due to the planet's much stronger gravity. The highland regions are less saturated with craters; instead they are mixed with rolling "intercrater plains" that constitute one of the oldest-known surfaces on the terrestrial planets.

The plains were laid down some 4.2 billion years ago during the Late Heavy Bombardment, when remnants from the solar system's birth rained down on the infant planets. Mercury was only a few hundred million years old, and the plains obliterated older craters, buried several large basins, and carved many of the pits and bowls seen today. The plains boast groups of secondary craters that occur in chains and clusters, covering the highlands.

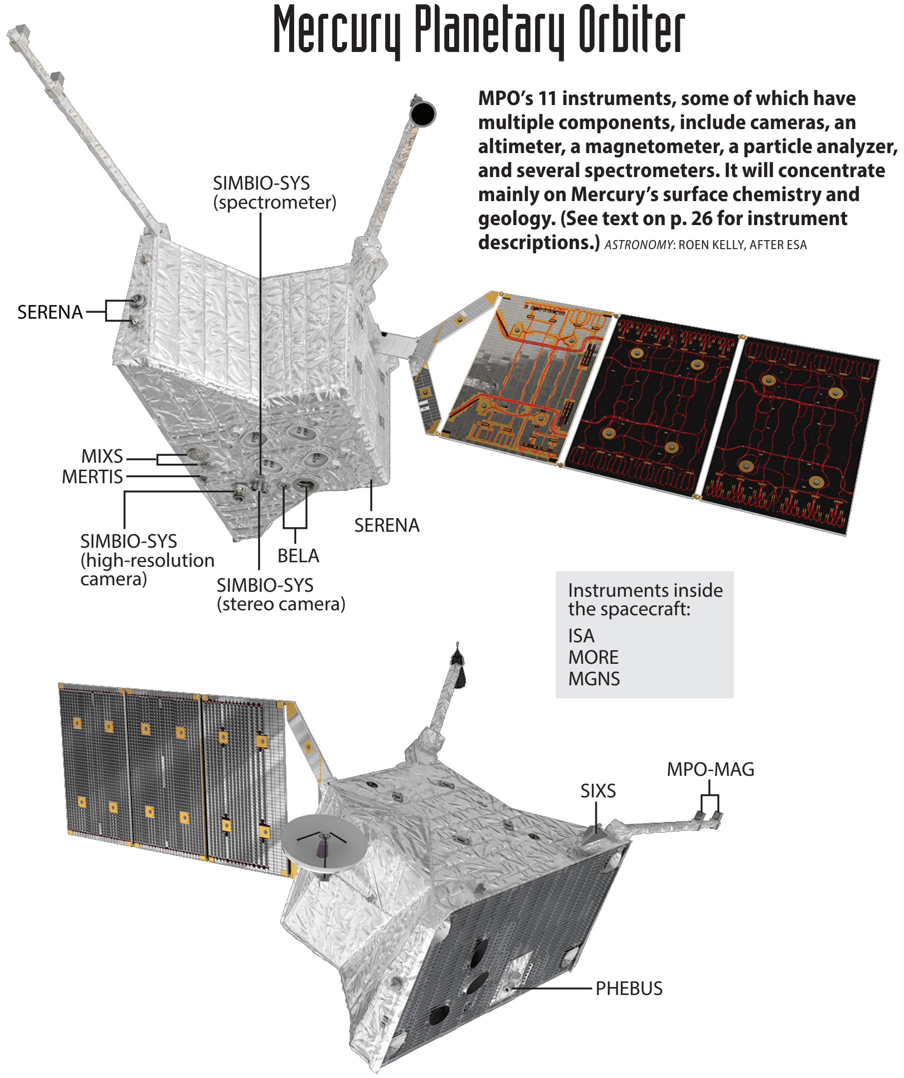
In contrast, the sparsely cratered lowlands formed near the end of the Late Heavy Bombardment, about 3.8 billion years ago. Mariner 10 data suggested that the lowlands formed either from volcanic activity or from the molten material splashed onto the surface after large impacts. Although the spacecraft found no obvious smoking gun for volcanism — such as lava flows, volcanic domes, or volcanic cones — it did uncover strong circumstantial evidence.

Mariner 10's successor, NASA's MESSENGER spacecraft, provided the proof. During its initial flyby in January 2008, the probe revealed a fractured region of ridges and furrows within the huge Caloris Basin. MESSENGER would go on to fly past Mercury twice more, in October 2008 and September 2009, and then orbit the inner world for four years

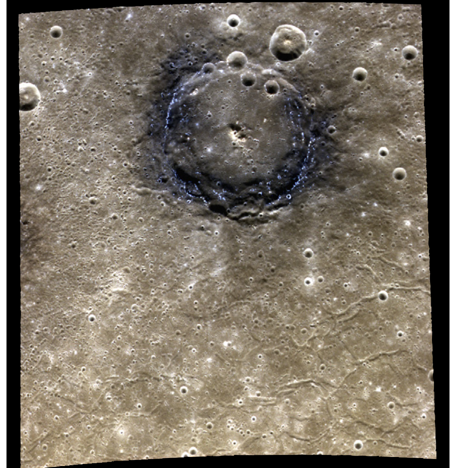


As Mercury's interior cooled, the planet's radius shrank by up to 4 miles (7 km). The contraction buckled the surface and left behind steep cliffs, including Carnegie Rupes, seen here cutting through Duccio Crater. The colors in this perspective view highlight elevation changes, with red indicating the highest terrain and blue the lowest.

Mercury Planetary Orbiter



MPO's 11 instruments, some of which have multiple components, include cameras, an altimeter, a magnetometer, a particle analyzer, and several spectrometers. It will concentrate mainly on Mercury's surface chemistry and geology. (See text on p. 26 for instrument descriptions.) *ASTRONOMY*: ROEN KELLY, AFTER ESA



The raven-colored rim of Poe Crater stands out from the smooth volcanic plains inside Caloris Basin. Note the hundreds of tiny blue-white hollows that dot the rim of this 48-mile-wide (77 km) crater.

starting in March 2011. While in orbit, the spacecraft discovered at least nine overlapping volcanic vents, each up to 5 miles (8 km) across and a billion years old, near Caloris' southwestern rim. Elsewhere on Mercury, MESSENGER uncovered residue from more than 50 ancient pyroclastic flows — violent outbursts of hot rock and gas — tracing back to low-profile shield volcanoes, mainly within impact craters.

Caloris itself is an impressive relic from Mercury's tumultuous early days. The Sun illuminated only half the basin during Mariner 10's visits, so it was left to MESSENGER to fully reveal its structure. Caloris spans 960 miles (1,550 km), placing it among the largest impact features in the solar system, and it is ringed by a forbidding chain of mountains that rises 1.2 miles (2 km) above the surroundings. Beyond its walls, ejecta radiate in meandering ridges and grooves for more than 600 miles (1,000 km). The impact that created Caloris was so globally cataclysmic that strong seismic waves pulsed through Mercury's interior and fragmented the landscape on the planet's opposite side, leaving a region of jumbled rocks, hills, and furrows that some scientists have dubbed "weird terrain."

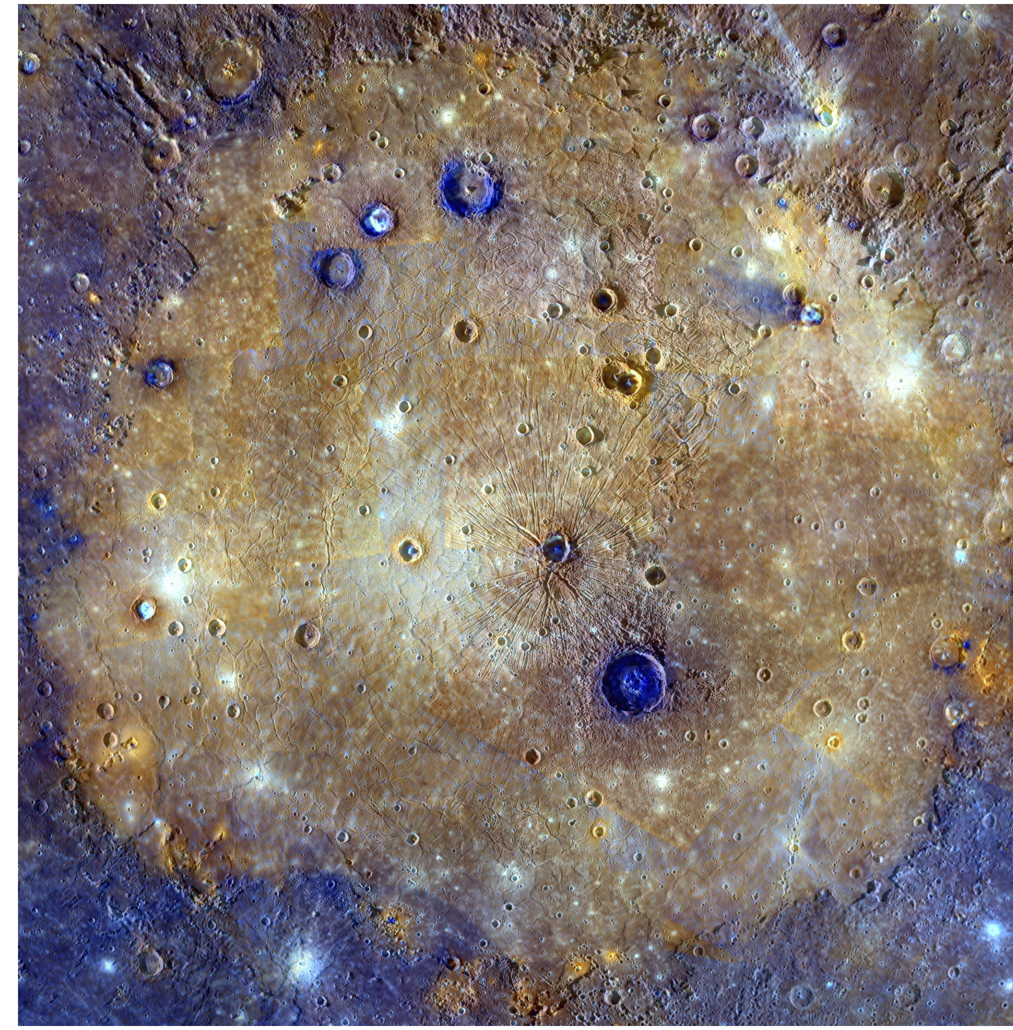
Despite Caloris' huge dimensions, Mercury itself is quite small — just 3,032 miles (4,879 km) in diameter. The planet's small size and high temperature led mid-20th-century astronomers to suspect it could not retain an atmosphere. But Mercury is full of surprises. Mariner 10 discovered a thin layer of loosely bound atoms, known as an exosphere, albeit with a surface pressure trillions of times less than that at sea level on Earth. It contains hydrogen and helium atoms captured from the solar wind — the stream of charged particles emanating from the Sun — together with oxygen atoms liberated from the surface by micrometeoroid impacts. Spectroscopic observations also revealed sodium, potassium, calcium, magnesium, and silicon. Caloris and the weird terrain appear to be key sources of sodium and potassium, indicating that impacts can release gases from below the surface.

DIGGING DEEPER

Farther down, the planet's interior remains a puzzle. Before Mariner 10, scientists assumed Mercury had a solid interior that produced no intrinsic magnetic field. They did realize, however, that the planet has an inordinately high density. Overall, Mercury's density averages 5.4 times that of water, close to those of the much larger Earth (5.5 times water) and Venus (5.2 times water). But the gravity of these bigger worlds crushes their interiors to far higher densities than they would have otherwise.

The only reasonable way to explain Mercury's high density is with the presence of heavy elements — some 70 percent iron and nickel overall — with most of them concentrated in the planet's giant core. This makes Mercury by far the most iron-rich planet in the solar system. Scientists think the winding cliffs that reach up to a mile high and run for hundreds of miles formed when the surface buckled as the interior cooled and contracted. Despite this shrinkage, MESSENGER revealed that Mercury's core stretches to within 250 miles (400 km) of its surface.

Scientists also were surprised when Mariner 10 discovered a magnetic field together with a small magnetosphere that weakly deflects the solar wind around the planet. A solid, slowly rotating planet shouldn't be able to generate the strong internal dynamo needed to create an intrinsic field, even one that's just 1 percent as strong as Earth's. MESSENGER showed the field is offset along the



Caloris Basin spans about 960 miles (1,550 kilometers) and ranks among the oldest and largest impact features in the solar system. Lava eventually flooded the floor to a depth of about 1.6 to 2.2 miles (2.5 to 3.5 km). The lava appears orange in this enhanced-color mosaic; more recent impact craters exposed darker material (blue) from below.

rotational axis by 20 percent of Mercury's radius and suggested that the planet possesses a partially molten outer core that surrounds a solid inner core.

Astronomers still aren't sure what keeps the core in an electrically conductive, semi-liquid state. Perhaps it is the slow decay of the radioactive elements Mercury was born with. The Sun's gravity, which raises tides as the planet follows its eccentric orbit, could flex the interior and play a contributing role.

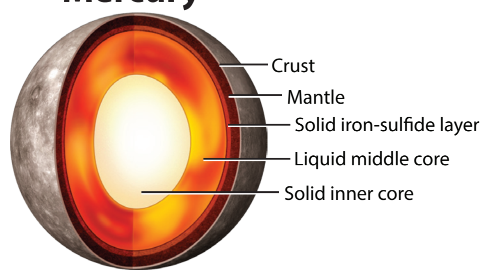
Despite this internal heat and the blazing Sun above, Mercury also appears to be a land of ice. In the 1990s, ground-based radar observations revealed a number of bright spots within 6.5° of the planet's north and south poles. Many scientists interpreted these findings as evidence for ice deposits on the floors of permanently shadowed craters, where temperatures can drop as low as –370 F (–225 C). In November 2012, MESSENGER identified up to 1 trillion tons of water ice near the poles — enough to encase Washington, D.C., in a frozen block 2.5 miles (4 km) deep.

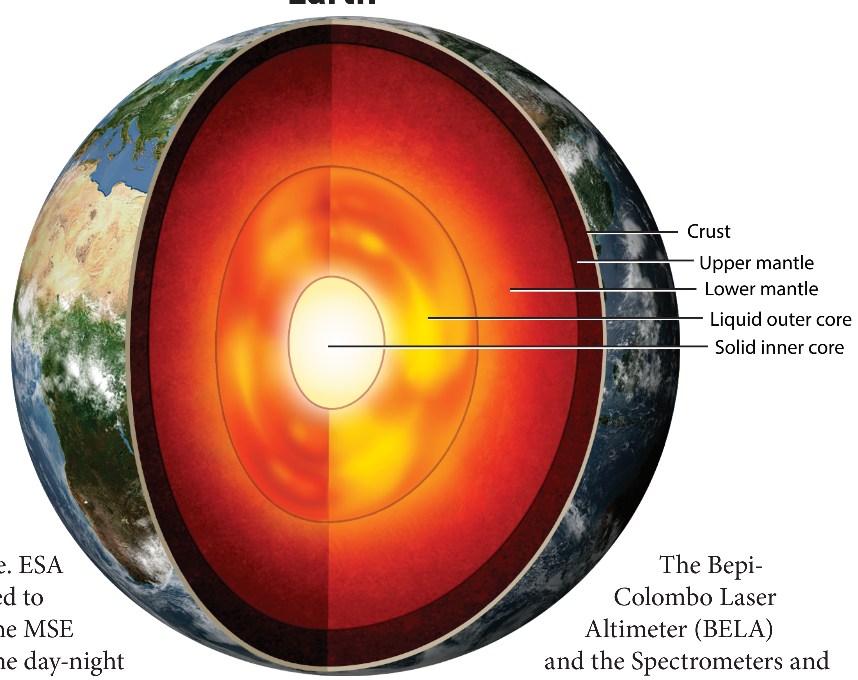
BEPICOLOMBO COMES ON THE SCENE

Despite Mariner 10's and MESSENGER's incredible discoveries, scientists still have many questions about this enigmatic world. That's where BepiColombo comes in. The European Space Agency (ESA) initially envisioned three spacecraft for this ambitious venture: The Mercury Planetary Orbiter (MPO) and Mercury Magnetospheric Orbiter (MMO) would work in tandem to unlock Mercury's mysteries from above, and the Mercury Surface Element (MSE) would explore the

Beneath two planets' skin

Mercury's interior differs significantly from Earth's. The inner world's gigantic core starts just 250 miles (400 kilometers) below the surface and is surrounded by a relatively thin mantle and crust. Most of Earth's volume resides in its mantle. The liquid parts of both planets' cores help generate their magnetic fields. *ASTRONOMY*: ROEN KELLY





surface. ESA planned to land the MSE near the day-night terminator and have it survive for about a week in the harsh environment. The lander would carry heat-flow sensors, a spectrometer, a magnetometer, a seismometer, a soil-penetrating device, and a tiny rover.

Unfortunately, budget considerations forced ESA to abandon the lander in November 2003. "The decision to cancel the lander was a loss for the mission," says BepiColombo project scientist Johannes Benkhoff. "What we miss is a so-called 'ground truth.' We can do many things remotely with our instruments, which are already on the other spacecraft, but the measurements of a lander would have been used to calibrate them, and that can unfortunately not be recovered."

The rest of the mission continued, however. ESA led the development of the 2,535-pound (1,150 kilograms) MPO spacecraft. The probe's 11 instruments were fabricated by 35 scientific and industrial teams in Switzerland, Germany, Italy, the United Kingdom, Russia, Finland, Sweden, Austria, France, and the United States.

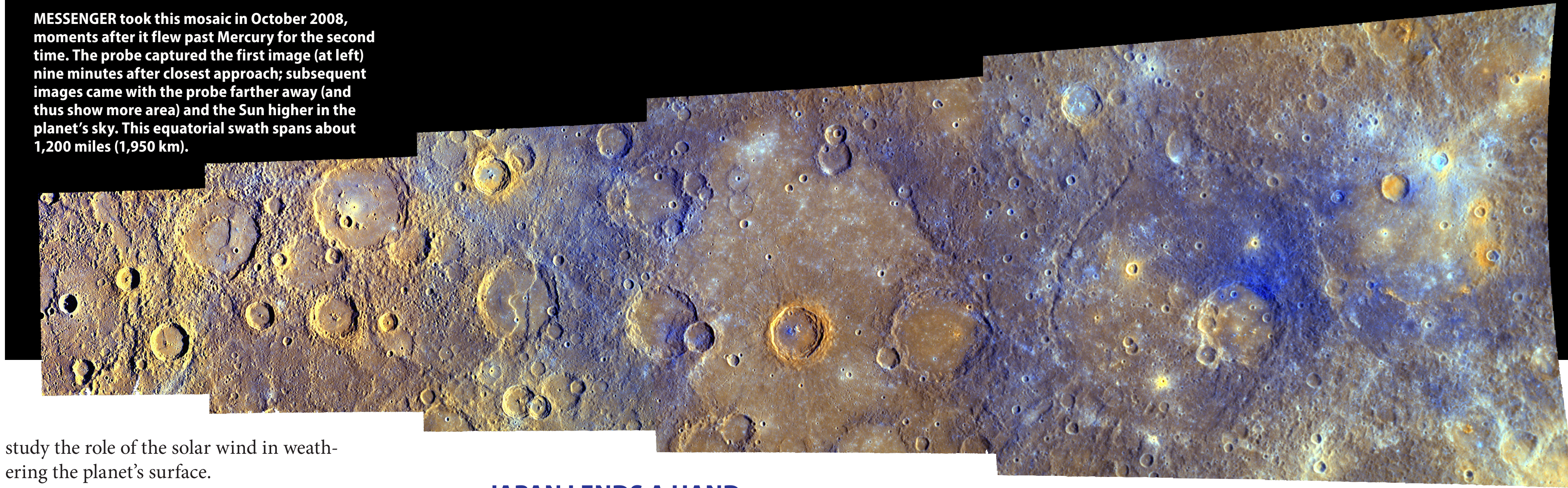
The BepiColombo Laser Altimeter (BELA) and the Spectrometers and Imagers for MPO BepiColombo Integrated Observatory System (SIMBIO-SYS) will create digital terrain models to quantitatively map Mercury's geology, elemental composition, and surface age. Together with the Mercury Radiometer and Thermal Infrared Spectrometer (MERTIS), Mercury Gamma-Ray and Neutron Spectrometer (MGNS), and Mercury Imaging X-Ray Spectrometer (MIXS), they will identify key rock-forming minerals, measure global surface temperatures, and address competing theories of the planet's origin and evolution. These tools also will search for additional ice deposits and other volatile substances at high latitudes as well as provide insights into the role of volcanism.

To analyze the composition, structure, and formation of Mercury's exosphere, MPO provides BepiColombo's Probing of Hermean Exosphere by Ultraviolet Spectroscopy (PHEBUS) and Search for Exosphere Refilling and Emitted Neutral Abundances (SERENA) instruments. Meanwhile, the Solar Intensity X-Ray and Particles Spectrometer (SIXS) will study the role of the solar wind in weathering the planet's surface.

MPO carries two instruments to help understand why Mercury has so much iron and what this reveals about its evolutionary history. The Italian Spring Accelerometer (ISA) and Mercury Orbiter Radioscience Experiment (MORE) will investigate the planet's global gravitational field to understand the size and nature of the core as well as the structure of the mantle and crust. MPO also houses one-half of the Mercury Magnetometer (MERMAG) that will study the magnetic field for clues to the dynamo lurking inside.

MPO carries a 24.6-foot-long (7.5 meters) solar array with integrated optical reflectors designed to keep the spacecraft at a temperature below 390 F (200 C). When in orbit around Mercury, the array must continuously rotate to balance MPO's power requirements with the need to keep the probe under its redline temperature. Meanwhile, a radiator angled toward the planet will reflect the intense infrared radiation coming from Mercury's searing surface.

"The solar arrays will be exposed to high-frequency, high-intensity ultraviolet radiation, combined with high temperatures, which was discovered to induce an unexpectedly fast degradation in solar-cell performance," explains BepiColombo project manager Ulrich Reininghaus. "This was resolved by a complex method of continuous solar array steering control, in order to maintain the temperature always below an allowed maximum, and by a specific redesign of the solar cells."



MESSENGER took this mosaic in October 2008, moments after it flew past Mercury for the second time. The probe captured the first image (at left) nine minutes after closest approach; subsequent images came with the probe farther away (and thus show more area) and the Sun higher in the planet's sky. This equatorial swath spans about 1,200 miles (1,950 km).

JAPAN LENDS A HAND

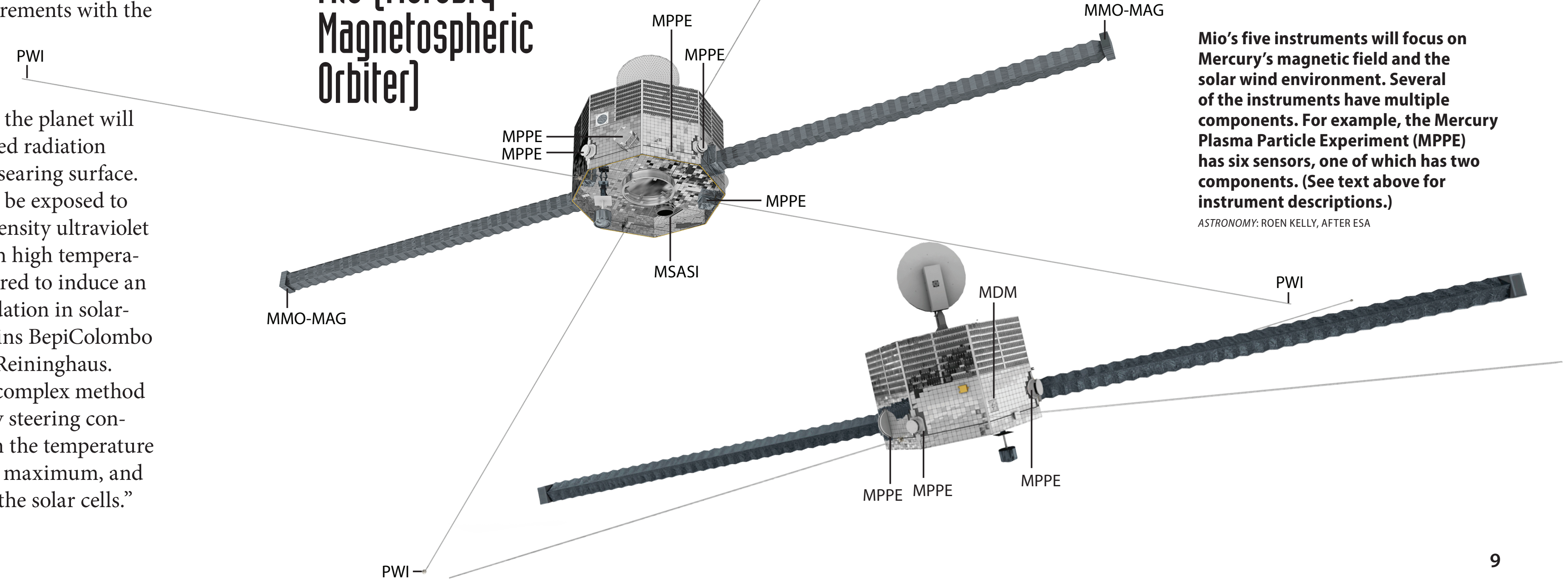
The mission drew more international collaboration when the Japan Aerospace Exploration Agency (JAXA) joined the project. JAXA developed the 630-pound (285 kg) MMO spacecraft. Earlier this year, the space agency renamed the craft Mio, which comes from a Japanese word meaning "waterway" or "fairway."

Mio carries five science instruments, including the second half of MERMAG. Its other tools are the Mercury Sodium Atmosphere Spectral Imager (MSASI), to study the origin and extent of sodium in the exosphere; the Mercury Dust Monitor (MDM), to explore space dust in the planet's vicinity and how it weathers the mercurian surface; the Mercury Plasma Particle Experiment (MPPE), to scrutinize the planet's magnetic field and its interaction with particles in the solar wind and particles coming from Mercury; and the Plasma Wave Investigation (PWI), to study the planet's electric and magnetic fields as well as look for evidence of aurorae and radiation belts.

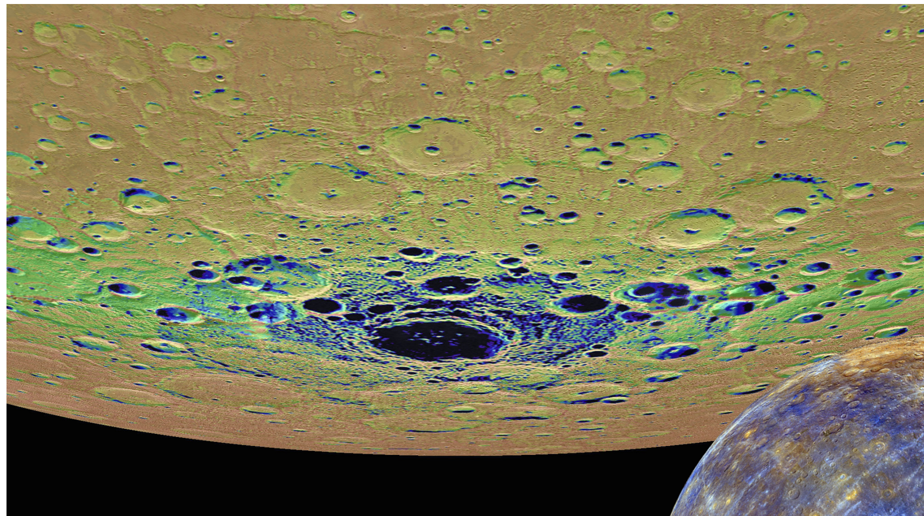
"The collaboration with our Japanese colleagues goes very well; we almost feel as one team," says Reininghaus. "However, the two spacecraft were designed and built totally independently, although we had to agree on interfaces. In the science area, we hold regular joint meetings. Some of our science goals can only be reached if we work closely together."

The final element of the spacecraft is the Mercury Transport Module (MTM). It holds four British-built xenon-ion engines, 24 chemical thrusters, and two large solar arrays that will provide electrical power to keep MPO and Mio alive during their seven-year journey to the Sun's closest planet. "Solar electric propulsion [SEP] allows very significant autonomous capabilities for readjusting the interplanetary trajectory, avoiding altogether large midcourse maneuvers," says Reininghaus.

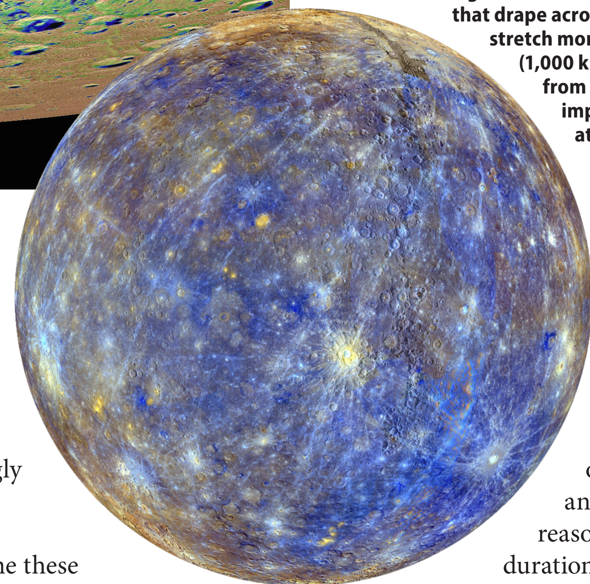
Mio (Mercury Magnetospheric Orbiter)



Mio's five instruments will focus on Mercury's magnetic field and the solar wind environment. Several of the instruments have multiple components. For example, the Mercury Plasma Particle Experiment (MPPE) has six sensors, one of which has two components. (See text above for instrument descriptions.) *ASTRONOMY*: ROEN KELLY, AFTER ESA



Left: Despite its proximity to the Sun, Mercury boasts some of the coldest spots in the solar system. The colors in this view of Mercury's south pole show the fraction of time that specific regions lie in sunlight. The black areas are those in permanent shadow, the largest of which is the crater Chao Meng-Fu. MESSENGER found solid evidence that abundant water ice exists in this crater.



Below: This enhanced-color view shows the half of Mercury centered at 0° latitude and 320° longitude. The bright bluish rays that drape across this hemisphere stretch more than 600 miles (1,000 km) and emanate from the relatively fresh impact crater Hokusai at upper right.

Although the solar electric thrusters provide low thrust, they operate over a long time, delivering what rocket scientists call high impulse. In fact, the thrusters will accumulate the greatest total impulse ever achieved by a space mission. This posed considerable challenges during preflight testing. "[We resolved this through] multiple test campaigns in different chambers and with different test articles, combined with a sophisticated modeling approach that allowed us to accurately predict end-of-life performance of the thrusters," explains Benkhoff.

GETTING THERE

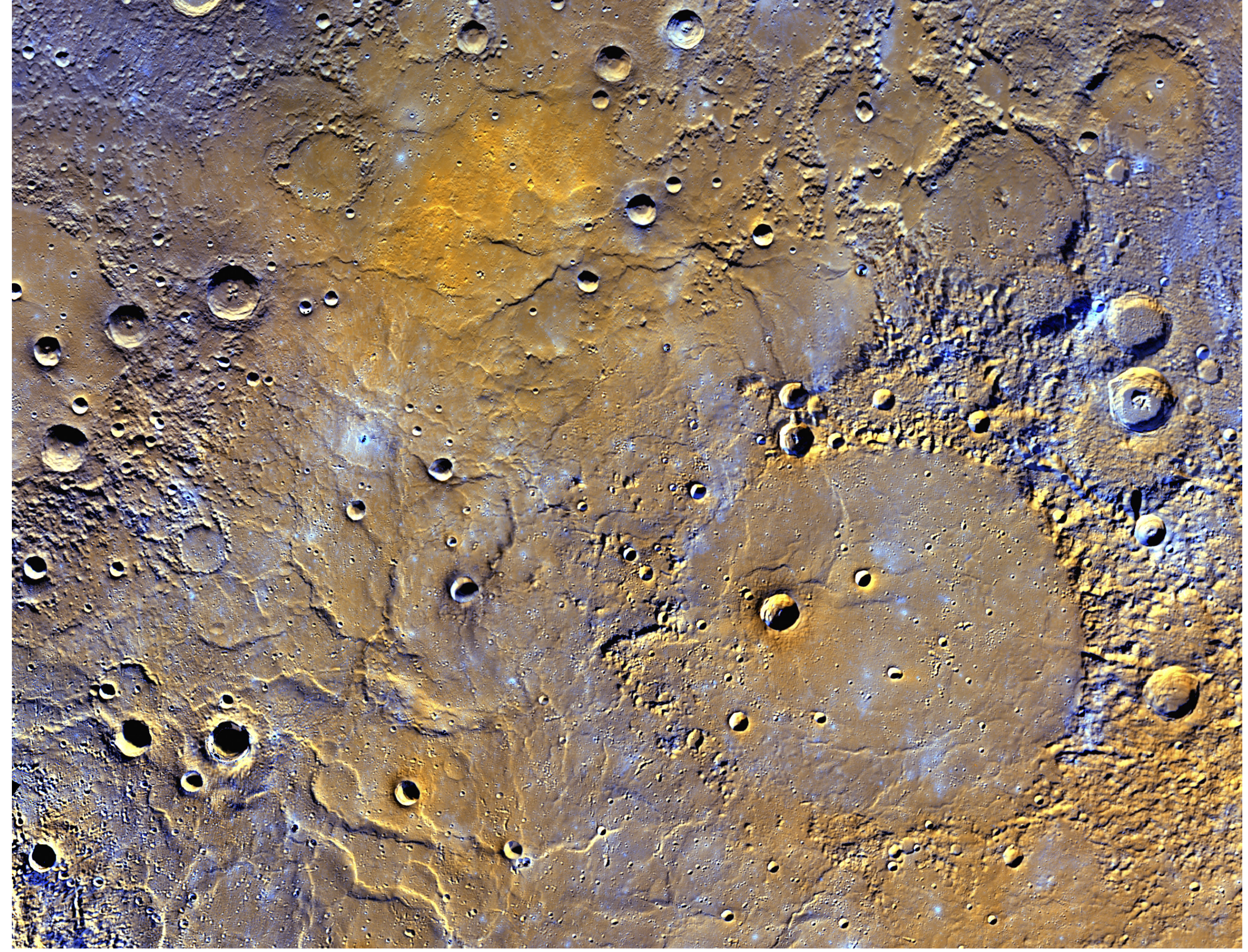
Like Mariner 10 and MESSENGER before it, BepiColombo will take a circuitous route to reach Mercury. The spacecraft will launch from Kourou, French Guiana, atop a giant Ariane 5 rocket, perhaps as early as October 19 (the first chance during a six-week launch window). It will depart Earth 7,770 mph (12,510 km/h) faster than the escape velocity from our planet. Although impressive by many standards, this speed is problematic for a spacecraft heading directly into the Sun's powerful gravitational field. In fact, the energy needed to get to Mercury is larger than it would be to reach Pluto and leave the solar system. Moreover, Mercury's orbital velocity of 105,900 mph (170,500 km/h) is 60 percent greater than Earth's, demanding a substantial velocity change and correspondingly high fuel consumption.

To overcome these obstacles, BepiColombo initially will enter an orbit similar to Earth's, using its high-impulse, low-thrust xenon-ion engines to slowly decelerate against solar gravity and adjust its orbital plane. "Solar electric propulsion was the only option to reach Mercury," says Benkhoff. "In principle, one can fly a mission to Mercury with chemical propulsion, but it all depends on the thrust-to-mass ratio. SEP is about eight times more efficient than chemical fuel. Thus, for BepiColombo, we would have needed at least 2 tons more mass to accommodate this."

The spacecraft will complete 1.5 circuits of the Sun, returning to Earth in April 2020 to pick up a gravitational boost. This will propel it to Venus for rendezvous in October 2020 and August 2021, which will reduce BepiColombo's perihelion to about the same distance as Mercury. Critically, this ingenious use of gravitational fields requires little propulsive intervention from the spacecraft. "These flybys depend on the [arrangement] of the planets, and that is the reason for the long duration," says Benkhoff. "The flybys provide almost half of the needed energy to go to Mercury. The SEP engine will be used for about 50 percent of the time."

Six flybys of Mercury between October 2021 and January 2025 will slow BepiColombo's inbound trajectory until its orbit nearly matches that of the planet. Finally, in December 2025, Mercury will weakly capture the spacecraft into a polar orbit that comes within 420 miles (675 km) of the planet's surface and swings out to 110,600 miles (178,000 km). This so-called weak-stability-boundary technique adds flexibility compared with traditional approaches, where a single engine firing typically brings a spacecraft into orbit. BepiColombo's chemical thrusters will stabilize the orbit gradually and, after traveling 5.5 billion miles (8.9 billion km), the mission will at last be underway.

After the MTM separates from the probes, Japan's Mio will be spring-ejected from its protective sunshield and part company with Europe's MPO. Three months later, the pair will commence autonomous operations, the former controlled from the Usuda Deep Space Centre in Nagano, Japan, and the latter from the Cebreros ground station near Madrid, Spain. "However, from the standpoint of science operations, coordination planning will be maintained among the principal investigators of the two spacecraft, and a certain amount of joint observations will certainly take place," explains Reininghaus.



Molten lava once covered Mercury's vast northern volcanic plains. Lava nearly filled the 181-mile-wide (291 km) Mendelssohn impact basin, which lies at the lower right of this enhanced-color image. As the lava cooled, it formed large ridges that appear particularly prominent at bottom left. Meanwhile, the bright orange region near the scene's top shows the location of a volcanic vent that unleashed one of the planet's largest pyroclastic flows.

All told, the two spacecraft will bring about 275 pounds (125 kg) of scientific instruments to bear upon one of the least-known worlds in the solar system. MPO will occupy a looping, 2.3-hour orbit at a distance that ranges from 300 miles (480 km) to 930 miles (1,500 km); Mio will follow a highly elliptical path that will carry it as close to Mercury's surface as 365 miles (590 km) and as far away as 7,230 miles (11,640 km) during a 9.3-hour orbit.

Scientists expect the baseline mission to last until May 2027, but there's a good chance ESA will grant a one-year extension. As a bonus, BepiColombo will make precise measurements of Mercury's orbital parameters. Because the planet lies so close to the Sun, this should allow astronomers to chart our star's gravitational field in detail and provide a rigorous test of Albert Einstein's general theory of relativity.

Although the spacecraft's roundabout route to Mercury is hardly in keeping with the fleet-footed nature of the planet's mythological namesake, the mission and the god do share some similarities. Both will deliver an abundance of learning, and both will accomplish their goals through ingenuity, an element of trickery, and a pinch or two of old-fashioned good fortune.

British spaceflight writer **Ben Evans** *authored the multivolume* History of Human Space Exploration, *published by Springer-Praxis.*

On the road to Mercury

- *Launch: October 19, 2018*
- *Earth flyby: April 6, 2020*
- *First Venus flyby: October 12, 2020*
- *Second Venus flyby: August 11, 2021*
- *First Mercury flyby: October 2, 2021*
- *Second Mercury flyby: June 23, 2022*
- *Third Mercury flyby: June 20, 2023*
- *Fourth Mercury flyby: September 5, 2024*
- *Fifth Mercury flyby: December 2, 2024*
- *Sixth Mercury flyby: January 5, 2025*
- *Arrival at Mercury: December 5, 2025*
- *End of nominal mission: May 1, 2027*
- *End of extended mission? May 1, 2028*

Mission planners expect to launch BepiColombo as early as October 19, 2018. As long as the mission commences by November 29, subsequent timeline dates will remain the same.

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.

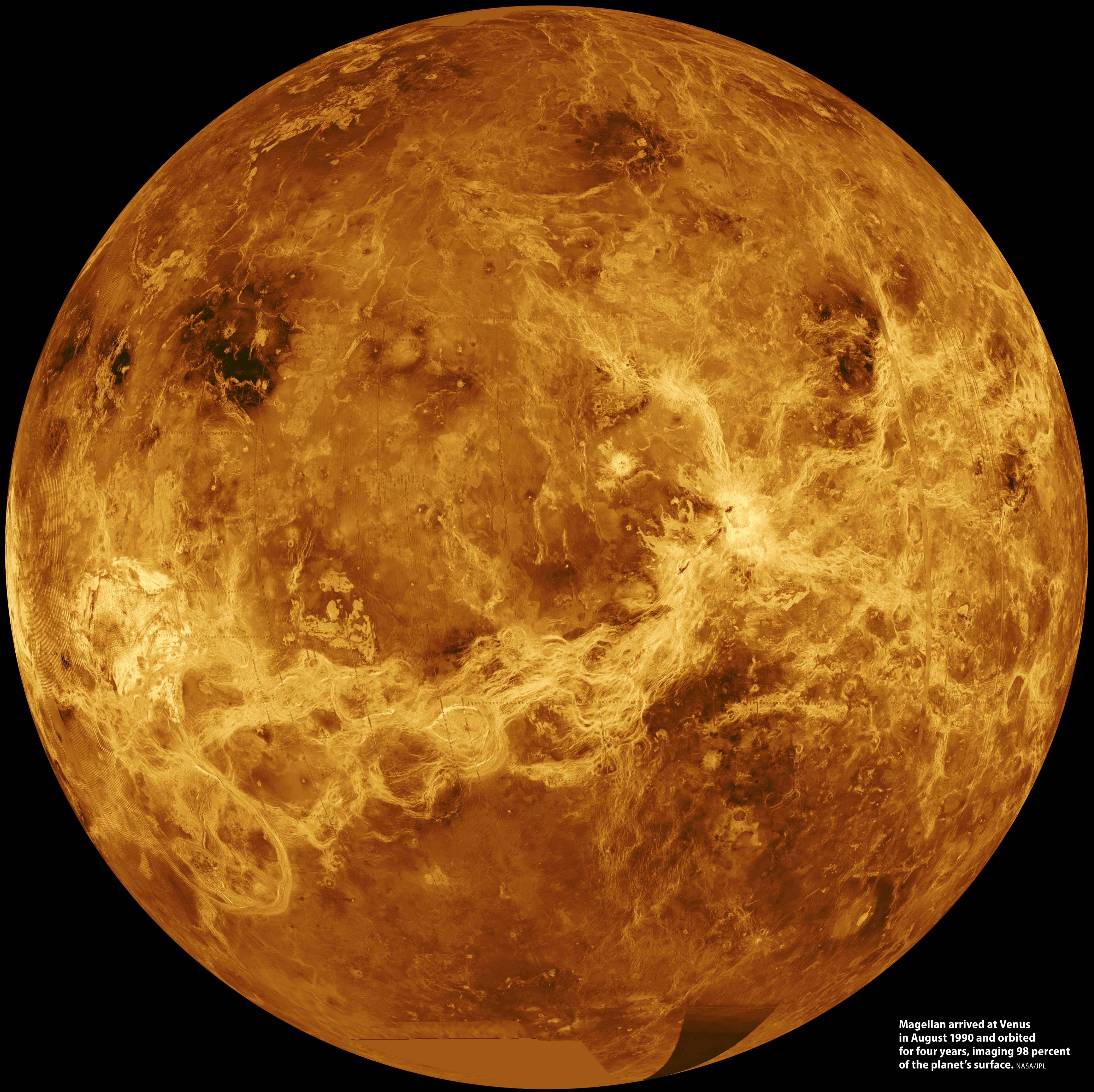
Venus wasn't always so unloved. From 1960 to 1984, more than 20 spacecraft investigated Venus — nearly as many as Mars up to that point. The USSR's Venera and Vega programs resulted in no less than 18 orbiters and landers (though not all missions were successful), and the U.S. added five spacecraft.

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.

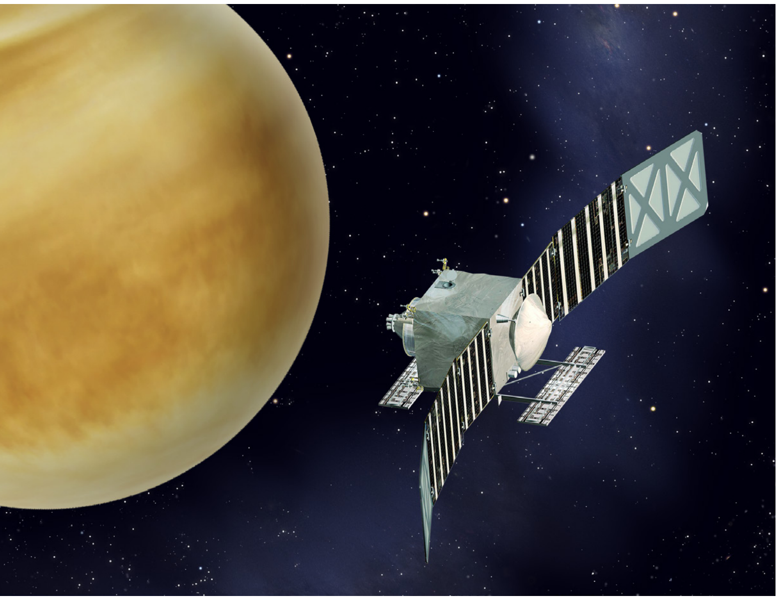
The twin paradox

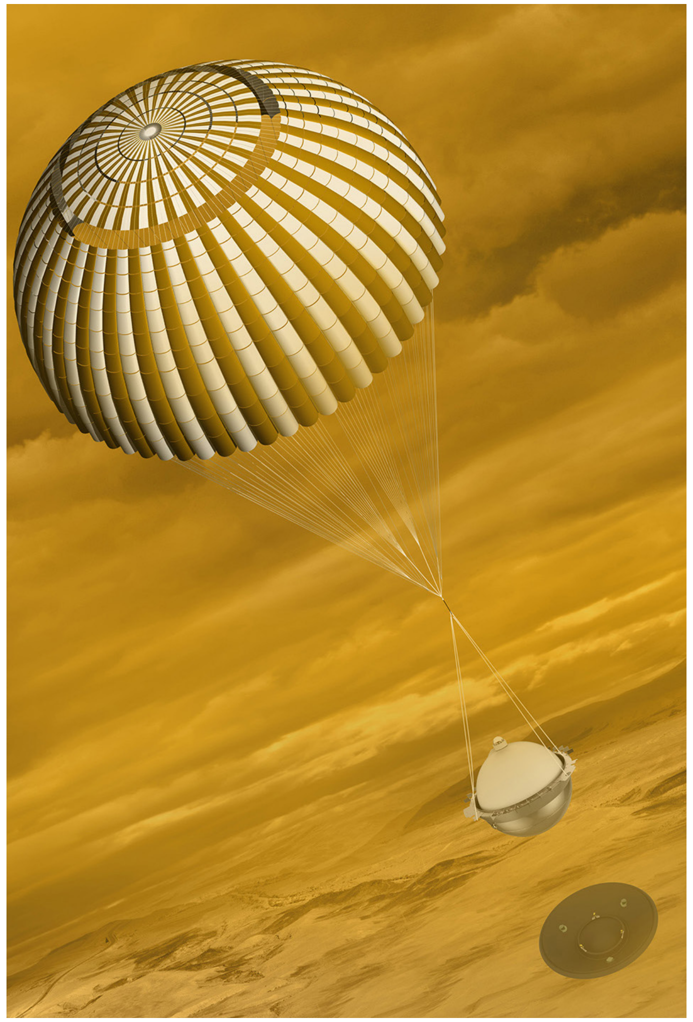
Venus is often referred to as Earth's twin for a reason: The two planets' most basic physical properties are nearly identical. "If we found Venus around a sunlike star,

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.

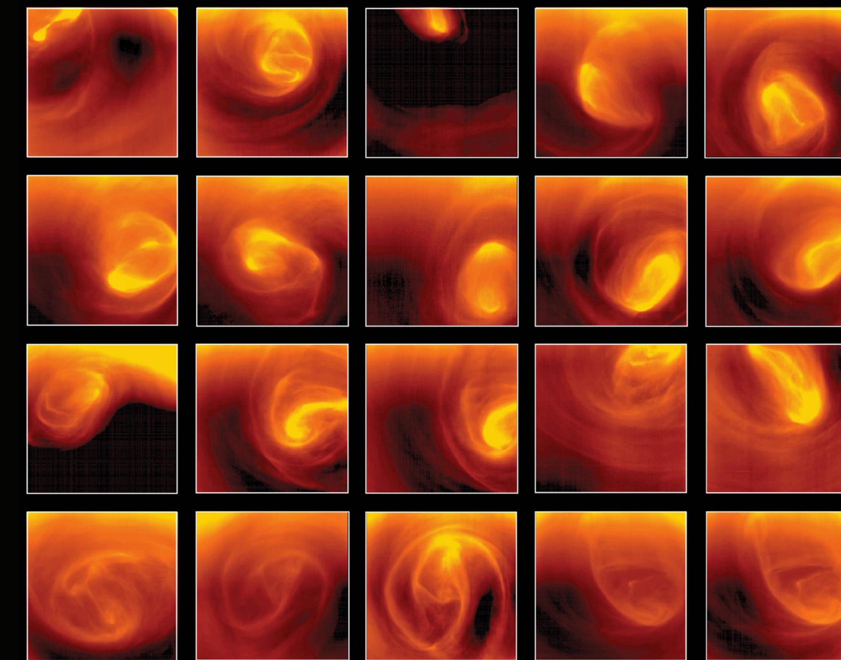
NASA's other option is the Venus Emissivity, Radio Science, InSAR, Topography, and Spectroscopy (VERITAS) mission. The VERITAS orbiter would operate similar to Magellan, but the big difference would be that its radars will have much better resolution, able to spot features as small as about 100 feet (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.

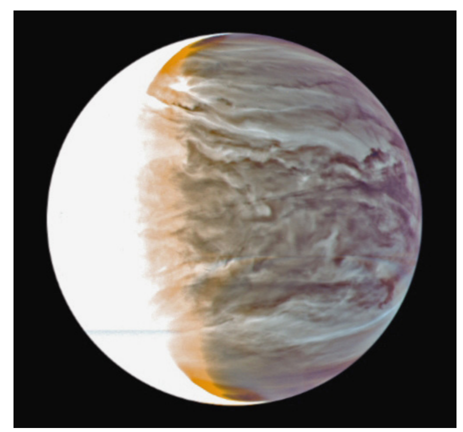
From ESA, there's EnVision, an orbiter also equipped with advanced radar, and it likely won't launch until 2029, says Richard Ghail, a lecturer in engineering geology at Imperial College London, who proposed the mission. Aside from a more advanced set of radars than Magellan, EnVision will be able to "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.

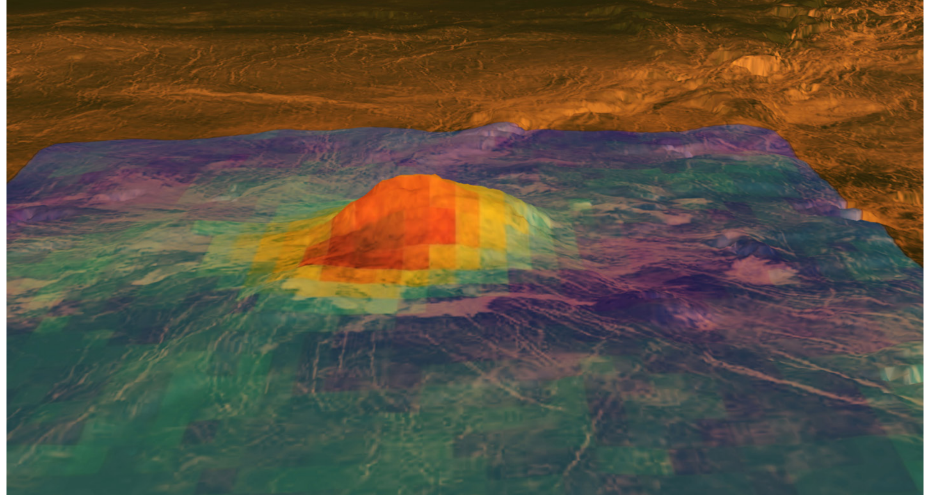
The Russian proposal is called Venera D. This spacecraft would bear some resemblance to the Vega missions because it involves a combined orbiter and lander. It might even include a balloon probe, also like the Vega missions. Like many missions before it, Venera D would focus on Venus' atmosphere and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



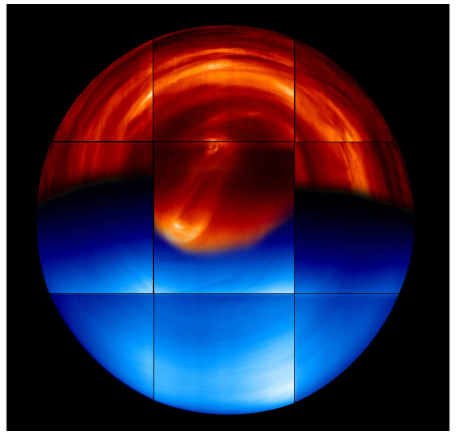
The Venus Express mission imaged clouds swirling above Venus' south pole at dizzying speeds. The high-altitude clouds, like those seen here, can travel 60 times faster than the planet rotates, contributing to the polar vortex Venus Express studied in detail during its eight-year stay. ESA/VIRTIS-VENUS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



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



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 improvised orbit, which allows for longer periods of observation as Akatsuki swings out to its farthest position.

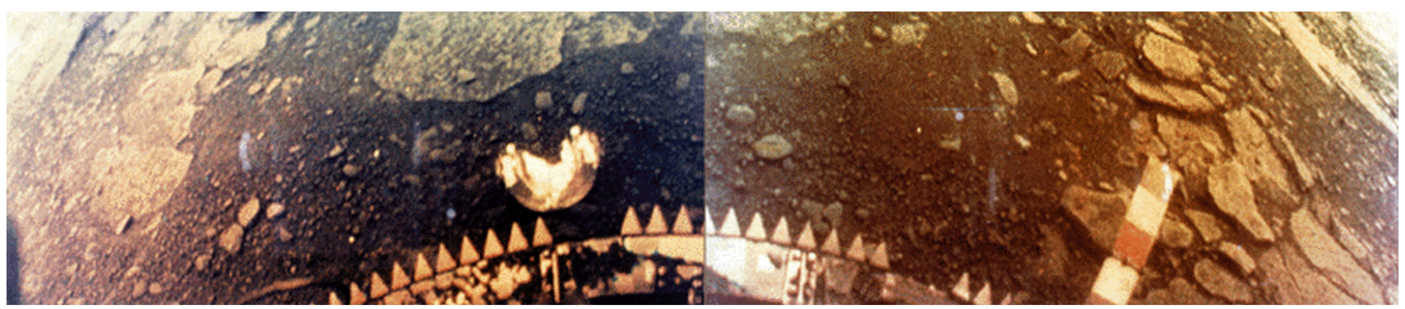
Two of Akatsuki's cameras work in the near-infrared and study the planet's surface, the motion of clouds, and the particles that comprise them. A long-wave infrared camera tracks the temperatures at the cloud tops, about 40 miles (65km) above the planet's surface. The other two instruments are an ultraviolet 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.

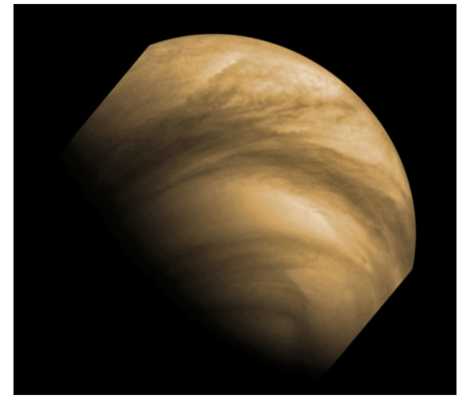
A smoking gun for volcanism

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.

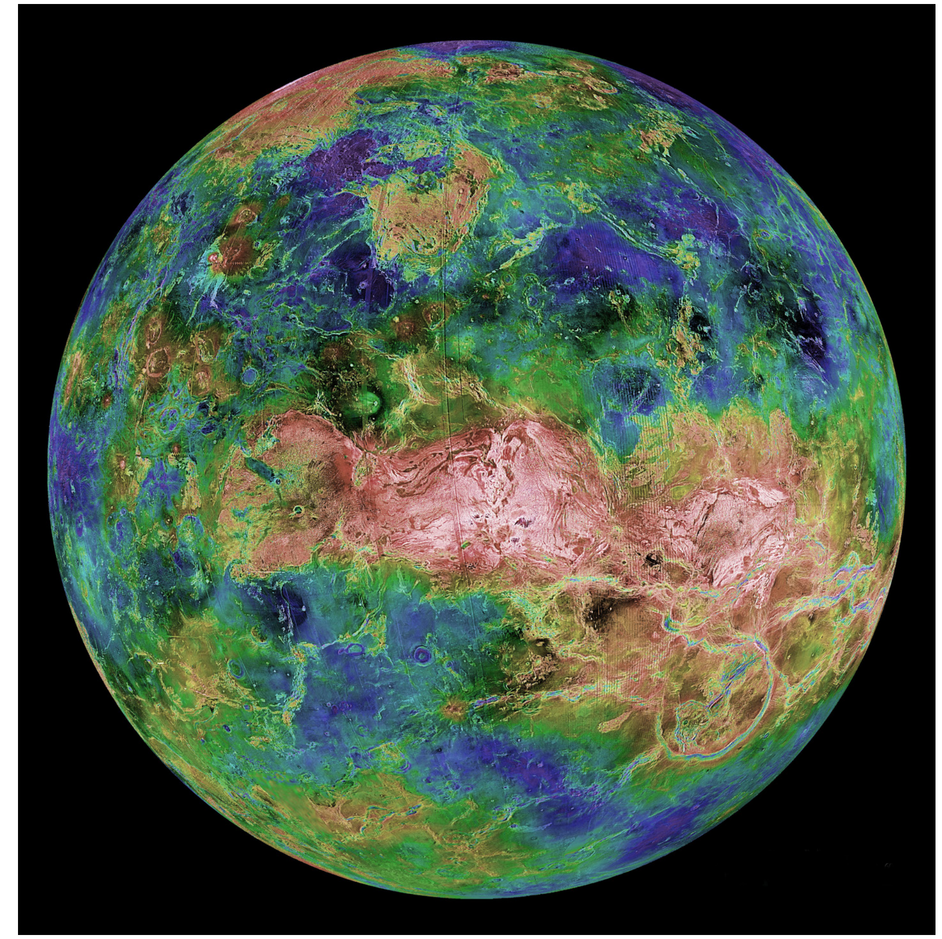
There are three strong lines of evidence of active volcanoes on Venus, Wilson says. First is the way the detected sulfur behaves. In the first year of Venus Express' observations, sulfur levels spiked and then decreased tenfold over five to six years. That points to a source that "burped" sulfur, as 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



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

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.

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."

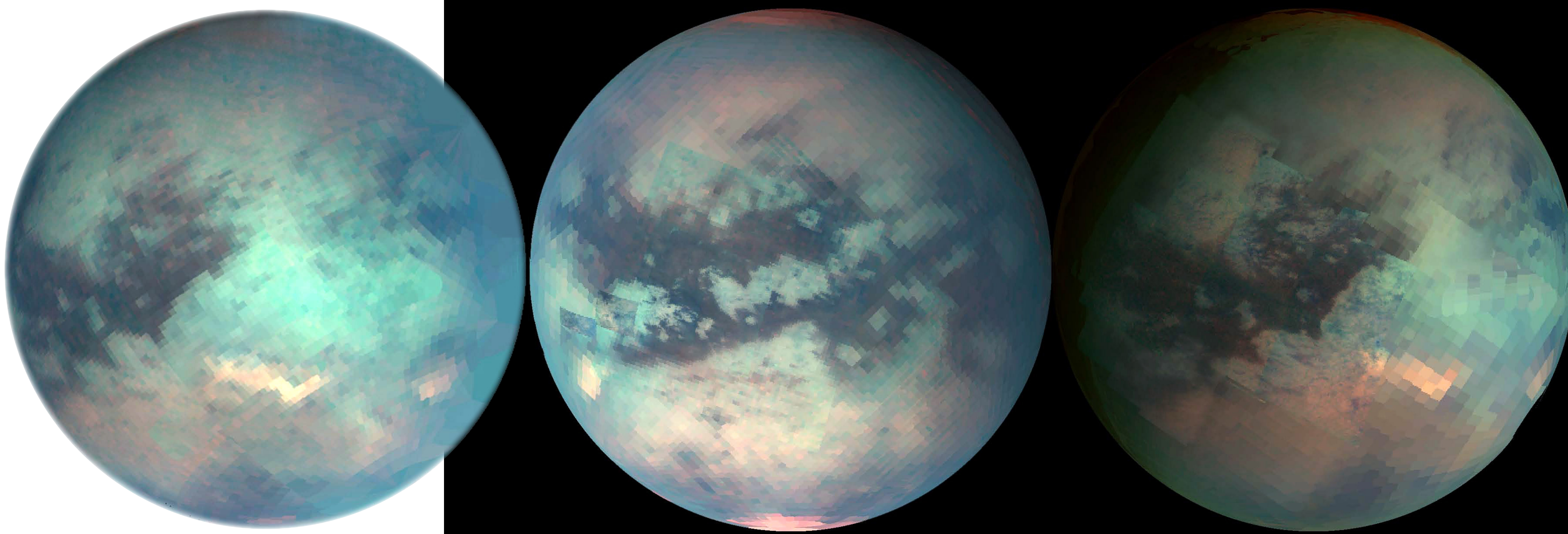
To make granite, you need water. "If you don't have water, you end up with things that approach granite but never get that far," Ghail notes. Finding granite, therefore, would mean Venus once had oceans — or at least enough water to allow for the reactions that make granite.

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?"

Secrets from Titan's seas

By probing "magic islands" and seafloors, astronomers are learning more than ever about the lakes and seas on Saturn's largest moon. **by Alexander G. Hayes**



These images show Titan, from left to right, in October and December 2005 and January 2006. The view from December is roughly the opposite side of the moon from the October and January flybys, but careful inspection of Titan's polar regions shows how dynamic and variable the polar weather can be. NASA/JPL/UNIVERSITY OF ARIZONA

IMAGINE YOURSELF standing at the shoreline of a picturesque freshwater lake, surrounded by soft grass and leafy trees. Perhaps you are enjoying a peaceful lakefront vacation. In the calm water, you see the mirror-like reflection of a cloudy sky just before it begins to rain. Now, let the surrounding vegetation disappear, leaving behind a landscape you might more reasonably expect to see in the rocky deserts of the southwestern United States. The temperature is dropping too, all the way down to a bone-chilling –295° F (92 kelvins). The air around you feels thicker, although you yourself feel seven times lighter, courtesy of reduced gravity. As the clouds pass overhead, you notice that the lake surface now reflects a hazy orange sky with the brightness of early twilight. After the clouds have moved on, you finally begin to feel rain hitting your hands. However, the rain falls much slower than normal and the drops are bigger, with large splashes following each impact. The ground you stand on is a loose sandy mixture of broken-up water ice and organic material like plastic shavings or Styrofoam beads. On closer inspection, the lake holds not water, but a liquid not unlike natural gas. And you'd better be holding your breath because the surrounding air has no oxygen.

If you can picture all of this, welcome to the surface of Saturn's largest moon, Titan.

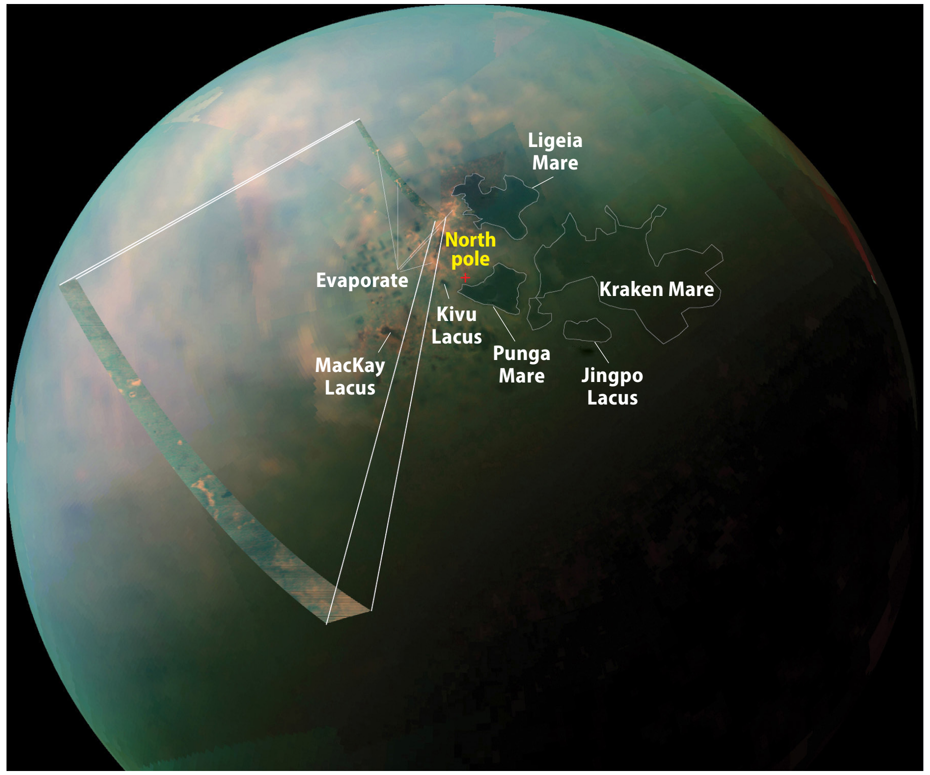
Titan is the only extraterrestrial body known to support standing bodies of liquid on its surface and the only moon with a dense atmosphere. It is also an explorer's utopia, supporting landscapes that are uncannily similar to those found on Earth while also presenting a seemingly endless supply of intriguing mysteries, with fresh questions following each new discovery. Two recent findings in particular have revolutionized our understanding of Titan's lakes and seas: their unexpected transparency to microwave radiation and the appearance of mysterious "magic islands," which our research team has been privileged to bring to light. But Titan's environment amazed well before these latest discoveries.

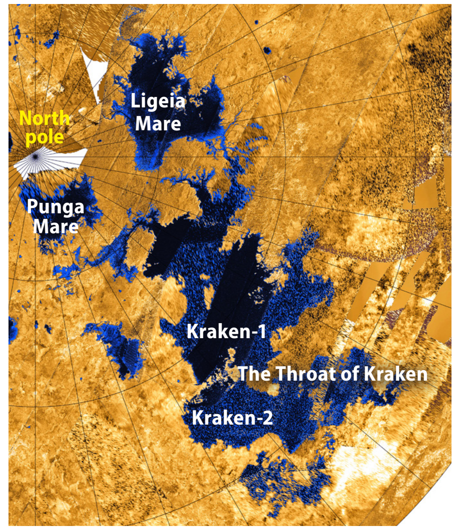
Alexander G. Hayes *is an assistant professor of astronomy at Cornell University. He and his research group focus on comparative planetology and solar system exploration, specializing in the development and operation of remote sensing instruments on unmanned planetary spacecraft.*

Strange but familiar

In many ways, Titan's landscapes are eerily similar to their terrestrial counterparts. You can find sand dunes similar in both

This Titan mosaic taken by the Cassini spacecraft shows the seas that speckle its north polar region and sunlight that glints off of them. NASA/JPL-CALTECH/UNIVERSITY OF ARIZONA/UNIVERSITY OF IDAHO





▲ **Cassini's RADAR instrument took this detailed image of Titan's north pole and the many lakes and seas that cover its surface.** NASA/JPL-CALTECH/ASI/USGS

◄ **Many of Titan's intriguing details are visible in this Cassini infrared image. The surface appears largely in green, while dry lakebeds show up in orange. The lakes and seas that dot Titan's northern hemisphere are the darkest regions.** NASA/JPL-CALTECH/UNIVERSITY OF ARIZONA/UNIVERSITY OF IDAHO

size and shape to the largest in the dune fields of the Saharan and Namibian sand seas of Africa. Alluvial fans (cone-shaped sediment flows left behind by rivers, streams, and landslides) resemble those found in the Atacama Desert of central Chile, and mountain chains are formed by tectonic forces similar to those responsible for the Himalayas that span southern Asia. Perhaps most astonishingly, lakes and seas scatter the polar landscape with shoreline features reminiscent of both marine and freshwater coastal environments found across our planet.

However, the dunes are not silicate sand; they are instead organic materials more like plastic than quartz. Rather than rock fragments delivered by flowing water, alluvial fans on Titan are a mixture of water ice and organic sediment delivered by flowing hydrocarbon liquids (methane and ethane). The mountains are broken-up sections of dirty water ice, and the lakes and seas are vast pools of liquid hydrocarbons. Despite these differences, the same mechanisms (such as wind and rain) sculpt and transport sediment across the landscape on Titan as they do on Earth. The similarities make Titan a natural laboratory for studying the processes that shape our own planet, including extreme conditions impossible to recreate in earthbound laboratories.

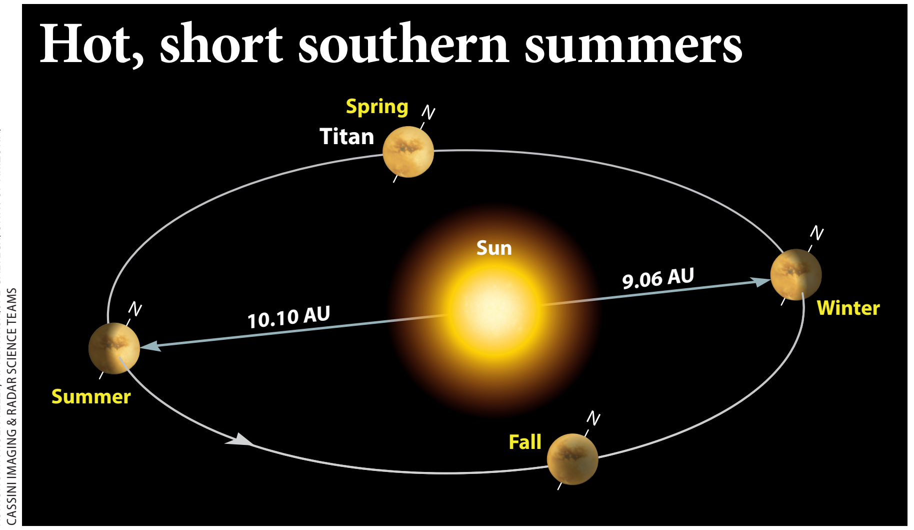
The forces that sculpt Titan's landscapes resemble Earth's water cycle, except that the key liquid is methane. Near the surface, methane makes up 5 percent of Titan's nitrogen-dominated atmosphere and, like water on Earth, condenses out of the atmosphere as rain and can persist as a liquid on the surface. If all of the methane in Titan's atmosphere were to fall down to the surface, it would make a global layer 23 feet (7 meters) deep. If you were to do the same thing to the water in Earth's atmosphere, the layer would be only 1 inch (3 centimeters) thick. On Titan, methane rain falls from the sky, flows on the surface, cuts channels into the bedrock, and fills depressions to form polar lakes and seas.

High in Titan's atmosphere, sunlight breaks apart methane in a process called photolysis (this also happens to methane in Earth's upper atmosphere). The methane splits into hydrogen, which escapes into space, and highly reactive compounds that quickly recombine to form more complex hydrocarbons like ethane and propane. These hydrocarbons rain out onto the surface and, over geologic time, rework themselves into the solid particles that make up Titan's dunes and coat the world's surface. Carl Sagan referred to laboratory-generated versions of the kinds of compounds Titan's atmosphere generates as "tholins" and noted that they are similar to the organic material that may have been important to the development of life on Earth. On Titan, these tholin-like materials form haze layers that obscure the surface from visible-light cameras, such as those on board the Pioneer 11 and Voyager 1 spacecraft.

Close encounters

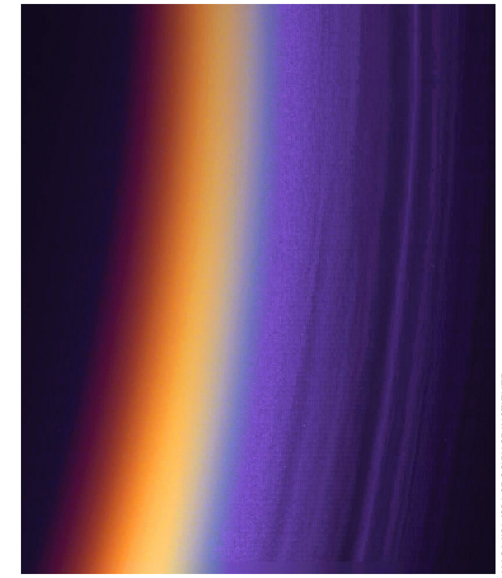
The presence of a thick atmosphere makes Titan unique among the moons in our solar system. It also made the saturnian moon one of the primary targets for exploration by Voyager 1. In fact, in order to reach Titan, Voyager 1 had to follow a specialized trajectory that eliminated the possibility of visiting Uranus or Neptune as Voyager 2 did on its "grand tour" of the solar system. While the cameras on Voyager 1 were not able to see down to Titan's surface, the spacecraft was able to use radio instruments to determine the surface pressure (1.5 times that of Earth) and temperature (92K). Following the Voyager encounter, scientists knew liquid methane and ethane were raining down and stable on Titan's surface but had no idea how they were distributed.

Prompted by the exciting results of the Voyager mission and the near two decades of ground-based imaging campaigns that followed, NASA and the European Space Agency (ESA) launched the Cassini/Huygens mission to Saturn in 1997. As a multipurpose mission, Cassini must divide its limited orbits around Saturn between many different moons (as well as the planet itself) and carefully allot its close flybys, but the spacecraft came specially prepared for Titan. In order to penetrate Titan's thick atmosphere,



ASTRONOMY: ROEN KELLY, AFTER NASA/JPL-CALTECH/UNIV. OF ARIZONA/CASSINI IMAGING & RADAR SCIENCE TEAMS

Seasons on both Earth and Titan are caused by each world's tilt, so that one side receives more direct sunlight. But on Titan, Saturn's eccentricity varies how far Titan orbits the Sun by more than an astronomical unit (AU; the average Earth-Sun distance), as well as speeding it up and down. This means the hemispheres don't share equal seasons, so the south has hotter, shorter summers than the north, driving liquid to the upper pole over eons.



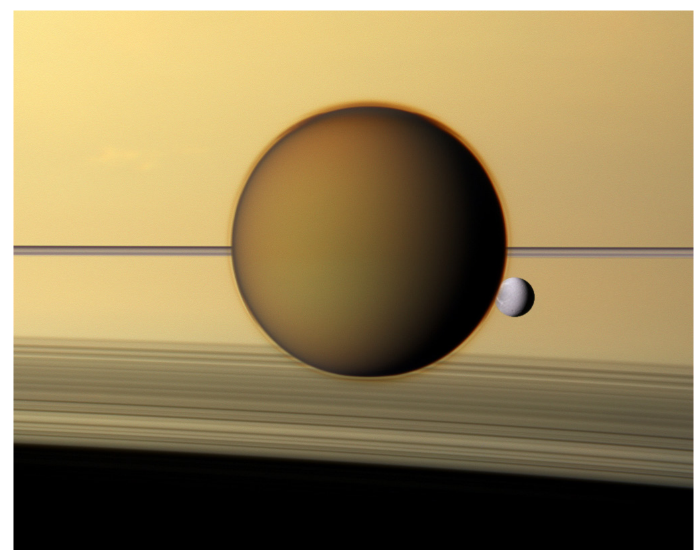
NASA/JPL/SPACE SCIENCE INSTITUTE

Titan's "purple haze" of an atmosphere is thanks to a thick shroud of methane, which separates into distinct layers upon closer inspection.

Cassini carries a radar mapper capable of obtaining images of the surface at a resolution of 1,000 feet (300m). The RADAR works by sending out bursts of microwave energy and measuring how much reflects back. Cassini contains two additional infrared instruments it uses to study Titan's surface, but their resolution is usually less than that of the RADAR. The Cassini orbiter also carried an ESA-provided probe, Huygens, which landed on Titan's surface in early 2005. Because at the time the surface of Titan was a mystery, engineers designed Huygens either to touch down on a solid surface or to land in an ethane sea. The probe touched down near Titan's equator on what appears to be a flood plain strewn with rounded cobblestones about 4 inches (10cm) in diameter.

Seasons and sunlight

The Saturn system tilts by 27° from the plane of its orbit, and thus Titan, like Earth, has seasons. Saturn and Titan, however, take 30 years to circle the Sun, so their seasons are 7.5 years long.



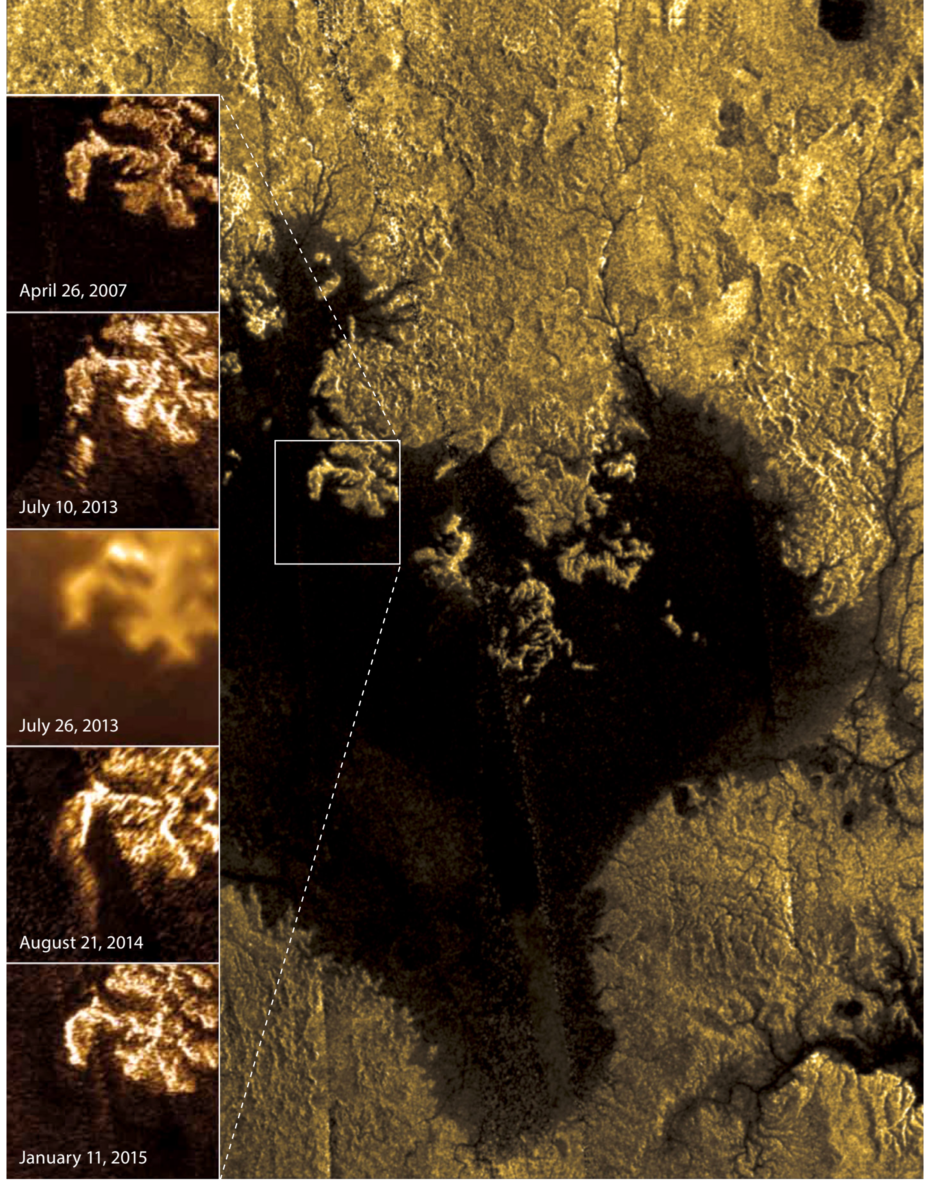
Titan poses here in front of Saturn's rings with its much smaller sibling moon Dione. The fuzzy outline of Titan is due to its thick, hazy atmosphere. NASA/JPL-CALTECH/SPACE SCIENCE INSTITUTE

The Cassini RADAR discovered Titan's lakes and seas in the north polar region during a flyby in July 2006, during northern winter. Since then, Cassini has discovered more than 300 liquid-filled depressions that range in size from moderately sized lakes at the limits of detection (about 90 acres, or 0.4 square km) to vast bodies larger than Earth's Great Lakes. The three largest, Kraken Mare, Ligeia Mare, and Punga Mare, hold the title "mare," which is Latin for sea. Collectively, the lakes and seas cover 1 percent of Titan's surface and lie mostly in the northern hemisphere, where they cover 35 times more area than in the south. We believe Saturn's eccentric orbit around the Sun causes this contrast between north and south.

Saturn is closest to the Sun during summer in Titan's southern hemisphere, when it tilts areas below the equator toward our star's most direct light. Northern summer, on the other hand, happens to occur when the Saturn system is farther from the Sun. As a result, southern summers are both hotter and shorter, with more intense sunlight than their northern counterparts. Over many seasons and years, the stronger, hotter sunlight in the south drives methane and ethane toward the northern hemisphere. But if this is the explanation for Titan's lake distribution, we should also note that it changes with time. The position of Titan's seasons on Saturn's eccentric orbit varies over periods of 50,000 years. In fact, 35,000 years ago, the situation was the exact opposite of today's scenario: Northern summers were hotter and shorter than southern summers. This suggests that the liquid in Titan's polar regions shifts between the poles over timescales of 50,000 to 100,000 years. And, in fact, there are large-scale depressions in the south that include features reminiscent of old shorelines along their borders. These paleo-seas encompass an area similar to the northern maria and suggest that Titan's south pole once looked similar to the north. This orbitally driven mechanism is analogous to the cycles on Earth that drive the frequency and duration of the ice ages.

Wind and waves

For most of Cassini's mission, its instruments observed Titan's lakes and seas to be calm and flat, with vertical deviations of



Titan's "magic islands" appear and disappear in Ligeia Mare from one observation to the next. They are more likely to be debris, waves, or bubbles than any supernatural occurrence. CORNELL UNIV./JPL-CALTECH

Titan's surface (left) can bear striking resemblance to Earth, where eons of flowing liquid — hydrocarbons or water — have shaped their surfaces and scattered debris across the landscapes. NASA/JPL/ESA/UNIVERSITY OF ARIZONA AND S.M. MATHESON

less than a few millimeters. This was surprising because the lower gravity and reduced surface tension and viscosity of liquid methane, as compared to water on Earth, should make it easier to excite wind waves.

Furthermore, we know that winds blow near Titan's equator because we see dunes. So why don't we see waves in polar lakes? After applying modern theories of wind-wave generation to Titan, scientists realized the absence of waves was most likely a seasonal effect resulting from light winds during the fall and winter. Researchers expected winds to freshen as Titan approached northern summer, with predicted speeds sufficient to sporadically ruffle the faces of hydrocarbon lakes and seas. Now, as predicted, Cassini has recently started to see indications of wave activity, such as sunlight glinting off ripples on the surface. Spurred by these results, research groups — my own included — began actively searching for activity in the lakes and seas, and the effort is delivering rich and often unexpected rewards.

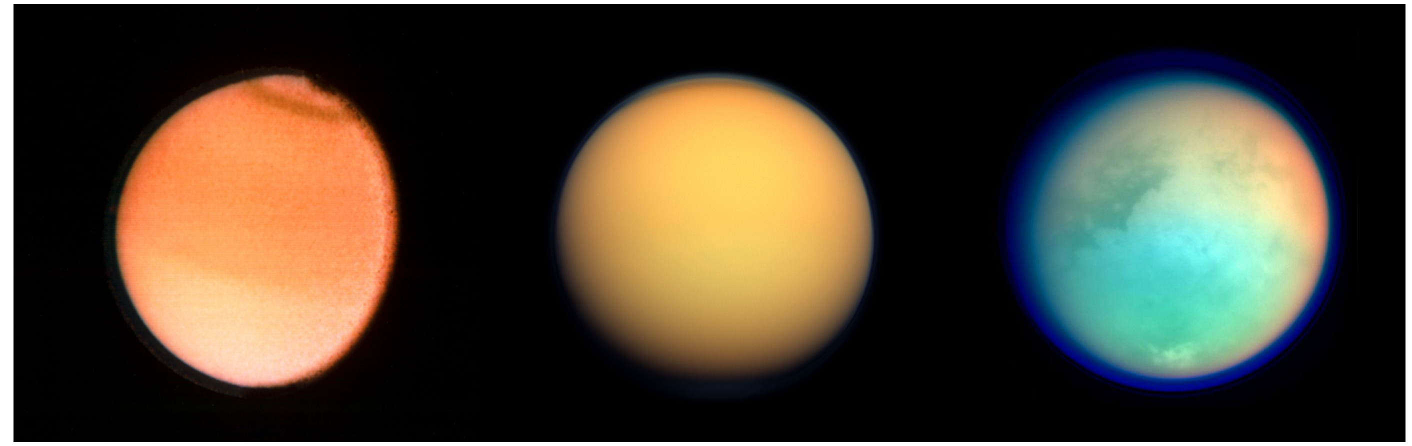
Old instrument, new tricks

In May 2013, the Cassini RADAR observed Ligeia Mare using its altimetry mode. In this mode, the instrument points straight down and measures the distance to Titan's surface by the round-trip travel time of the echo, similar to sonar. It also can read the roughness and composition of the surface through the intensity of the observed reflection. We intended this particular measurement to search for waves on the surface of Ligeia Mare.

While we didn't find any sign of waves, Cornell researcher Marco Mastrogiuseppe, an associate member of the Cassini RADAR team, re-examined the data and discovered two returns for each transmitted radio burst over the sea. The first return was from the surface of Ligeia, while the second was from the seafloor! The time delay between these two returns provided the first depth measurement of a Titan sea, showing that Ligeia Mare varied from 0 to 525 feet (160m) in depth along the observed range. This measurement is remarkable because it required the transmitted radio waves to pass through over 1,000 feet (300m) of liquid (to the floor and back again) without being completely absorbed. For comparison, the RADAR only would be able to penetrate 1 centimeter of seawater. The absorptivity of the liquid tells scientists what it is made of — primarily methane. This substance is four times less absorptive than ethane and 10,000 times less absorptive than seawater.

As a result of Mastrogiuseppe's discovery, the RADAR team redesigned two of Cassini's final three north polar flybys to obtain altimetry observations over the Kraken and Punga maria. These passes revealed the depth and composition of all three seas and proved that, contrary to expectations, methane, not ethane, is the dominant component. We have also applied Mastrogiuseppe's techniques to previous observations of the largest southern lake, Ontario Lacus, and showed it to be up to 300 feet (90m) deep and have 50 percent higher absorptivity then Ligeia. This increased absorption means the lake holds even more complex hydrocarbons, which may have slowly accumulated in Ontario with the transport of methane and ethane to the north over thousands of years.

These results have literally added a new dimension (liquid depth) to our understanding of Titan's lakes and seas and also showcase the adaptability and collaborative nature of the Cassini science team, who gave up long-standing observations of other key areas on Titan in order to accommodate these new altimetry observations. When considered collectively, the findings reveal that the surface liquid on Titan encompasses a volume of 17,000 cubic miles (70,000 cubic km), which is 15 times larger than the volume of Lake Michigan and equivalent to 300 times the mass of the entirety of the natural gas reserve on Earth.

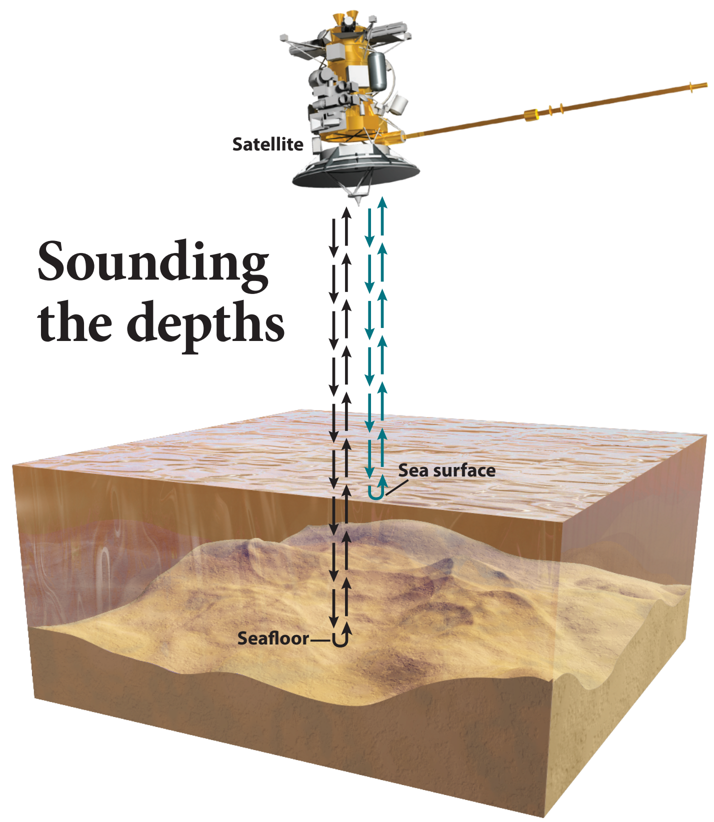


Views of Titan change dramatically from Voyager 2's flyby in 1981 (left) to Cassini, shown both in natural colors (center) and then peering through different cloud layers by using infrared and ultraviolet cameras. NASA/JPL (LEFT); NASA/JPL-CALTECH/SPACE SCIENCE INSTITUTE (CENTER, RIGHT)

"Magic islands"

Two months after the altimetry pass over Ligeia Mare, the RADAR re-observed the sea in imaging mode. Near a peninsula along the southeastern shoreline, it saw a 6-mile-long (10km) region of previously dark sea now to be nearly as bright as the surrounding shore. At first, the RADAR team collectively dismissed the bright feature as merely a blip in the data. But it intrigued Jason Hofgartner, a Cornell University graduate student in our research group, who pursued the analysis. Hofgartner's work proved that the features were not a blip but represented real changes at Ligeia. Despite the significant resource reallocation required, the team modified several of the precious few remaining RADAR passes in order to re-observe the area and document its evolution.

During this campaign, transient features appeared and disappeared at both the Ligeia and Kraken maria. Researchers affectionately dubbed them Titan's "magic islands," and they highlight the moon's dynamic seasonality. While the origins of the islands remain unknown, the most likely hypotheses include waves, floating debris, or bubbles. Whatever their cause, without the tenacity and determination of a young scientist who was in elementary school when Cassini launched from Earth, we would have not discovered the magic islands at all.

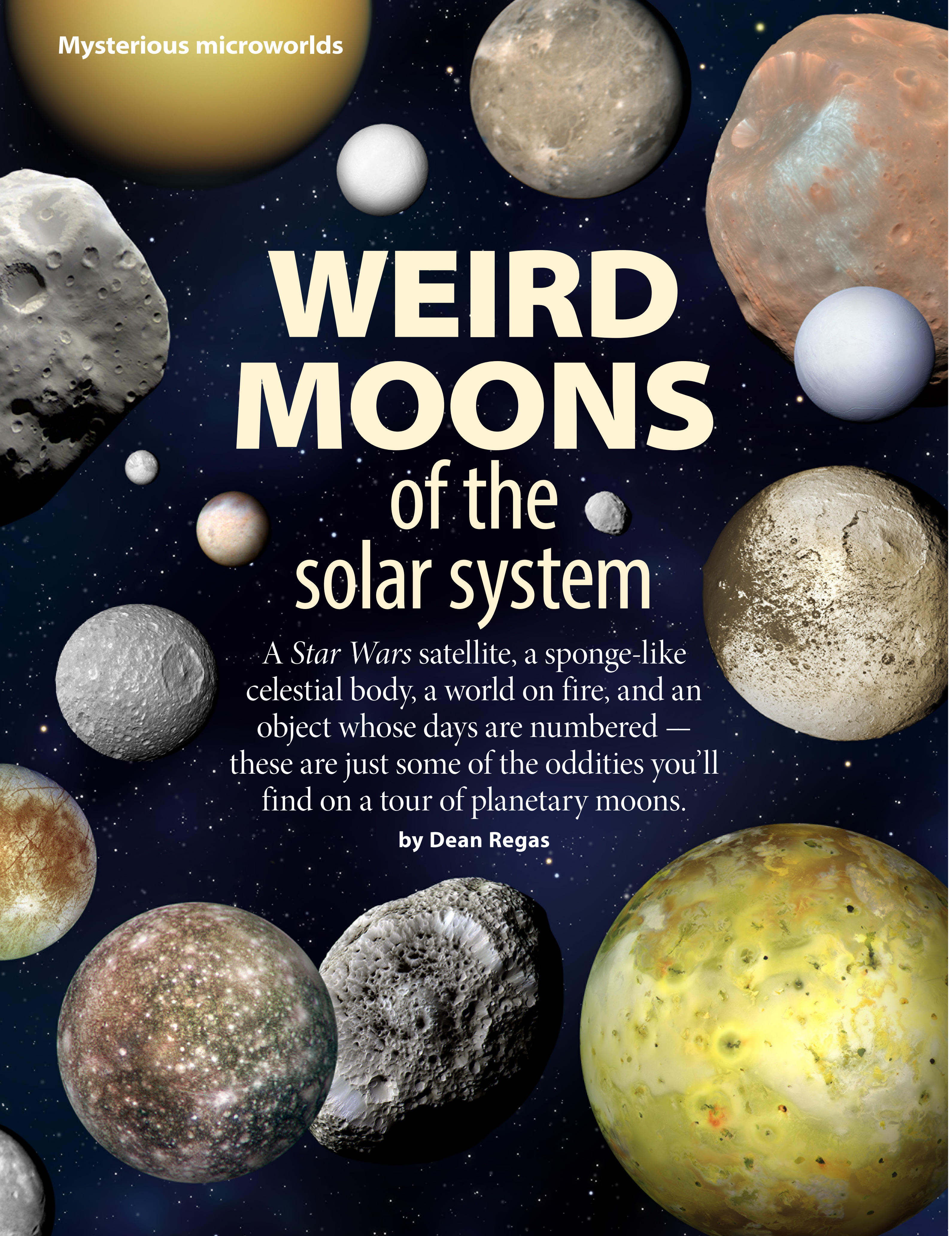


Cassini's RADAR instrument operates in altimetry mode by bouncing radar signals off Titan's surface. By measuring the difference in timing between bounces off the sea's floor and surface, astronomers measured the changing depth of Titan's seas. *ASTRONOMY*: ROEN KELLY, AFTER SCRIPPS INSTITUTION OF OCEANOGRAPHY

Learning more

Just as Earth's history is tied to its oceans, Titan's origin and evolution are chronicled within the nature of its lakes and seas. Their discovery has shown us that oceanography is no longer just an Earth science. Despite vastly different environmental conditions, Titan is arguably the most Earth-like body yet discovered and presents a mirror — however distorted — through which we can learn about our own planet. While the Cassini/Huygens mission has provided a wealth of information on the location and depth of Titan's lakes and seas, it has only scratched the surface regarding their composition and interactions with the atmosphere. Addressing these fundamental questions requires visiting them close-up.

Various groups have proposed a wide range of concepts for future Titan missions, including exploration of its maria. While no missions are currently scheduled, NASA nearly selected a capsule called the Titan Mare Explorer (TiME) in 2010, and interest remains high. On-site exploration of Titan's lakes and seas would let us directly observe liquid-atmosphere interactions, read the history of the moon's evolution in its atmosphere and surface, and investigate a natural laboratory for the limits and requirements of life by examining trace organics in the seas. It is my enduring hope that, within our lifetimes, someone will write this article's sequel describing discoveries from the first extraterrestrial boat to explore a Titan sea.



WEIRD MOONS of the solar system

A *Star Wars* satellite, a sponge-like celestial body, a world on fire, and an object whose days are numbered — these are just some of the oddities you'll find on a tour of planetary moons.

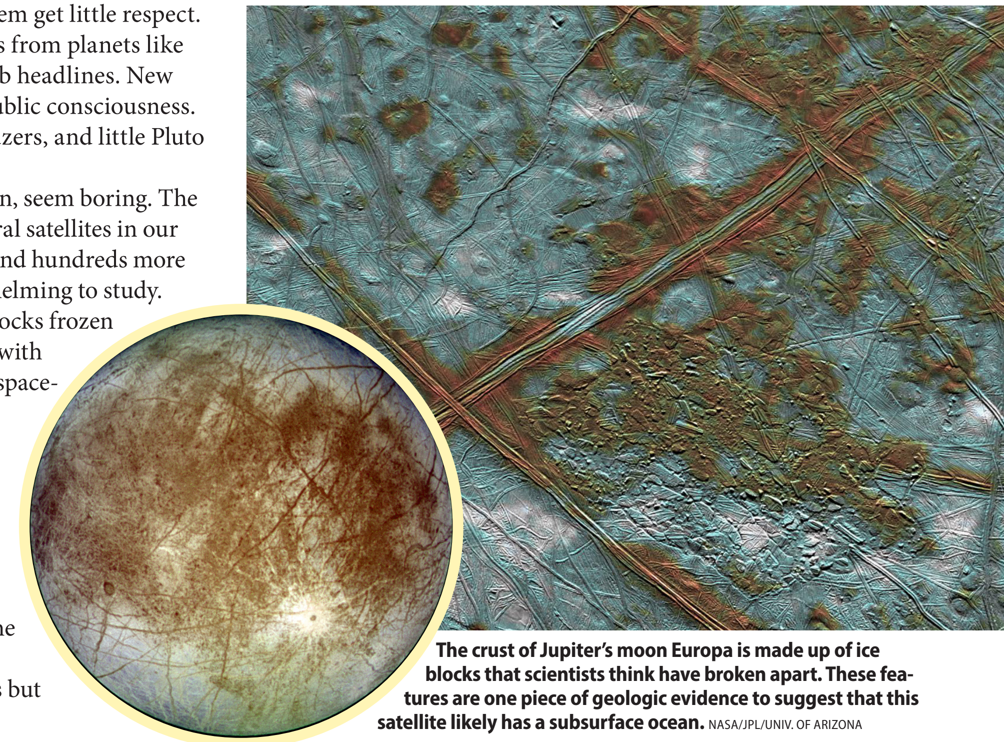
by Dean Regas

ASTRONOMY: ROEN KELLY (BACKGROUND); NASA/JPL/DLR (CALLISTO, EUROPA); NASA/JPL-CALTECH/SSI (ENCELADUS, EPIMETHEUS, HYPERION, IAPETUS, JANUS, MIMAS, TETHYS, TITAN); NASA/JPL (GANYMEDE, MIRANDA, TRITON); NASA/JPL-CALTECH/UNIV. OF ARIZONA (IO, PHOBOS)

Moons in our solar system get little respect. The latest discoveries from planets like Mars and Saturn grab headlines. New comets invade the public consciousness. Meteors dazzle skygazers, and little Pluto attracts a fan club.

Moons, in comparison, seem boring. The sheer number of these natural satellites in our solar system — currently 173 circling planets and hundreds more orbiting smaller bodies — makes them overwhelming to study. From afar, the moons look like cratered, gray rocks frozen in time and space. As astronomers look closer with more sophisticated telescopes and unmanned spacecraft, however, they are beginning to discover these objects' unique and colorful identities.

Many of our solar system's moons are surprisingly dynamic worlds with ongoing geologic activity. Volcanoes blow their tops, liquids flow, and geysers erupt. These objects experience rock tides and display cliff faces like nothing on Earth. Many moons present the scars of violent pasts. They are peculiar places that not only interact with their parent planets but also shake up other moons and disturb rings.



The crust of Jupiter's moon Europa is made up of ice blocks that scientists think have broken apart. These features are one piece of geologic evidence to suggest that this satellite likely has a subsurface ocean. NASA/JPL/UNIV. OF ARIZONA

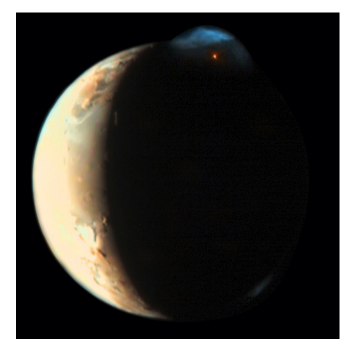
Fire and ice

With 67 moons and counting, Jupiter is a solar system in miniature, full of many weird worlds to explore. But two of its moons excite the imaginations of science enthusiasts like no others: Io and Europa.

Io is the most volcanic world in the solar system. Slightly larger than our Moon, the world fosters multiple erupting volcanoes on a daily basis, some of which shoot plumes of lava 250 miles (400 kilometers) above the surface. Vast lakes and rivers of dark magma flow while a caldera named Loki emits more heat than all the volcanoes on Earth combined.

Why so hot? Io is caught in a cosmic tug-of-war between gigantic Jupiter on one side and large jovian moons (Europa and Ganymede) on the other. The varying gravitational pulls stretch Io like a rubber band. On Earth, we experience ocean tides from the Moon's gravity. On Io, there is a ground swell. The stretching of all that rock produces heat, which melts a layer not far below the moon's crust that then bursts out of volcanoes that pepper its surface. Io is literally turning itself inside out.

The satellite's rapidly changing terrain presents a challenge for mapmakers. In April 1997, the Galileo spacecraft imaged Pele, Io's most distinctive volcano, and its ring of bright orange sulfur deposits 870 miles (1,400km) in diameter. On a subsequent flyby five months later, a mountain the size of Arizona had materialized on Pele's flank.



Jupiter's moon Io is home to hundreds of active volcanoes that reshape its surface. When the New Horizons spacecraft flew past the satellite in 2007, it captured the plume of the Tvashtar volcano (upper right) rising 200 miles (330 kilometers) above Io's north pole. NASA/JHUAPL/SWRI

Since Galileo's exploration, Jupiter and its moons also entertained a visit in 2007 by the New Horizons mission en route to Pluto. John Spencer and his team from the Jupiter Encounter Science Team at the Southwest Research Institute (SwRI) analyzed New Horizons data to discover an explosive blast that reshaped the surface of Io around the Tvashtar volcano.

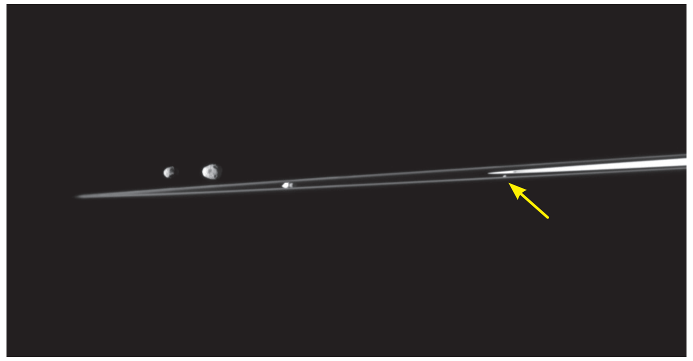
Ground-based telescopes also can see volcanic activity on Io. Imke de Pater from the University of California, Berkeley, using the Keck II Telescope in Hawaii to look at Io in 2013, measured one of the 10 biggest eruptions ever witnessed in the solar system. Who knows what the next Jupiter mission, the Juno spacecraft, will find on Io when it arrives in 2016?

Like its jovian sibling, Europa is experiencing many changes, but it's devoid of fire. The satellite is only slightly smaller than our Moon, and water ice coats its surface. Deep down, though, it is not as cold as it looks: Europa is not frozen solid.

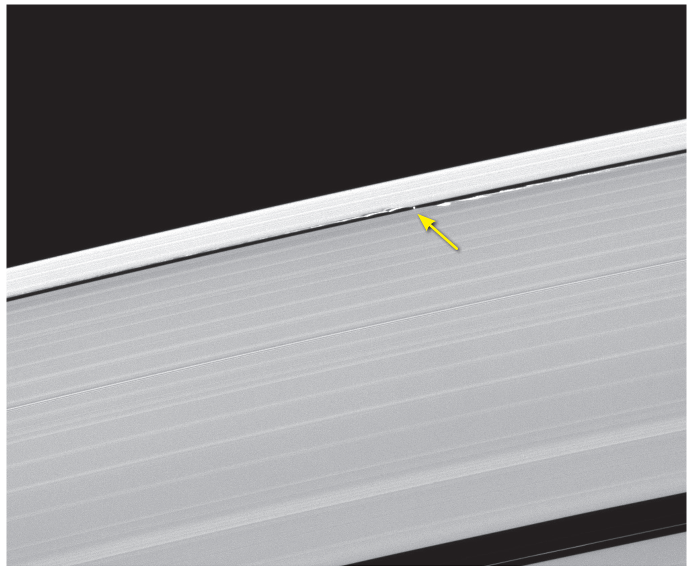
Most of the surface features on the satellite have formed in the past 100 million years. Compared to Earth's Moon, which has remained essentially unchanged for billions of years, Europa's landscape is relatively new. The smooth surface is broken by stress cracks and shattered sporadically by meteor impacts. Huge swaths of the europan surface look like broken glass molded together with clear glue. This "chaos terrain" may result from upwellings of new ice deposited in mammoth sheets that shift, slide, and collide.

The tug of gravity from Jupiter that creates Io's volcanoes also warms Europa's interior. Internal heat drives this chaotic change on the moon's surface and led astronomers to speculate that liquid sloshes around underneath. The ice-covered satellite may harbor

Dean Regas *is the outreach astronomer at the Cincinnati Observatory and co-host of the syndicated, bite-sized astronomy program* Star Gazers.



Several small moons orbit within or near the rings of Saturn. This particular quartet includes (from left) 70-mile-wide (113 kilometers) Epimetheus, 111-mile-wide (179km) Janus, 53-mile-wide (86km) Prometheus, and 19-mile-wide (30km) Atlas (arrow). NASA/JPL/SSI



The gravity of tiny Daphnis (arrow) is great enough to perturb the particles in Saturn's rings and create wavelike patterns. NASA/JPL/SSI

an ocean of liquid water more than 60 miles (100km) deep that melted because of the tidal heating. If this proves true, Europa would contain more water than Earth.

And where there is water — especially water that contains salts — there could be life. Many scientists consider Europa to be a prime candidate to host life within our solar system, but many questions remain. How much water is on Europa? Is the surface ice old or new, thick or thin?

In December 2013, scientists led by Lorenz Roth of SwRI created a buzz when they reported that the Hubble Space Telescope had found evidence of plumes of water vapor breaking through Europa's icy facade. Perhaps the ice is thin enough to allow life to flourish in the europan waters.

Shepherd moons

While Jupiter's moons remain somewhat mysterious, many of Saturn's 62 satellites are revealing their secrets thanks to the unmanned Cassini spacecraft, which has been orbiting the ringed world since 2004. For one, scientists are beginning to uncover the bizarre and unlikely dances between the moons and those breathtakingly beautiful rings.

Saturn's extensive ring system is not a solid mass. The rings are actually made up of individual bits of rock, ice, and dust that circle the planet at varying distances with different velocities. In effect, each ring particle is a moon. Some ring particles are the size of small mountains and even cast shadows across the thinner sections of material.

But where did these moonlike particles in the rings come from? Cassini Project Scientist Linda Spilker of the Jet Propulsion Lab considers two possible origins. "They could be as old as Saturn and formed with the planet," she says. "Or they could be much younger, formed by broken-up moons or comets."

Several small satellites also orbit within or near Saturn's distinctive rings. Astronomers believe that two "shepherd moons," Pandora and Prometheus, play a vital role in maintaining the size and shape of one ring. They act as gravitational tugboats that keep the ring from flying into space or joining with an interior ring.

Meanwhile, the ring moons Janus and Epimetheus orbit Saturn in nearly the same path. They will not crash into each other, but instead switch places about every four years. Like racecars, each moon takes a turn on the inside track.

The gravitational interactions of ring particles with the moons twist them into complex patterns. One tiny, 5-mile-wide (8km) moon named Daphnis was nicknamed the "wave maker" because it leaves a visible gravitational wake in the rings bracketing its orbit. From Daphnis' perspective inside the Keeler Gap, as the rings slide past it, rock and ice wave from both sides.

Funny features

Saturn's larger moons have their own weird attributes. Mimas, for example, looks suspiciously like the "Death Star" from *Star Wars*. But the likeness is purely coincidental; the passing Voyager 1 spacecraft captured the first detailed image of 250-mile-wide (400km) Mimas in 1980, while the movie franchise debuted in 1977.

With a giant crater overlaying a third of Mimas' face, this moon is a world of hurt. A violent impact rocked its surface with such force that the satellite barely held itself together. The resulting crater, named Herschel (in honor of the moon's 1789 discoverer, William Herschel) is 88 miles (140km) across and more than 6 miles (10km) deep. The ancient collision made Mimas decidedly egg-shaped and produced stress cracks in the rocky surface like ripples in a pond.

The Cassini spacecraft analyzed Mimas' surface in 2010 to create a global temperature map. Its heat is distributed in an irregular and surprising way: Thermally, Mimas resembles the video game icon Pac-Man. His face shows the warmer spots on this satellite and is most likely another remnant of the giant impact event.

Although not as in tune with pop culture as Mimas, Saturn's most dynamic satellite may be Enceladus. After one of Cassini's first flybys of the moon, Spilker discerned that this icy 300-mile-wide (500km) satellite might be special. "Magnetometer data showed something interesting at the south pole," she says. "The magnetic field was standing off the surface more like a comet than a moon."

To create such a magnetometer reading, Enceladus might have an atmosphere. The prospect convinced the Cassini team to take a closer look. "On the next flyby," Spilker remembers, "extra heat was coming out where we were so sure that there should be nothing." Cassini also watched as Enceladus passed in front of a background star. The light of the star flickered as if it was shining through cloudy material above the moon's surface.

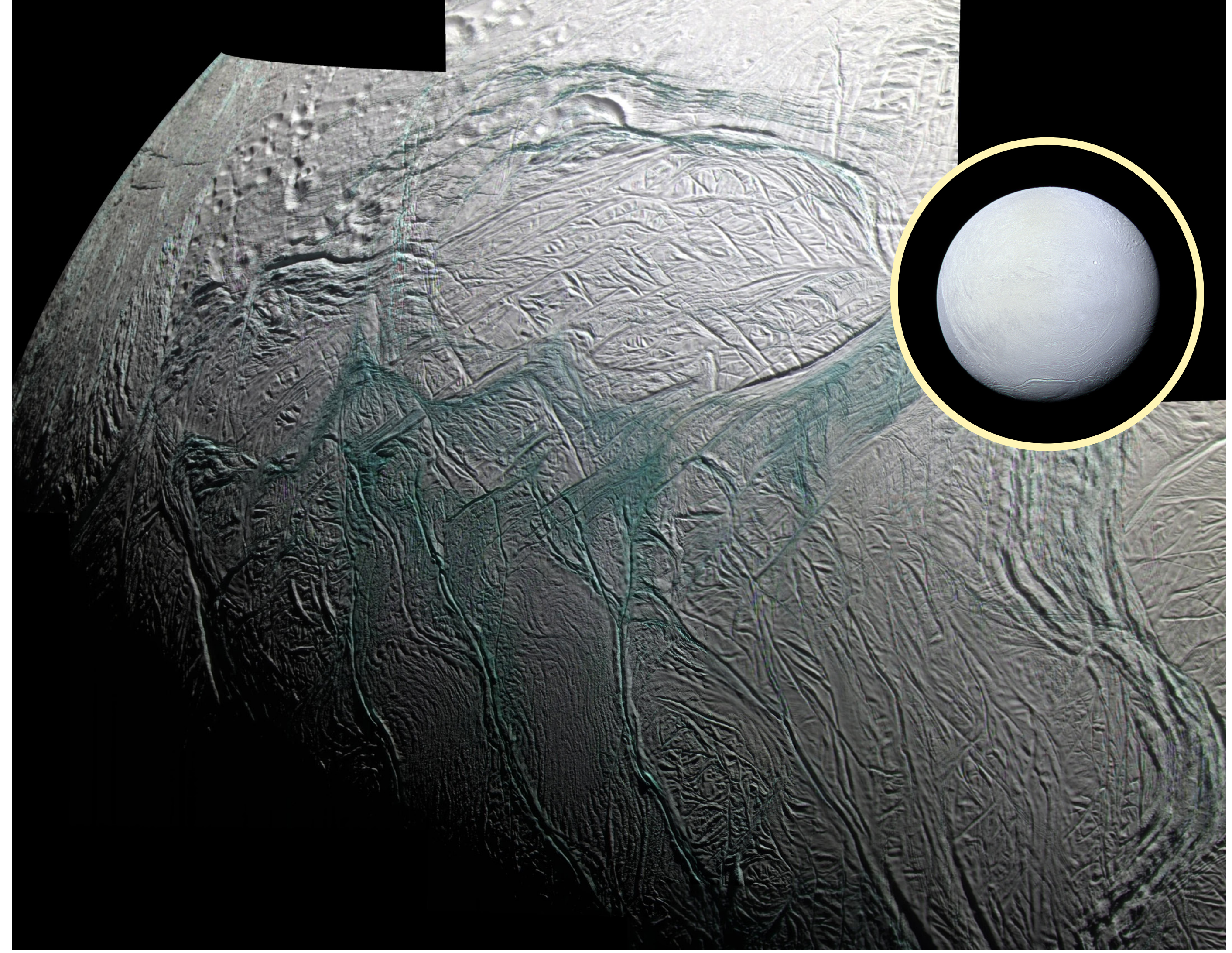
On the next flybys, Cassini discovered several exposed surface cracks at the south pole that scientists have named "tiger stripes." Often blue in false-color Cassini images, these structures are 80-mile-long (130km) fractures in Enceladus' crust that are much warmer than the surrounding plains. From them, dozens of cryovolcanoes eject water vapor and ice particles with enough force to escape the surface and fly into space. As Enceladus circles Saturn, this material is left behind as a tracing of its orbit. Enceladus has made its own ring!

A 2013 study by Cassini scientist Matt Hedman, now at the University of Idaho, describes how the tiger stripes actually open and close in a predictable manner. When Enceladus is near Saturn, the crevasses close significantly. When the moon is farther from the planet, they open up and output of the jets increases by a factor of three. Hedman compared them to nozzles of a garden hose squeezed by the tidal pull of Saturn.

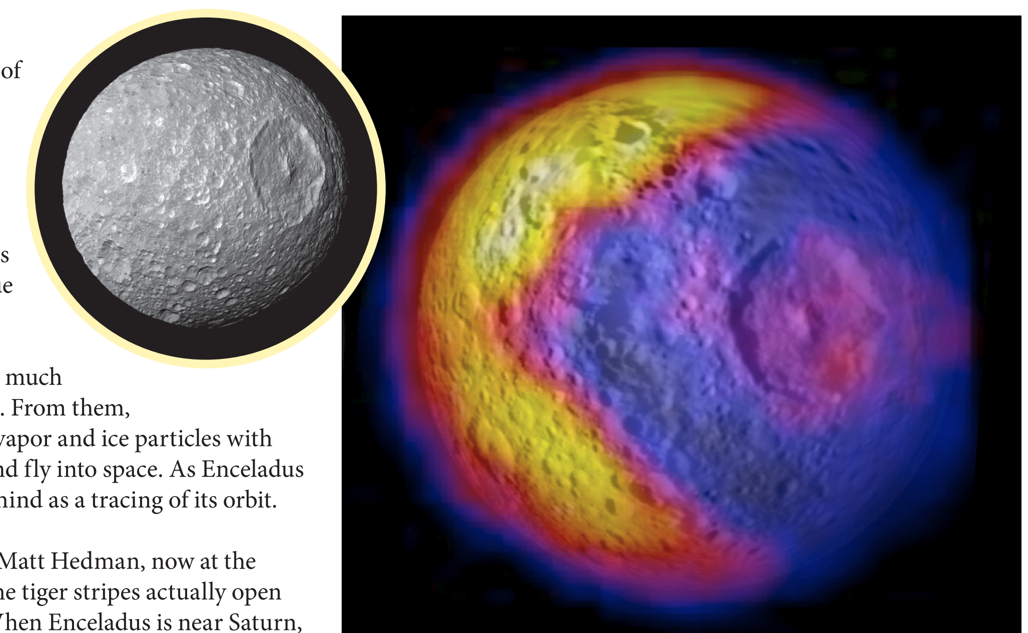
This revelation about Enceladus' geologic activity immediately deepened astronomers' understanding of ring formation and

MOON COUNT

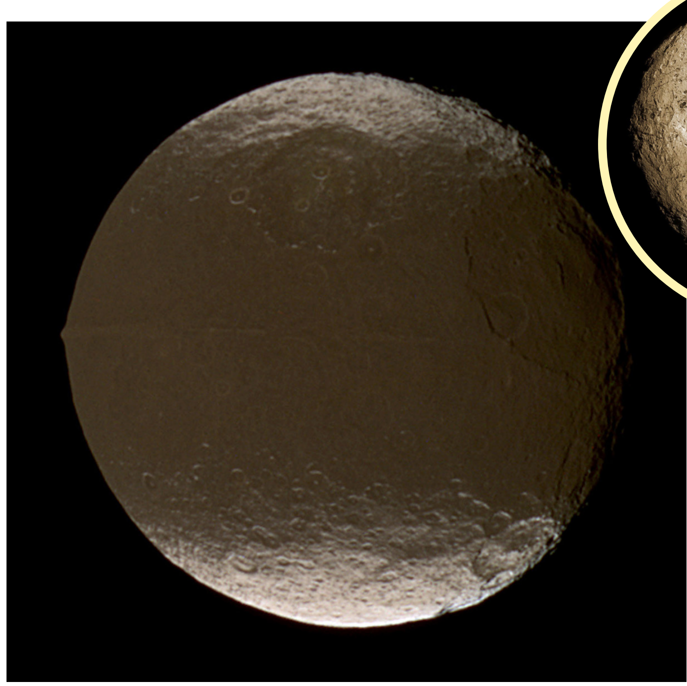
Mercury	0
Venus	0
Earth	1
Mars	2
Jupiter	67
Saturn	62
Uranus	27
Neptune	14
Asteroids	170
Kuiper Belt objects	85



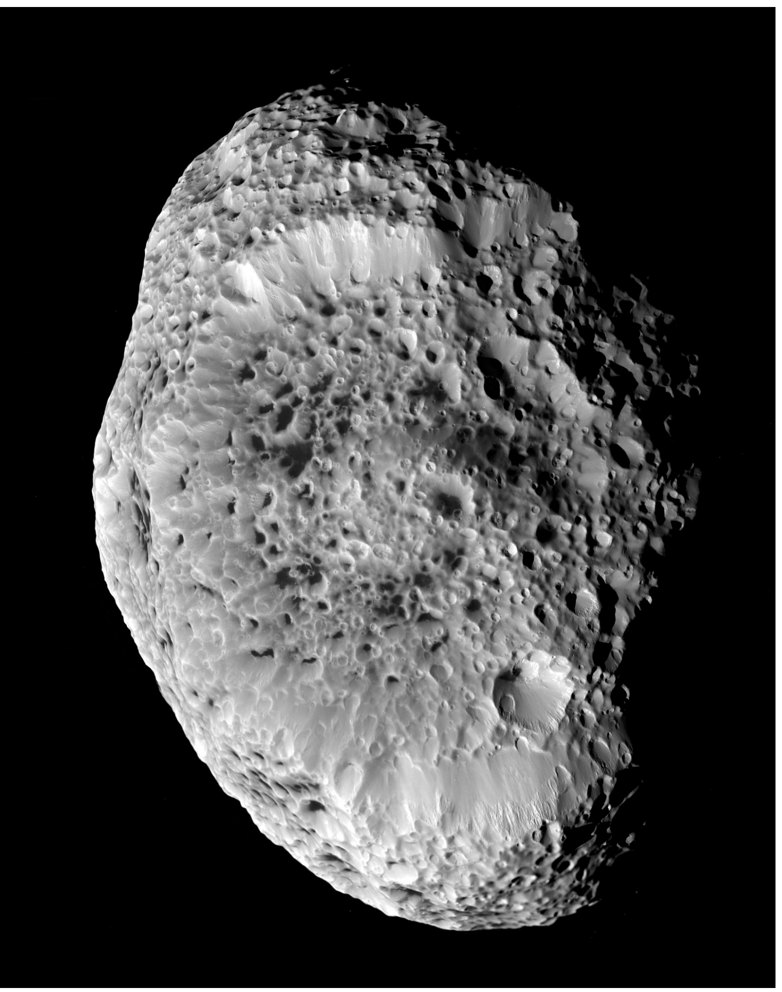
This false-color image of Saturn's moon Enceladus highlights one of its oddest features: "tiger stripes." These 80-mile-long (130 kilometers) fissures coated with fresh ice arc across the satellite's south pole. NASA/JPL/SSI



When scientists mapped daytime temperature data for Saturn's moon Mimas, they discovered an unexpected visitor: Pac-Man. Instead of the expected smoothly varying temperatures, this side of Mimas is divided into a warm part on the left and a cold part on the right with a sharp, V-shaped boundary between them. The cold side includes the giant Herschel Crater, which could be responsible in some way for the larger region of cold temperatures that surrounds it. NASA/JPL/GSFC/SWRI/SSI



Iapetus, Saturn's two-faced moon, resembles a walnut on one side thanks to dark ejecta coating its surface and a ridge that runs along its equator. NASA/JPL/SSI



Spongy Hyperion, maybe the weirdest-shaped moon in the solar system, has faced a violent past. Scientists think that the saturnian satellite's bizarre appearance is due to its unusually low density, which helps preserve the original shapes of Hyperion's craters by limiting the amount of impact ejecta coating the moon's surface. NASA/JPL/SSI

unveiled another place to look for life in the solar system. "This tiny moon should've been frozen solid, but here it is putting out all this water ice and gas," Spilker says. "We think of habitable zones being only regions around a star, but we could have them around planets, too."

Crazy shapes

But Mimas and Enceladus aren't the only strange large satellites of Saturn. The planet's moon Iapetus has a dual personality and a giant mountain range ringing its equator. This large satellite, nearly 925 miles (1,500km) in diameter, reveals a dark side and a light side. Iapetus rotates so slowly — once every 79 days — that it has a huge temperature difference between the daytime and nighttime sides.

This thermal segregation reinforces the dark/light dichotomy. Ices that change directly to gas on the warmer hemisphere are then deposited on the cooler side, giving it a frosted appearance. Material falling on the darker region has continually sandblasted it. "We saw enough from Cassini to tell us that the dark material on Iapetus is exogenic," says Spilker, "meaning it came from outside the moon." The source of the dark material is most likely a far-flung ring of dust called the Phoebe ring, first detected by NASA's infrared Spitzer Space Telescope in 2009.

The darker side may be only a thin coating. Ejecta from more recent meteor impacts on Iapetus' surface have thrown out brighter rays of material, indicating that the dark coating might not run deep and that the moon may be light as snow underneath.

Iapetus also has a unique mountain range along its equator. Some 6 miles (10km) high and 800 miles (1,300km) long, this ridge may date back to the formation of the moon. Coupled with the browner dark side, the mountain range makes Iapetus look like a colossal walnut.

But it's another Saturn moon's shape that wins the award for weirdest. Whenever the Cassini spacecraft flies by Hyperion, some 225 miles (360km) wide on its longest axis, scientists are amazed by the oddity of this world. This saturnian satellite resembles a giant sponge with deep, dark craters pitting the surface. The likeness is more than passing since much of Hyperion is hollow and the majority of its volume is ice rather than rock. Hyperion is so under-dense that it could be just a loose collection of rubble.

The giant craters and irregular shape suggest that Hyperion had a violent past. Today's Hyperion may be merely the largest remnant of a much larger body that was smashed to bits. This is what almost happened to Mimas.

Outer oddities

Saturn's moons continue to reveal their mysteries thanks to Cassini, but the moons of Uranus and Neptune have had only one visitor: the Voyager 2 spacecraft. Astronomers received tantalizing glimpses of these distant worlds as the probe flew through the two planetary systems in 1986 and 1989, respectively. And what they saw puzzled them. For one, Uranus' 290-mile-wide (470km) moon Miranda appears to have had a mysterious past. Its patchwork terrain includes a huge chevron-shaped outcropping that rises above the surface, the tallest cliff in the solar system, and enormous grooves that look like the bite marks of a giant. Why is Miranda so jagged?

Scientists originally hypothesized that an impacting object fragmented the satellite. Gravity then brought the pieces back together and loosely jammed them every which way. But now astronomers think Miranda had enough tidal interaction with Uranus and the nearby moons to stimulate extreme geologic processes. Instead of volcanoes of lava like on Io, though, Miranda had huge upwellings of ice that shot out of the interior like white daggers.

Voyager 2 also discovered that Neptune's largest moon, Triton, is definitely an oddball. It is the biggest moon in the solar system to revolve around its planet in the "wrong" direction. As Neptune rotates rapidly in one direction every 16 hours, Triton orbits in the opposite direction in a little under six days. This peculiar behavior suggests to astronomers that Triton did not form with Neptune; instead, the big blue planet's gravity probably captured the world billions of years ago.

Triton most likely came from the Kuiper Belt, a region of icy objects beyond Neptune's orbit that includes Pluto. In fact, astronomers believe that Triton could be Pluto's closest twin. Triton is about 1,700 miles (2,700km) in diameter with interlaced icy patterns of frozen nitrogen, carbon dioxide, and water on its surface. The moon is not geologically frozen, however, as it spouts nitrogen geysers and maintains a tenuous atmosphere.

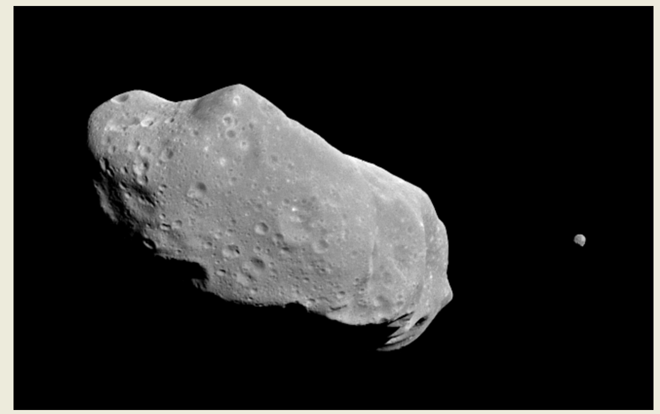
MOONS OF NON-PLANETS

Moons don't just orbit planets. More than 150 known asteroids also retain satellites. Astronomers discovered the first asteroidal moon in 1993. The Galileo spacecraft, on its way to Jupiter, flew near the potato-shaped asteroid Ida and spied a tiny spherical rock circling 55 miles (90 kilometers) from Ida's surface. Astronomers named this new moon Dactyl.

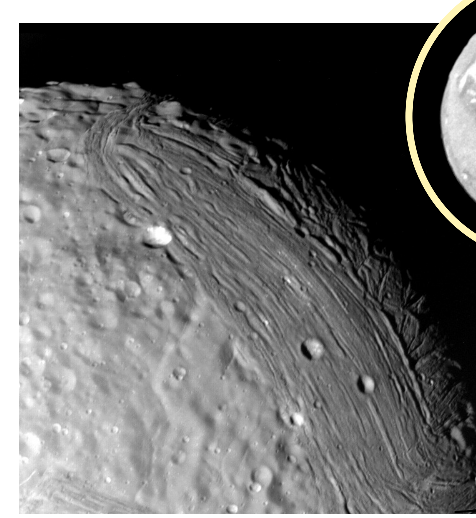
Dozens of objects in the Kuiper Belt also have satellites. Out of all the small bodies in the solar system, Pluto has the most known moons with five. The most bizarre Kuiper Belt system, however, is that around somewhat football-shaped Haumea.

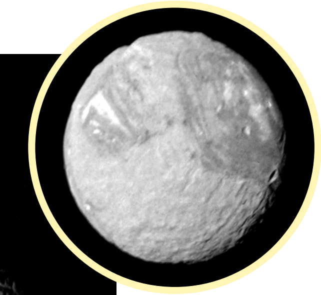
Discovered in 2004, Haumea is considered a dwarf planet because it orbits the Sun and is massive enough to form into a nearly spherical shape. Haumea rotates every four hours — faster than any object of its size in the solar system — and holds on to two little moons named Hi'iaka and Namaka. Astronomers link the odd shape, rapid rotation, and moons to one cataclysmic event. "Something smacked it a long time ago," says the California Institute of Technology's Mike Brown, Haumea co-discoverer, "creating two moons and a debris field left over from the ancient impact."

Astronomers can trace the origins of several recently found Kuiper Belt objects to the Haumea impact event. These chips off the old block may have spread due to multiple collisions smashing moons into other moons during the early days of the solar system. — *D. R.*

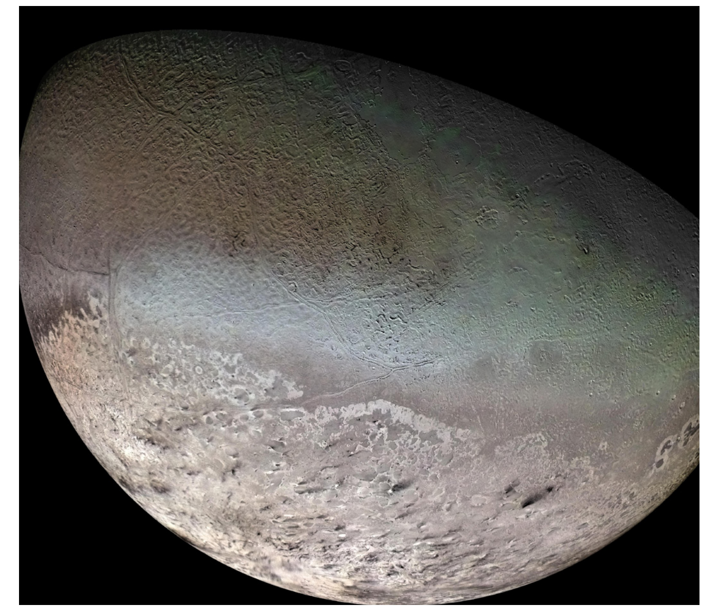


The Galileo probe provided conclusive evidence that asteroids can host moons when it discovered Ida's tiny satellite, Dactyl, during a 1993 flyby. Since then, astronomers have found 169 more asteroid satellites. NASA/JPL





When Voyager 2 passed Uranus' moon Miranda in 1986, it saw a world of diverse terrain, from subdued hills to linear valleys and ridges to partly curved troughs. NASA/JPL



Neptune's cantaloupe moon Triton is such an oddball that scientists now believe it originates from the more distant Kuiper Belt and was later captured by the eighth planet. NASA/JPL/USGS

Take a trip to the moons

Although undeniably fascinating, moons seem to get little respect from NASA. The space agency has repeatedly failed to fund a Europa orbiter mission (though it's again in the budget) and has turned down a proposed mission to Enceladus. Without a mission to Uranus or Neptune in the books, the farthest-flung satellites in the solar system likely will remain in the dark.

But because every moon in our planetary neighborhood is rocky, we could visit them — if not with spacecraft, then at least with our imaginations. Picture scaling the mountain inside Mimas' Herschel Crater. From the peak, we would have a close-up and never-ending view of Saturn and its rings. Because Mimas is tidally locked to Saturn, two-thirds of the giant planet and most of the rings would eternally sit above the western horizon.

Stop by Daphnis for an embedded view of Saturn's rings. Spelunk the caves of Hyperion, or base-jump off one of Miranda's cliffs. Watch a ring form from the tiger stripes of Enceladus, or ride the rock tides of Io.

Forget the planets. For sheer strangeness, there is nothing like the many moons in our solar system.