SPECIAL ISSUE The search for new life

SEPTEMBER 2019

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Hunting for life in the solar system

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Our special report looks at the prospects for life, past or present, in the solar system. NASA/JHUAPL/SwRI

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»

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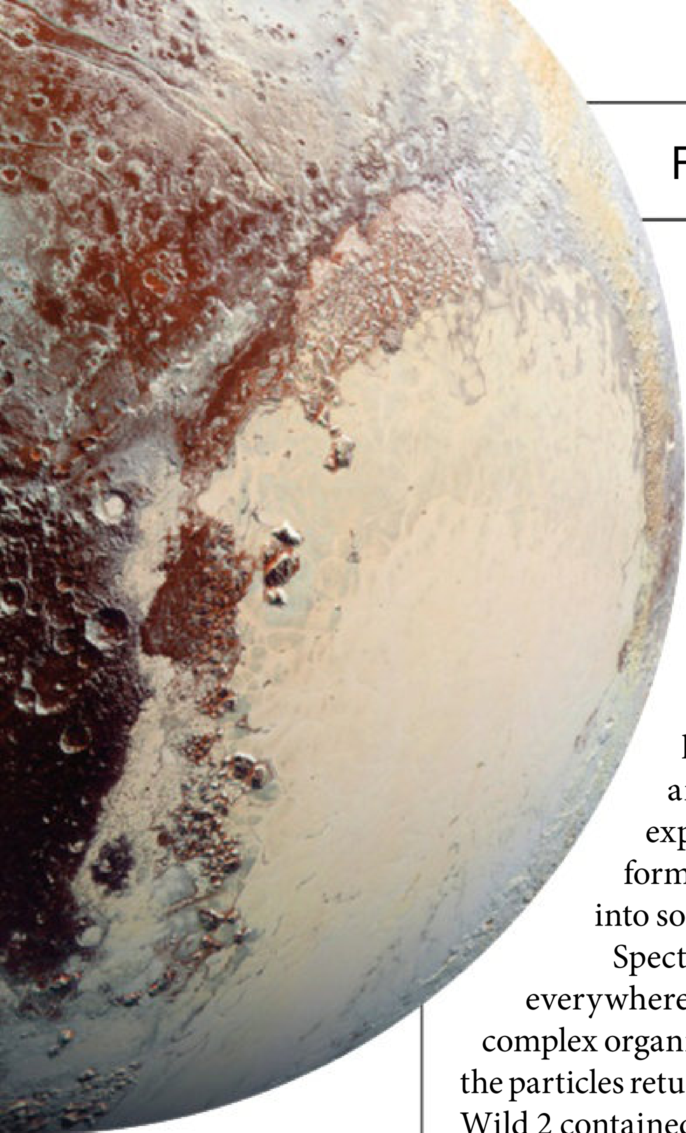


Pluto's Sputnik Planitia provides a tantalizing clue that the world harbors an underground ocean — and thus could be an abode for life. NASA/JHUAPL/SwRI

"Life can't be magicked into existence," the great evolutionary biologist Richard Dawkins has said. And it doesn't need to be. When most astronomy enthusiasts think of life in the cosmos, they immediately dream of aliens and UFOs. But statistically speaking, one might expect many worlds filled with microbes, the simplest forms of life, for every one world that might evolve life into something more complex, like on Earth.

Spectroscopy tells us that chemistry works the same way everywhere in the universe. We know from meteorites that complex organic molecules are abundant in the solar system. And the particles returned in 2006 by the Stardust spacecraft from Comet Wild 2 contained glycine — the simplest amino acid and one of the fundamental building blocks of life.

Experiments going back to the 1950s, when Stanley Miller and Harold Urey set up their lab equipment, have shown that the primordial soup, along with energy sources on early Earth such as lightning, could have straightforwardly created complex organics and led to the development of RNA and DNA. Chemical processing from simple elements to complex organics seems to have happened quickly on our planet, soon after the quieting of the Late Heavy Bombardment, when numerous asteroids, comets, and other bodies were smashing into Earth and the other inner solar system worlds.

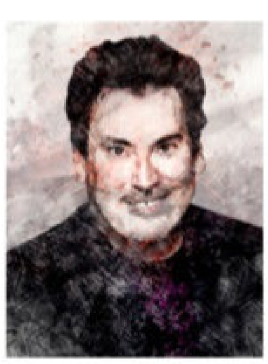
The more we investigate our own planet — under icy crusts, in searing volcanic calderas, at extremely high altitudes, or on the seafloor — the more we see that life is tenacious and able to flourish under extreme environments.

Life doesn't need magic. It simply needs systematic biochemistry. So the issue may not be, "How could life possibly have started on Earth?" so much as, "It's probable that many, many worlds with the right conditions harbor life."

Some of these worlds might even exist within our solar system, away from our blue planet. Could microbes be floating in Titan's methane lakes? Hurling skyward in the icy cryovolcanoes of Enceladus? Could the subsurface aquifers on Mars hold microbial life-forms, or could they have once evolved there, when the planet was wetter? Before New Horizons flew by Pluto, no one would have guessed that microbes could exist in the icy crust of that distant world, but now scientists consider it a possibility. And Triton and Europa could be hosts, too. The Europa Clipper mission is now on the boards as a first dive into investigating this question.

I hope you enjoy this special issue of the magazine, and that you'll ponder not just the fragility of life, but also its tenacity — and the fact that we might not even be completely alone in our own planetary system.

Yours truly,
David J. Eicher



Follow the Dave's Universe blog: **www.Astronomy.com/davesuniverse**
Follow Dave Eicher on Twitter: **@deicherstar**

Debunking COSTAR

It was with great interest that I read Jeff Hester's column in the May issue regarding the overhyped role of COSTAR in saving the Hubble Space Telescope from eternal scorn and ridicule. The *NOVA* episode mentioned in his column certainly did imply that COSTAR was almost single-handedly responsible for saving Hubble. While COSTAR did play an important role, and Jeff does give some credit to it, COSTAR was completely removed from Hubble in the final shuttle servicing mission in 2009. All optical corrections have since been done by other equipment, making COSTAR obsolete and putting its contributions to science since 2009 at about zero.

Regardless, I think most people can agree that Hubble has truly become, through the efforts of many different individuals, one of the most valuable instruments ever created for the advancement of science and astronomy. Good luck, James Webb, but you've got a tough act to follow. **— Dave Vavak,** Nevada City, CA

Asteroid or alien?

'Oumuamua is back in the news and still a mystery, according to Bob Berman's column in the May issue. Bob reports that it unexplainably picked up speed as it rounded the Sun and headed out of the solar system to parts unknown. This reminds me of Arthur C. Clarke's book *Rendezvous With Rama*. Clarke's uncanny tale, about an alien ship mistaken for an asteroid, could be unfolding before our eyes! **— Dmitri Tumin,** Andover, NJ

Molecule mistakes

I found "Where did Earth's water come from?" in the May issue to be extremely fascinating and informative. I did notice a minor error in the diagram of the structures of water and deuterium oxide (page 25) which did NOT detract from the high quality of the article. Each molecule is missing two electrons. The diagram shows single electrons at the interfaces of the hydrogen (or deuterium) and oxygen atoms; in reality, it should have shown pairs of electrons at these locations (forming covalent bonds). **— Peter Conigliaro,** Greendale, WI

From the editors: *You're correct, Peter — there were two electrons each missing from our diagrams of* D_2O *and* H_2O*. Our apologies for the error, and thanks for catching that!*

We welcome your comments at Astronomy Letters, P.O. Box 1612, Waukesha, WI 53187; or email to **letters@astronomy.com**. *Please include your name, city, state, and country. Letters may be edited for space and clarity.*

QUANTUM **GRAVITY**

EVERYTHING YOU NEED TO KNOW ABOUT THE UNIVERSE THIS MONTH

SNAPSHOT

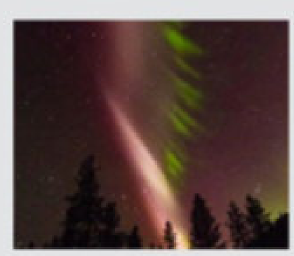
STUNNING SPIRAL

A galaxy spreads its arms wide.

Like most galaxies, NGC 2903 hides a dark secret: a supermassive black hole at its core. The inner regions of the spiral galaxy serve as the focal point for this image, taken with the Hubble Space Telescope as part of a survey to better understand how such supermassive black holes influence the gas, dust, and stars that lie in the center of the galaxy around them. NGC 2903, which sits about 30 million light-years from Earth in the constellation Leo the Lion, is intriguing because its central regions are forming stars at a more rapid rate than average, leading researchers to wonder about the cause. In addition to its glowing, elongated center, the galaxy also shows off bright star-forming regions and dark lanes of interstellar dust in this close-up view. —ALISON KLESMAN

HOT BYTES

LUNAR GOALS
On May 13, NASA announced the Artemis program will return humans to the Moon by 2024, requesting an initial $1.6 billion to jump-start the project.



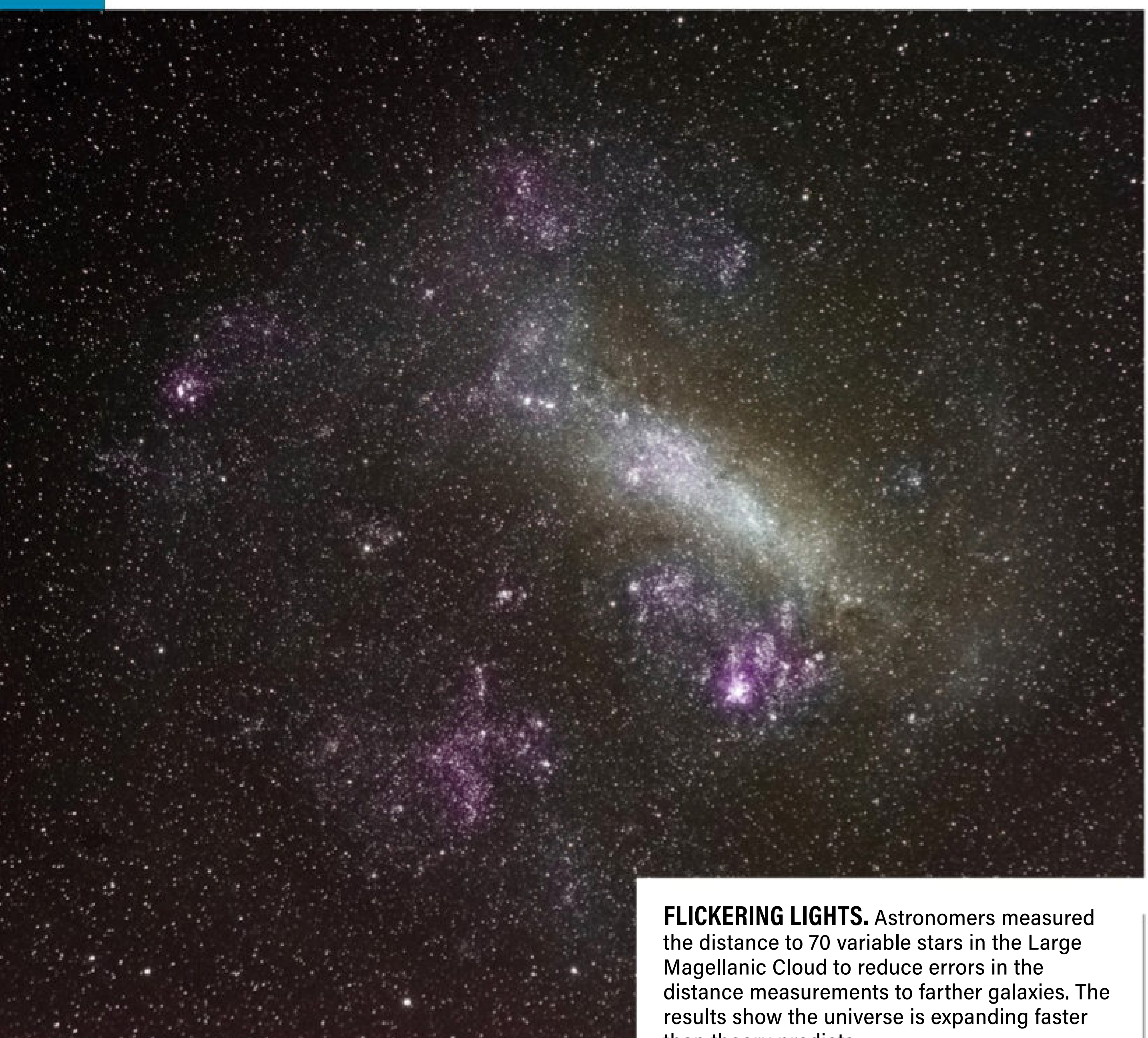
POWER SOURCE
Scientists have finally discovered the source of the glowing STEVE phenomenon: heated charged particles in the upper atmosphere. The effect is akin to a glowing lightbulb.

NEW SIGNALS
LIGO and VIRGO spotted gravitational waves from two colliding neutron stars for the second time April 25. One day later, they recorded gravitational waves that researchers think may be from a neutron star colliding with a black hole.

ESA/HUBBLE & NASA, L. HO ET AL. BOTTOM FROM LEFT: NASA; ROCKY RAYBELL; NASA/SWIFT/DANA BERRY

HUBBLE CONFIRMS UNIVERSE'S FAST EXPANSION RATE

The cosmos is expanding more quickly than expected, prompting astronomers to ask why.



FLICKERING LIGHTS. Astronomers measured the distance to 70 variable stars in the Large Magellanic Cloud to reduce errors in the distance measurements to farther galaxies. The results show the universe is expanding faster than theory predicts. CAFUEGO/FLICKR

» Scientists know the universe is expanding. But there's a conundrum: Studies of the early universe to derive the expansion rate, called the Hubble constant or H_0, don't mesh with measurements of the universe today. Instead, observations suggest it is expanding about 9 percent *faster* than the theoretical value obtained from the early universe.

There are two ways to determine how fast the universe is expanding. One is to use measurements of conditions in the very early universe to calculate the expansion rate, based on cosmological models. The other is to measure directly how quickly objects are receding from our position. Based on previous measurements, astronomers believed there was a 1 in 3,000 chance that the calculated and measured expansion rates don't actually disagree. (That is, there was a 1 in 3,000 chance the universe is actually expanding at the rate predicted by cosmological models.) But in a paper published April 25 in *The Astrophysical Journal Letters*, researchers led by Nobel laureate Adam Riess at Johns Hopkins University reduced those chances to 1 in 100,000. Their conclusion: The universe is definitely expanding faster than expected, although the cause remains unknown.

MEASURING UP

Astronomers measure the expansion of the modern-day universe based on the distances and speeds of faraway galaxies. But measuring distance can be quite tricky. Since 2005, Riess and the Supernovae H_0 for the Equation of State of dark energy (SH0ES) team have been using the Hubble Space Telescope (HST) to measure distance, and thus the expansion rate, more accurately.

Their recent work used HST to look at 70 variable stars, called Cepheid variables, in the Large Magellanic Cloud (LMC), a nearby satellite galaxy of the Milky Way. Cepheids cycle in brightness with a relationship related to their intrinsic brightness. So, measuring how long a Cepheid takes to change brightness allows astronomers to determine how bright it actually is. Then they compare that number to how bright it appears; the difference gives the star's distance.

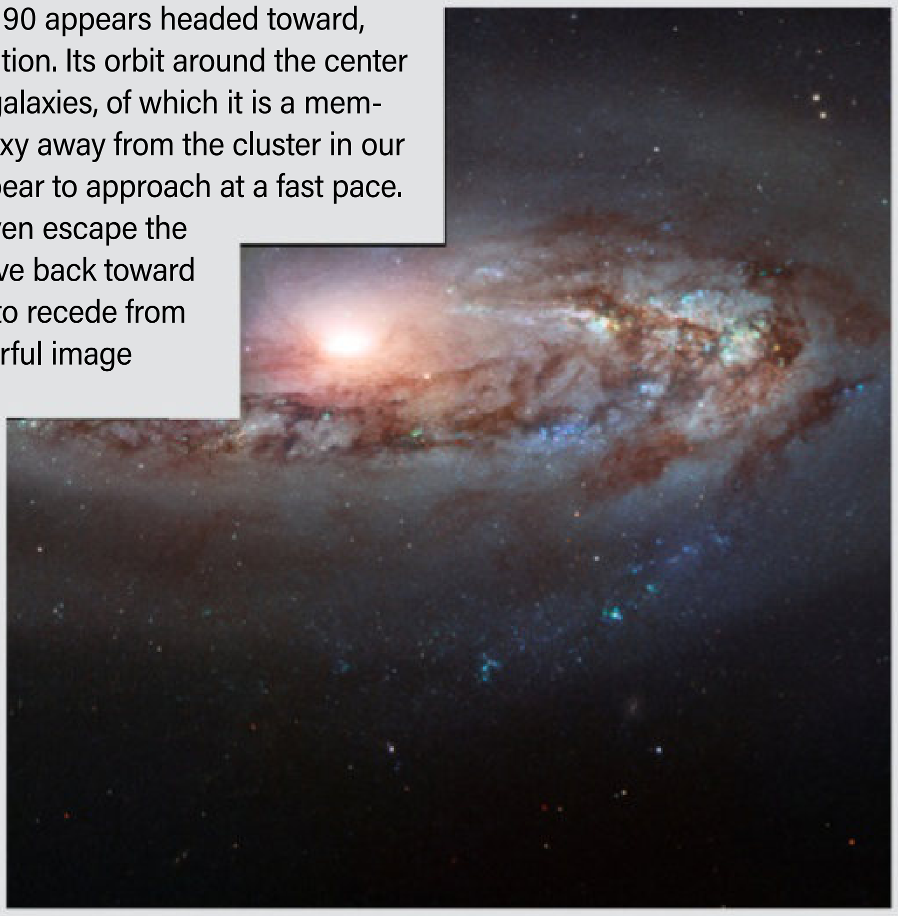
Cepheids are one rung on astronomers' cosmic distance ladder. Because these stars are only visible in nearby galaxies, they are used to measure distances in the local universe. Once

BONUS

For a deeper dive into this topic, check out "Tension at the heart of cosmology," on page 20 of our June issue.

A distant galaxy speeds closer

Unlike most galaxies, M90 appears headed toward, not away from, our location. Its orbit around the center of the Virgo Cluster of galaxies, of which it is a member, is carrying the galaxy away from the cluster in our direction, making it appear to approach at a fast pace. Eventually, M90 may even escape the cluster; if not, it will move back toward the center and appear to recede from Earth instead. This colorful image of M90, taken with the Wide Field and Planetary Camera 2 on the Hubble Space Telescope, includes visible, infrared, and ultraviolet light. The camera, which operated from 1994 until 2009, produced images with a distinct staircase shape. — A.K.



ESA/HUBBLE & NASA, W. SARGENT ET AL.

a galaxy's distance has been established with Cepheids, astronomers can use the same galaxy to calibrate the next rung on the ladder: stellar explosions called type Ia supernovae. Supernovae are brighter than Cepheids and can be seen at greater distances, allowing astronomers to measure distance, speed, and the Hubble constant based on farther galaxies. The process then continues, using new distance indicators each time the previous one becomes too dim.

NEW SHOES

Because uncertainty in any rung of the ladder propagates into every other step, minimizing the uncertainty in measuring distances to Cepheid variables is key to the entire process. Based on their new work, Riess' team reduced the uncertainty in the distance to Cepheid variables in the LMC from 2.5 percent to 1.3 percent.

Using their new calibrations, the team confirmed that earlier measurements of the Hubble constant in the nearby universe were spot-on. This also confirms the disagreement with the expansion rate calculated using conditions in the early universe, making it more likely than ever that the two rates are different.

"This is not just two experiments disagreeing," Riess said in a press release. "We are measuring something fundamentally different. One is a measurement of how fast the universe is expanding today, as we see it. The other is a prediction [of the current expansion rate] based on the physics of the early universe and on measurements of how fast it ought to be expanding. If these values don't agree, there becomes a very strong likelihood that we're missing something in the cosmological model that connects the two eras."

Riess said their next goal is to reduce the uncertainty in Cepheid distance measurements to 1 percent. The team hopes that by further shrinking the uncertainty, astronomers will be better able to determine why the two rates differ — which remains a hotly debated issue. – KOREY HAYNES, A.K.

QUICK TAKES

ASTROBEES

The International Space Station recently received two small cube-shaped robots named Honey and Bumble, which will aid astronauts with mundane tasks like checking and moving inventory.

WI-FI IN THE SKY

SpaceX has launched its first batch of 60 Starlink satellites, which Elon Musk hopes will become a network of 12,000 orbiting devices providing cheap, global internet coverage.

ICE BLANKET

New research suggests gases like methane trapped in a thin layer of ice may keep Pluto's suspected underground ocean from completely freezing over.

SHAKY SPIN

Astronomers witnessed a black hole's jets wobbling like a top, thanks to a misalignment between the black hole's axis of spin and the disk of material around it, which feeds the jets.

TRIP TO MARS

NASA is offering to send your name to the Red Planet aboard the Mars 2020 rover. Sign up by September 30 and receive a souvenir boarding pass at https://mars.nasa.gov/participate/send-your-name/mars2020/

LUNAR IMPACT

The meteorite that struck the Moon during January's total lunar eclipse hit the surface at about 38,000 mph (61,000 km/h), producing a crater 33 to 50 feet (10 to 15 meters) wide.

DUAL PERSONALITY

Researchers used positrons — the antimatter equivalent of electrons — to re-create the classic double-slit experiment, showing that antimatter acts as both a particle and a wave, just like normal matter. – JAKE PARKS

LAYER CAKE. Exposed alternating layers of ice (white) and sand (blue) at Mars' north pole reveal the planet's climate history in this false-color composite image. NASA/JPL/UNIVERSITY OF ARIZONA

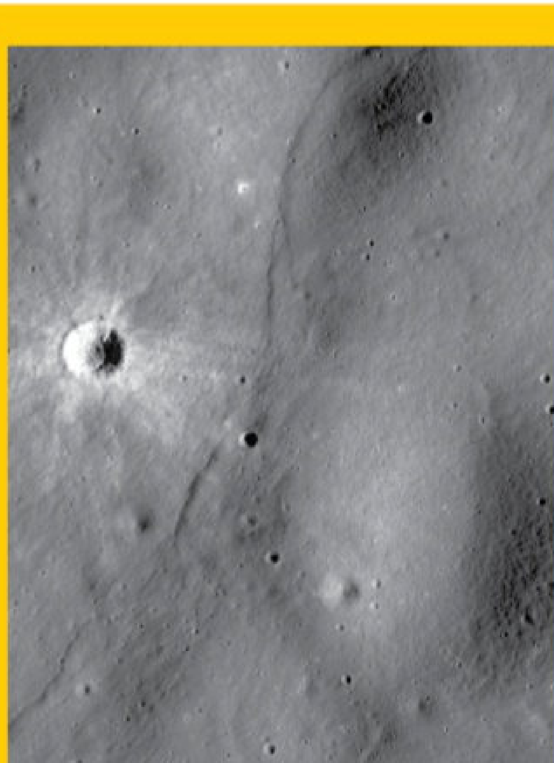
Polar ice offers a peek at Mars' past

» Geological evidence suggests water once freely flowed across Mars' surface. Now, the Mars Reconnaissance Orbiter's Shallow Radar (SHARAD) has found new clues about the Red Planet's past climate in layers of water ice and sand buried beneath the planet's northern ice cap. The newly discovered ice layers also make up the planet's third-largest reservoir of water, after the ice caps themselves.

The find was published May 22 in *Geophysical Research Letters*; a second paper, published the same day in the same journal, confirmed the reservoir independently, using gravity data. The researchers used SHARAD to peer 1.5 miles (2.4 kilometers) beneath Mars' north polar cap and study a site called the cavi unit. Radar data revealed alternating layers of sand and ice in the cavi unit, which the team believes preserves a record of Mars' past ice caps.

Astronomers know that Mars, like Earth, wobbles on its axis over tens of thousands of years. As its angle of tilt changes, the climate changes as well, growing warmer and cooler over time. The researchers think the ice in the cavi unit was laid down during colder, glacial periods in Mars' past. Previously, planetary scientists assumed that ice would melt away during warmer periods. But SHARAD revealed the ice was instead covered by sand, which insulated it from the Sun's rays and prevented it from melting or evaporating into space in Mars' thin atmosphere.

The discovery could shed light on Mars' past habitability. By understanding how much water was globally available on Mars in the past, the researchers say, they can develop a better idea of whether there was enough liquid water at the equator to support life. —K.H., A.K.



LUNAR LINES. Fault scarps, like the one seen here, are visible across the Moon's surface. New research suggests these faults may still be tectonically active. NASA/GSFC/ARIZONA STATE UNIVERSITY

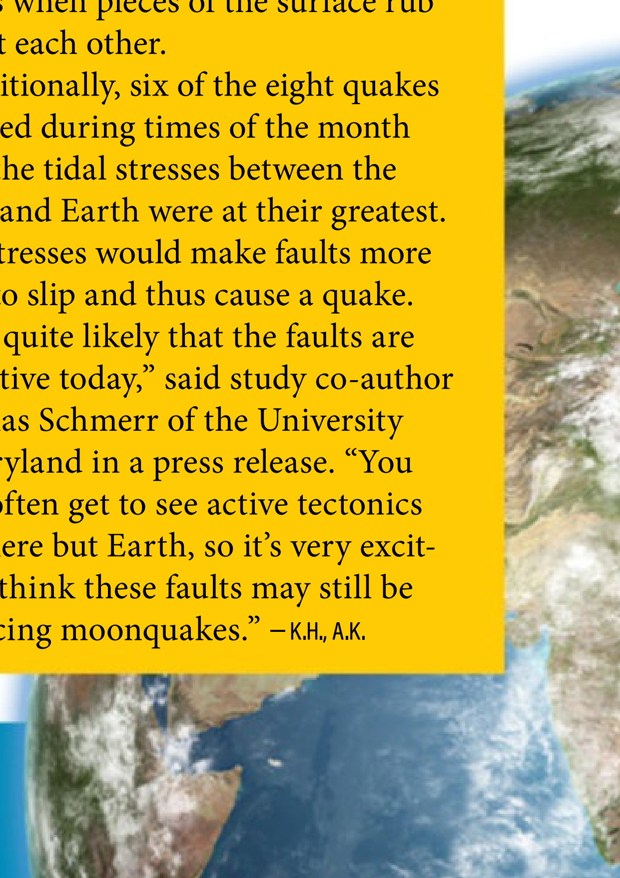
APOLLO-ERA QUAKES HINT THE MOON IS STILL ACTIVE

A new analysis of quakes on the Moon between 1969 and 1977 reveals that our satellite is likely still tectonically active.

The results, published May 13 in *Nature Geoscience*, are based on data from detectors laid down by Apollo astronauts half a century ago. Now, a team of scientists led by Thomas Watters of the Smithsonian Institution in Washington, D.C., has tracked the epicenter of 28 small moonquakes. They found that eight occurred within about 20 miles (30 kilometers) of fault scarps, which are cliffs that form when the Moon's surface shears away from itself as the crust slowly contracts. Based on these findings, it appears that lunar faults, like Earth's fault lines, cause quakes when pieces of the surface rub against each other.

Additionally, six of the eight quakes occurred during times of the month when the tidal stresses between the Moon and Earth were at their greatest. Such stresses would make faults more likely to slip and thus cause a quake.

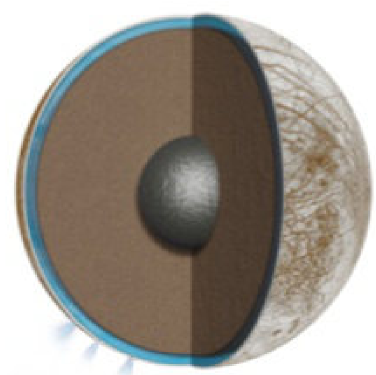
"It's quite likely that the faults are still active today," said study co-author Nicholas Schmerr of the University of Maryland in a press release. "You don't often get to see active tectonics anywhere but Earth, so it's very exciting to think these faults may still be producing moonquakes." —K.H., A.K.



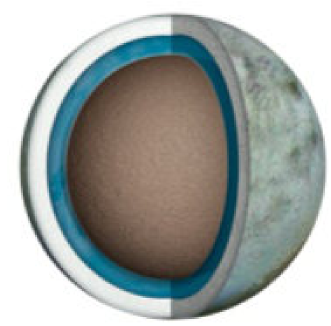
IT'S WHAT'S ON THE INSIDE THAT COUNTS

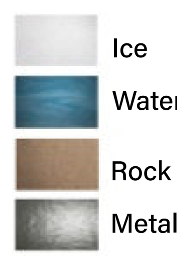
PEELING BACK THE ONION. It's astounding how far the ancient discipline of astronomy has progressed in just the past half-century. As humans continue to send increasingly sophisticated robotic scouts farther and farther out into the solar system, we continue to learn things about distant worlds that our ancestors would have thought nearly impossible to know. For instance, thanks to missions like Voyager, Galileo, Cassini, New Horizons, and many more, we now have good, data-based theories about the interior structures of many of the solar system's worlds. And one surprising feature we see on many worlds throughout the solar system is the presence of oceans hidden underground. These oceans, which are often expected to be filled with salty, liquid water, offer renewed hope for finding life on worlds previously written off as too cold and uninhabitable to support it. –J.P.

Europa (Jupiter)
Diameter: 1,940 miles (3,100 km)



Triton (Neptune)
Diameter: 1,680 miles (2,700 km)

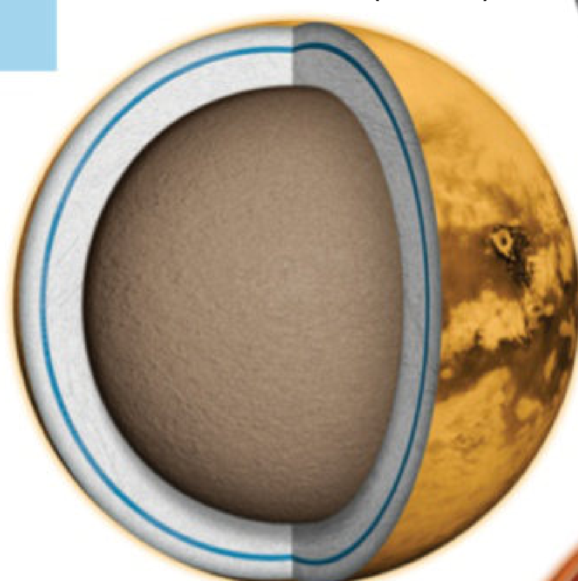




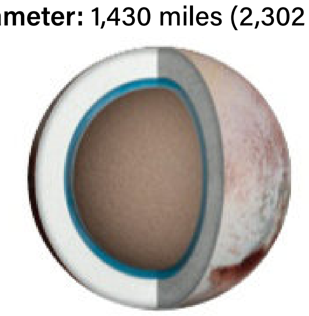
Unless noted, all images are to scale.

Enceladus (Saturn)
Diameter: 313 miles (504 km)

Titan (Saturn)
Diameter: 3,200 miles (5,150 km)

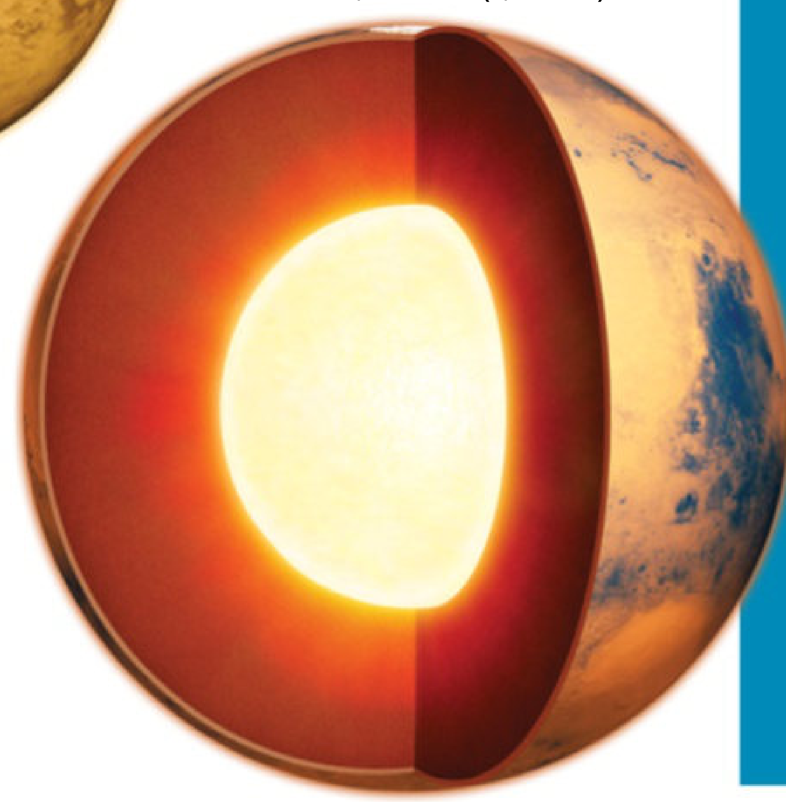


Pluto
Diameter: 1,430 miles (2,302 km)



Earth
Diameter: 7,918 miles (12,742 km)

Mars
Diameter: 4,212 miles (6,780 km)



ASTRONOMY: ROEN KELLY

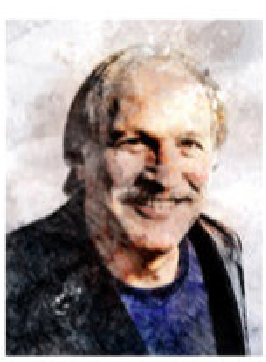
FAST FACT

It's still unclear whether Mars has a solid, liquid, or two-layered core like Earth. Fortunately, NASA's InSight mission deployed a seismometer late last year to help researchers find out.

Dangers from the sky

Are meteorites a health hazard?

Crushed fragments of the Sutter's Mill meteorite, a lighter-weight carbonaceous chondrite, pose less of a threat when raining down overhead than denser, iron meteorites.
NASA/ERIC JAMES



BY BOB BERMAN
Join me and Pulse of the Planet's *Jim Metzner in my podcast, Astounding Universe, at* **www.astoundinguniverse.com**

For some unknown reason, all the major showers plus the majority of sporadic meteors smash into us between August and early January. Most strike our atmosphere at 79,000–130,000 mph (35,000–60,000 meters per second). It sounds perilous.

Happily, atmospheric drag robs all meteoroids less than 8 tons of practically every bit of their cosmic velocity. By the time they've descended to where jetliners cruise, they will be falling solely from Earth's gravity and reach a terminal velocity between 200 and 400 mph (90–180 m/s). That's the speed at which meteorites hit Earth's surface.

Serious danger comes from meteoroids weighing more than 10 tons because these retain a portion of their original space velocity, and damage-producing kinetic energy depends far more on an object's speed than its mass. According to the American Meteor Society (AMS), "a 10-ton meteoroid entering the Earth's atmosphere perpendicular to the surface will retain about 6 percent of its cosmic velocity on arrival at the surface." If it started at 90,000 mph (40,000 m/s), it would strike the ground at 5,400 mph (2,400 m/s). Yikes!

Damage-producing kinetic energy depends far more on an object's speed than its mass.

It could be worse — much worse. The AMS also says that "a meteoroid of 1,000 tons would retain 70 percent of its cosmic velocity, and bodies of over 100,000 tons will cut through the atmosphere as if it were not even there."

Fortunately, larger meteoroids often break up around 10 miles (16 kilometers) above the surface, especially if they are stony. The fragments then abruptly slow down thanks to their reduced momentum. So, smaller, slower bodies are what commonly rain down.

Is there any way to assess their physical hazard to us? The surprising answer is yes, thanks to the strange human proclivity for celebratory gunfire. That's when people fire guns straight up, usually during occasions like New Year's Eve or the Fourth of July.

You'd think the chance of injury would be minuscule. Not so. In Puerto Rico alone, two people are killed and 25 injured each New Year's Eve because of celebratory bullets that come down on their heads. The density and mass of these objects can be similar to asteroid fragments that reach us as meteorites, so I did some research.

Bullets fired into the air during celebrations can return at a speed of up to 400 mph (180 m/s), which well exceeds the 157 mph (70 m/s) at which a bullet can penetrate the skin to damage organs. In Los Angeles between 1985 and 1992, doctors at Martin Luther King Jr./Drew Medical Center treated 118 people for random falling-bullet injuries, and 38 of them died. A 1994 study in the *Journal of Trauma: Injury, Infection, and Critical Care* showed that of those 118 patients, 77 percent were hit in the head, and these had a mortality rate of 32 percent.

Heft matters, too. In experiments conducted before World War II, .30-caliber rifle bullets fired straight up reached an altitude of 10,000 feet (3,050 m) and ultimately descended at 300–600 feet per second (90–180 m/s), which can easily fracture bone and cause intracranial penetration. Lighter bullets, like those fired from a 9mm handgun, return to Earth at lower speeds between 150 and 250 feet per second (45–75 m/s).

This suggests iron meteorites like octahedrites are more than twice as hazardous as the lower-density carbonaceous chondrites. And with meteorites and bullets alike, location matters. Falling objects slow dramatically in thicker air, whose resistance decreases with altitude. So, meteorites and bullets are more hazardous in Tibet than in, say, Brooklyn.

Are you worried now about our upcoming meteor showers? Don't be. Their "shooting stars" are skimpy ices that cannot survive their trip through the atmosphere. They can't hit you, ever. As for protecting yourself from celebratory fire, which although illegal in the United States can be a real concern, consider that if some friend ever fires straight up into the air, the easiest safety response is to simply walk into the house. That's because you'll typically have a full half-minute before it returns to Earth.

Only in this magazine will you find these vital health tips concerning dangers from the sky.

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★★★

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Are we alone in THE SOLAR

Mars, Pluto, and an array of icy moons offer possible places where microbial life might have existed — or might yet exist today.

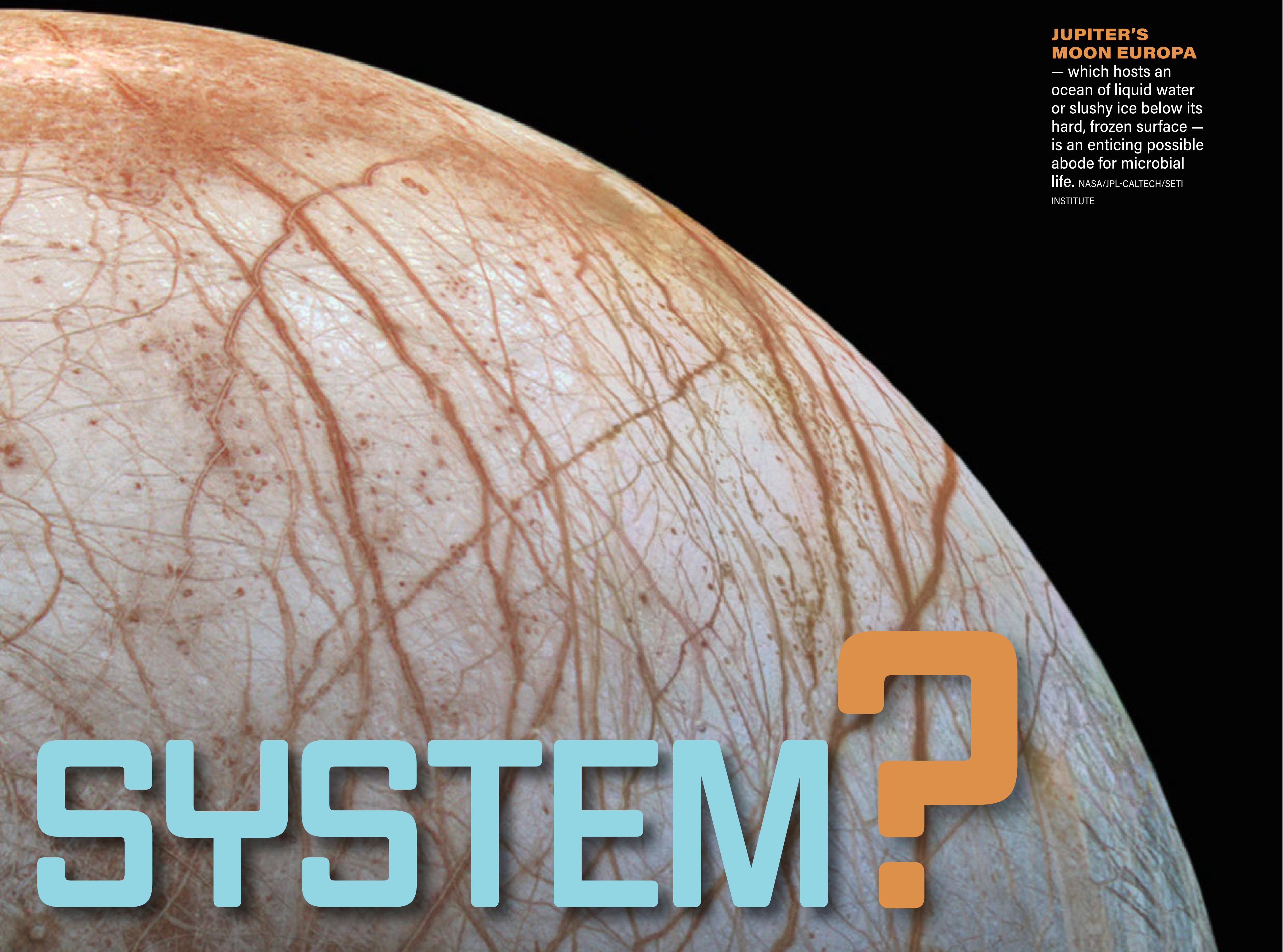
BY DAVID J. EICHER

STANDING UNDER A STARRY sky and gazing up at its wonder, it's easy to believe that we're alone in the cosmos. The distances are vast, and, after all, we know of only one planet in the universe that hosts life — ours. But it's possible we may not be alone even in our own solar system. Consider the facts.

What exactly is life, anyway? Biologists define life as self-replicating molecular systems that contain DNA and RNA and use energy, reproduce, and undergo Darwinian evolution. There are other characteristics, but those are the primary ones. And the possibilities for life are actually pretty intriguing. Spectroscopy tells us that chemistry is uniform throughout the cosmos. We know that basic organic molecules are spread liberally throughout the universe, even in the one and only comet sample to be returned to Earth.

It's also a big universe out there. We know of at least 10,000 billion billion stars in the cosmos. And exoplanetary systems near us in the Milky Way demonstrate that most, if not all, stars should also harbor planets. It's exciting to think of other sophisticated creatures we could run into one day, or at least communicate with from afar. That's the basis of the whole genre of science fiction. But what about more commonplace life? Biochemistry suggests that for every place you might find sophisticated life like us — hold the jokes — you would probably witness many more places hosting microbial life.

Some of those places might exist right under our noses. Our most storied planetary neighbor, Mars, has a long history



JUPITER'S MOON EUROPA — which hosts an ocean of liquid water or slushy ice below its hard, frozen surface — is an enticing possible abode for microbial life. NASA/JPL-CALTECH/SETI INSTITUTE

SYSTEM?

of speculation about its potential for life. Space missions put an end to science fiction thoughts about martian creatures, but ample evidence of past and recent liquid water on the surface — and of subsurface water and water ice — have fueled ideas about microbial life on past or present-day Mars.

Interestingly enough, research on the icy bodies in the outer solar system has led to a flood of ideas about possible microbial life out there. Before New Horizons flew by Pluto in 2015, no one really would have talked about the possible existence of microbes in slushy, icy reservoirs beneath the frozen crust of Pluto. But team members now talk about that as a distinct possibility.

For a long time, dating back to the Voyager missions, scientists have contemplated icy moons of the solar system as possible homes for microbes, past or present. The poster child has been Europa, one of the four Galilean moons of Jupiter. Europa undergoes tidal heating from its large planet and has either a subsurface liquid ocean or an icy, briny layer of warm convecting ice underneath its outer shell. Either one might make a comfy place for organic chemistry to do its magic and eventually produce some self-replicating molecules.

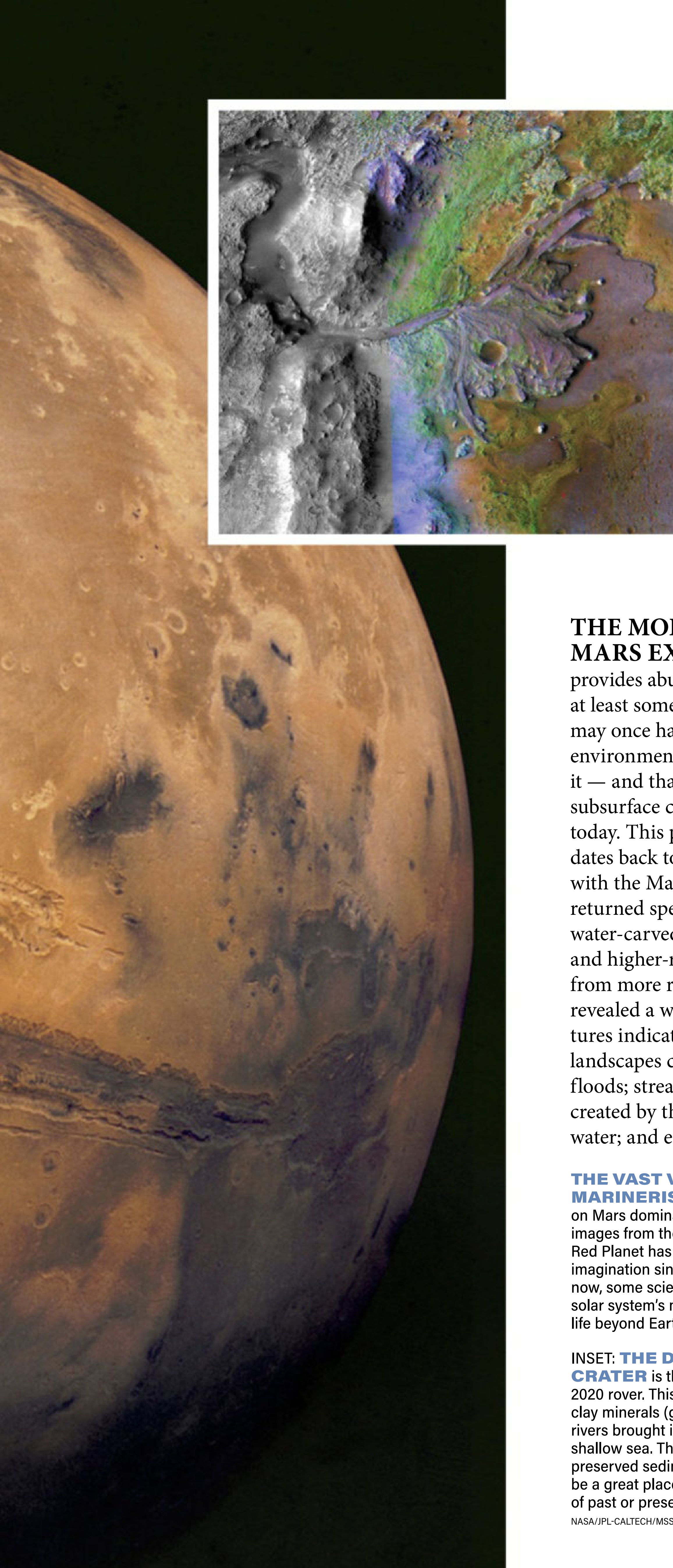
And Europa isn't the end game — saturnian satellites also offer intriguing prospects. Titan, the largest, has a dense atmosphere and an exotic environment consisting of methane and ethane lakes. It is sometimes half-jokingly called the "gasoline planet." This might sound like a strange place for microbes, but as researchers have learned more about microbial life on Earth, they have found it to be hardier than ever dreamed of before. If so-called extremophiles exist in the most awful environments imaginable, microbes could have evolved to thrive in a methane-rich environment, too.

Saturn's Enceladus also could offer a rich environment for tiny life. Cryovolcanoes on this icy moon shoot watery geysers high above the moon's surface, and scientists have discovered complex organic molecules in the moon's composition. Even farther out, Triton, Neptune's largest satellite, could also be an icy abode for small living organisms.

This special report examines the possibilities for life existing elsewhere in the solar system. It will take you on a journey of the mind that, if you're lucky, will reshape slightly how you see life on Earth, around you, every day of the year. What do you think?

Life in the SOLAR SYSTEM

Is there life on MARS?



Earth's neighbor once had a climate conducive to life. Now scientists are trying to learn if the Red Planet turned those chances into reality. **BY JIM BELL**

THE MODERN ERA OF MARS EXPLORATION provides abundant evidence that at least some of Mars' surface may once have been a habitable environment for life as we know it — and that parts of the planet's subsurface could still be habitable today. This parade of evidence dates back to the early 1970s with the Mariner 9 orbiter, which returned spectacular photos of water-carved landforms. These and higher-resolution images from more recent spacecraft have revealed a wealth of geologic features indicating water's presence: landscapes carved by catastrophic floods; streams, rivers, and deltas created by the persistent flow of water; and enigmatic gullies on hillsides and other channel-like landforms that hint at water running underground.

THE VAST VALLES MARINERIS canyon system on Mars dominates this mosaic of images from the Viking 1 orbiter. The Red Planet has captured the human imagination since time immemorial; now, some scientists think it is the solar system's most likely abode for life beyond Earth. NASA/USGS

INSET: **THE DELTA IN JEZERO CRATER** is the target for NASA's 2020 rover. This mineral map shows clay minerals (green) that ancient rivers brought into a long-departed shallow sea. The delta's well-preserved sediments should be a great place to search for signs of past or present martian life. NASA/JPL-CALTECH/MSSS/JHUAPL

All these features support the hypothesis of Mars' habitability because they invoke the presence of liquid water. Along with the existence of energy sources and organic molecules, water is one of the three key ingredients necessary for life as we know it.

Perhaps there was a period in the first billion years or so of the planet's history when the environment was significantly warmer and the atmospheric pressure at the surface was much higher than it is now. Today, Mars' average temperatures fall well below freezing and the atmospheric pressure is nearly 100 times lower than Earth's. The melting of subsurface ice and glaciers, or even rainfall, might have allowed significant amounts of liquid water to interact with the landscape over potentially lengthy spans of geologic time during such periods.

Or perhaps the martian climate warmed during shorter and more sporadic episodes, maybe as a result of rare large impacts or occasional intervals of increased volcanic activity. During such times, ground ice might have melted and formed groundwater

THE COLORFUL HUES of Grand Prismatic Spring in Yellowstone National Park come from microbes known as extremophiles, which prosper in the spring's blistering water. The microbes prove that life can exist in extreme conditions, perhaps similar to those found on Mars. NPS/JIM PEACO

systems that could have nurtured subterranean habitable environments. The presence of relatively fresh-looking gullies and seasonally changing dark slope streaks on some crater rims and other ridges provides evidence — though controversial — that groundwater might still be on the move in some places. This would be possible thanks to interior geothermal heat or some other energy source, which is another key ingredient to establish habitable environments.

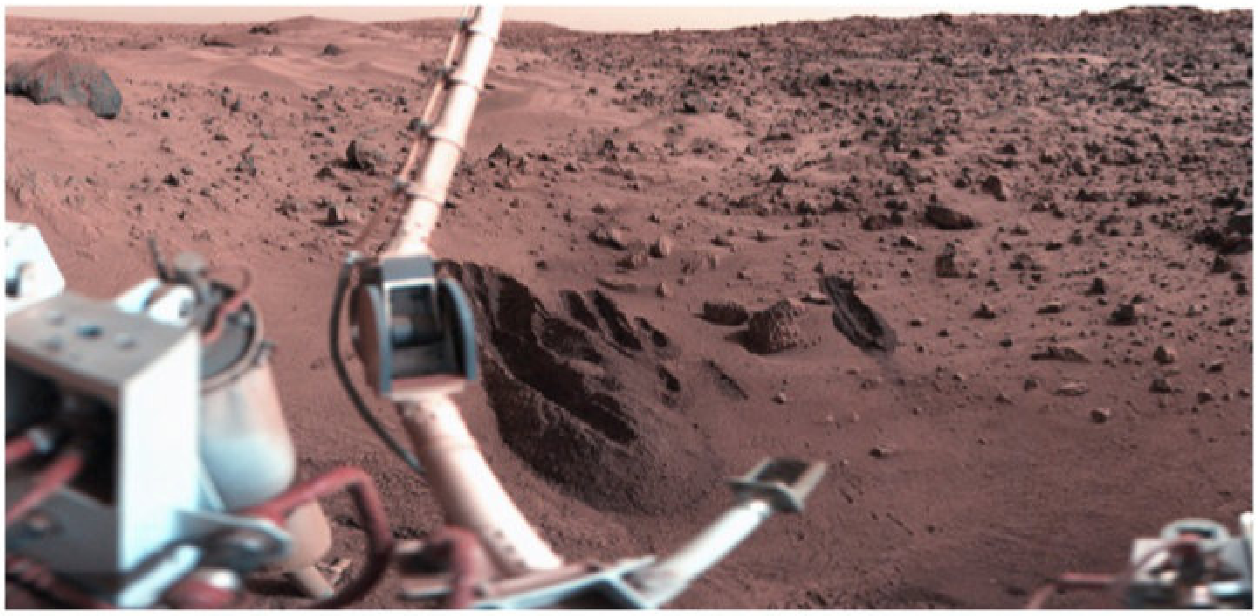
Learning whether Mars was, or still is, habitable has been a major focus of the astrobiological exploration of the Red Planet for the past few decades. Since the answer appears to be yes, the focus for future Mars exploration is turning toward asking the obvious follow-up question: Was there ever life on Mars, and is there anything alive there today?

Viking's tentative first steps

The twin Viking landers of the 1970s took a direct and somewhat risky approach to testing the hypothesis that life exists on Mars. The Vikings scooped up fine dust and soil from sites that were safe to land in but somewhat geologically unknown, and then performed organic chemistry and mass spectroscopy experiments on those materials. Given what was known at the time, the science team was taking a reasonable chance that the martian environment harbored no processes that would destroy organic molecules at the surface, and that the landing sites represented places that might have been or still were habitable.

The Viking biology results came out either negative or ambiguous. This soured many researchers on the prospects for life on Mars for several decades. However, the discoveries made by later missions have shown that neither assumption made in the Viking-era search for life was valid. Specifically, neither landing site shows any particularly strong geologic or compositional evidence that it might have been a promising place for either the existence or preservation of past (or present) life-forms.

In addition, the discoveries made by the Vikings and subsequent missions revealed not only that high-energy ultraviolet radiation from the Sun continuously bathes the surface and breaks down organic molecules, but also that the soils and dust are laced with a strongly

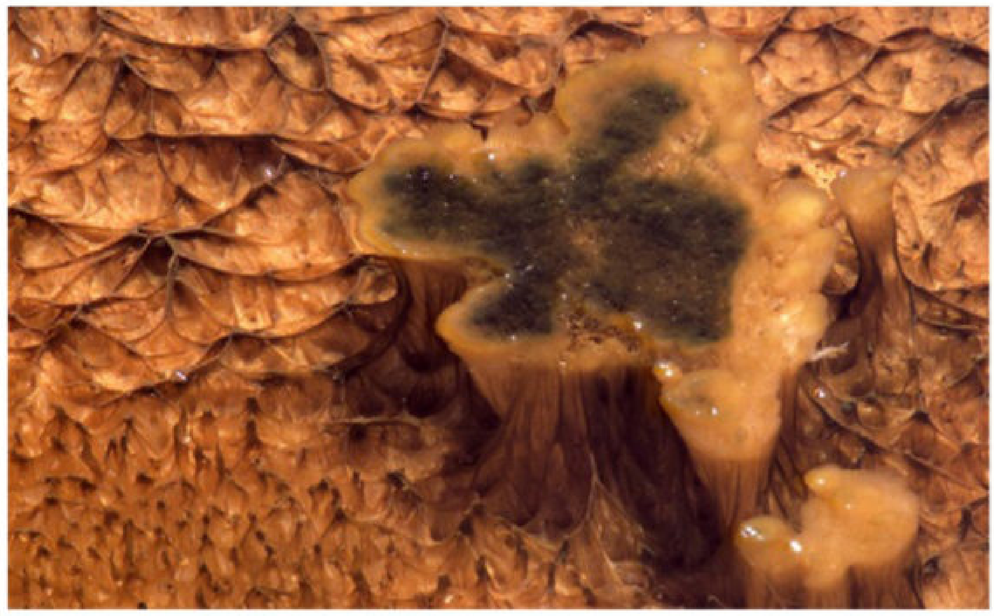


THE VIKING 1 LANDER made the first attempts to find life on Mars. The craft's robotic arm dug these trenches and delivered samples to three biology experiments, though the results proved ambiguous at best. NASA/JPL oxidizing compound — identified as perchlorate by the 2008 Phoenix Mars lander team — that *also* breaks down organic molecules. In retrospect, it shouldn't have been a surprise that the Vikings' search for organic compounds came up blank.

These findings opened up a new, two-pronged pathway in the search for martian life. First, scientists would need to find places whose geology or composition suggests that they are or once were habitable. Second, researchers would have to devise search strategies that could focus on sampling materials from beneath the surface that have had little or no exposure to the current harsh-for-organics surface environment. Sifting through data from more than a dozen successful orbiter, lander, and rover missions since the Vikings, geologists, geochemists, and mineralogists have helped resurrect the search for life on Mars using this approach.

Those missions have identified a diverse range of potentially habitable environments well beyond what scientists knew about based on Viking and earlier results. In particular, researchers have been able to interpret past and present environmental conditions through detailed spectroscopic measurements of the composition of the surface.

Just like on Earth, the kinds of minerals detected and even the specific ratios of different chemical elements in those minerals can sometimes provide unique information on the temperature, pressure, salinity, and acidity of the water prevalent at the time the minerals formed. The spectroscopy results nicely complement the geologic interpretations of the landscape that come from imaging at ever-finer scales. Detailed photos reveal that martian sedimentary rocks have experienced a rich and surprising history of buildup and erosion. Indeed, it is the fusion of both high-resolution imaging and spectroscopy that has allowed scientists to gain a deeper understanding of Mars' habitability.



THE HEAT-LOVING ALGAE in this close-up image thrive in the scorching waters of Yellowstone National Park. Scientists think that similar hydrothermal areas on the Red Planet could be good places to search for life on Mars. NPS/J. SCHMIDT

DARK, NARROW STREAKS arise from the boulder-strewn terrain at left, just one of many examples of such features seen across Mars. Some scientists think the streaks, which appear to flow down steep slopes and grow, fade, and reappear every martian year, could be seasonal flows of briny water. NASA/JPL/UNIVERSITY OF ARIZONA

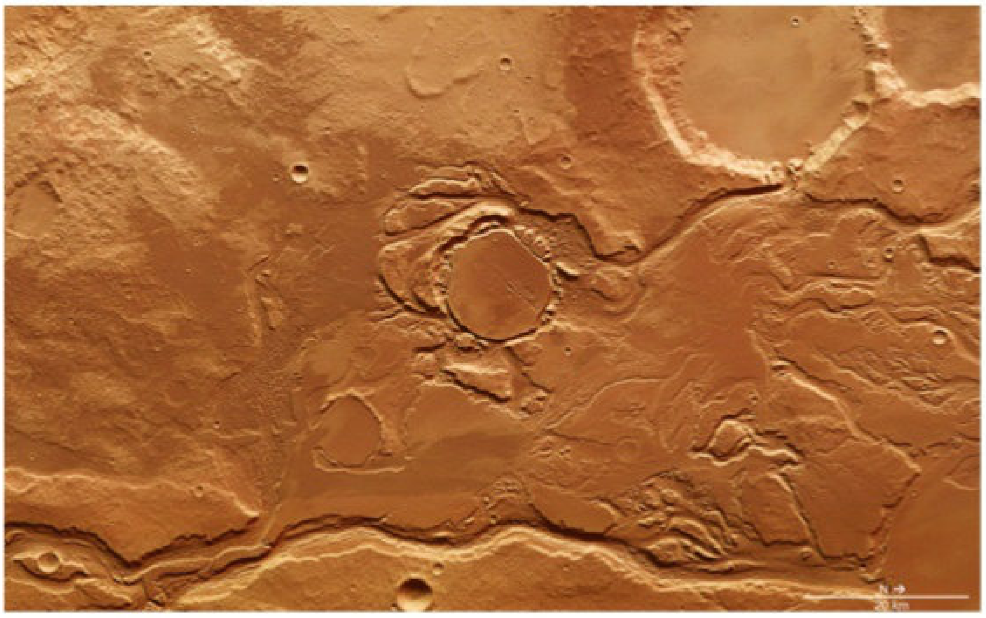
ENIGMATIC GULLIES occur on the steep slopes of many martian craters, particularly those at middle and high latitudes. Many planetary scientists believe liquid water carved the gullies, which typically show a branching pattern at their head and a fan-shaped debris apron at their base. NASA/JPL/UNIVERSITY OF ARIZONA

Mars as a living world?

The 1989 Russian Phobos 2 mission, the first successful Mars orbiter after Viking, acquired a number of high-resolution infrared spectra of the surface that revealed evidence for water or hydroxyl within specific kinds of clay minerals. This suggested that water interacted with rock in specific places early in Mars' history. Images from NASA's Mars Global Surveyor spacecraft (1999–2006), at 10 to 100 times better resolution than the Viking orbiters achieved, provided a detailed geologic context on those specific places, showing that they often associate with water-carved landforms, sedimentary layers, or both.

The ongoing Mars Reconnaissance Orbiter (MRO) mission has expanded on those earlier discoveries. Using even higher-resolution imaging and spectroscopy, this NASA spacecraft has uncovered the most diverse set of potentially habitable environments on Mars. In particular, MRO has found sedimentary layers all over the planet that contain hydrated minerals (those chemically united with water) like iron-bearing sulfates and silica materials like opal, as well as clays rich in iron, magnesium, and aluminum.

The detection and mapping of clay minerals, in particular, continues to yield



FLOWING WATER in huge volumes carved the intricate channels seen in the Mangala Valles region. Scientists suspect heat from the nearby volcanoes of the Tharsis bulge melted subsurface ice and triggered the formation of this outflow network. ESA/DLR/FU BERLIN

CURIOSITY ROVER has been exploring Gale Crater since 2012. Winds removed overlying layers from the formation and exposed the rocks some 70 million years ago. These ancient lake and stream deposits testify to a past environment that would have been favorable to microbial life. NASA/JPL-CALTECH/MSSS

exciting discoveries about the history of specific watery environments on Mars. In fact, some of that water is still there today, trapped inside these minerals. And a number of surface regions — including deltas, ancient lake beds, and hot springs environments — appear to have been persistently wet for significant periods of geologic time. This excites astrobiologists thinking about the implications of these long-lasting habitable environments on the origin and evolution of life on the Red Planet.

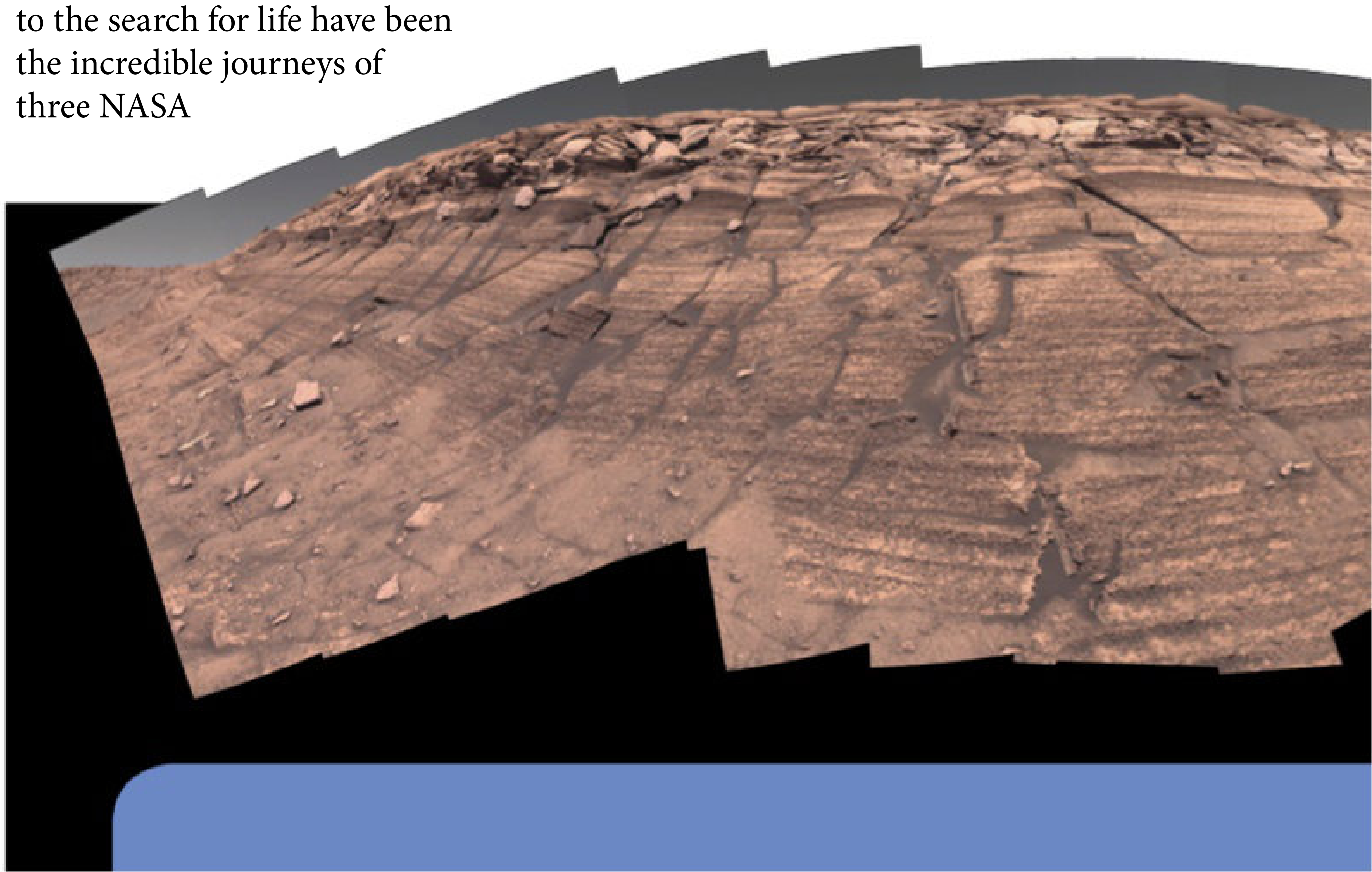
Indeed, astrobiologists studying our own planet have also played an important role in resuscitating the search for life on Mars. Over the past few decades, they have helped revolutionize our understanding of the limits of both simple and complex life on Earth. In particular, the study of extremophiles — organisms that can thrive in extreme temperatures, pressures, salinity, acidity, and/or radiation — has made the idea of ancient or even existing life in an extreme environment like the subsurface of Mars more mainstream than ever.

Roving Mars

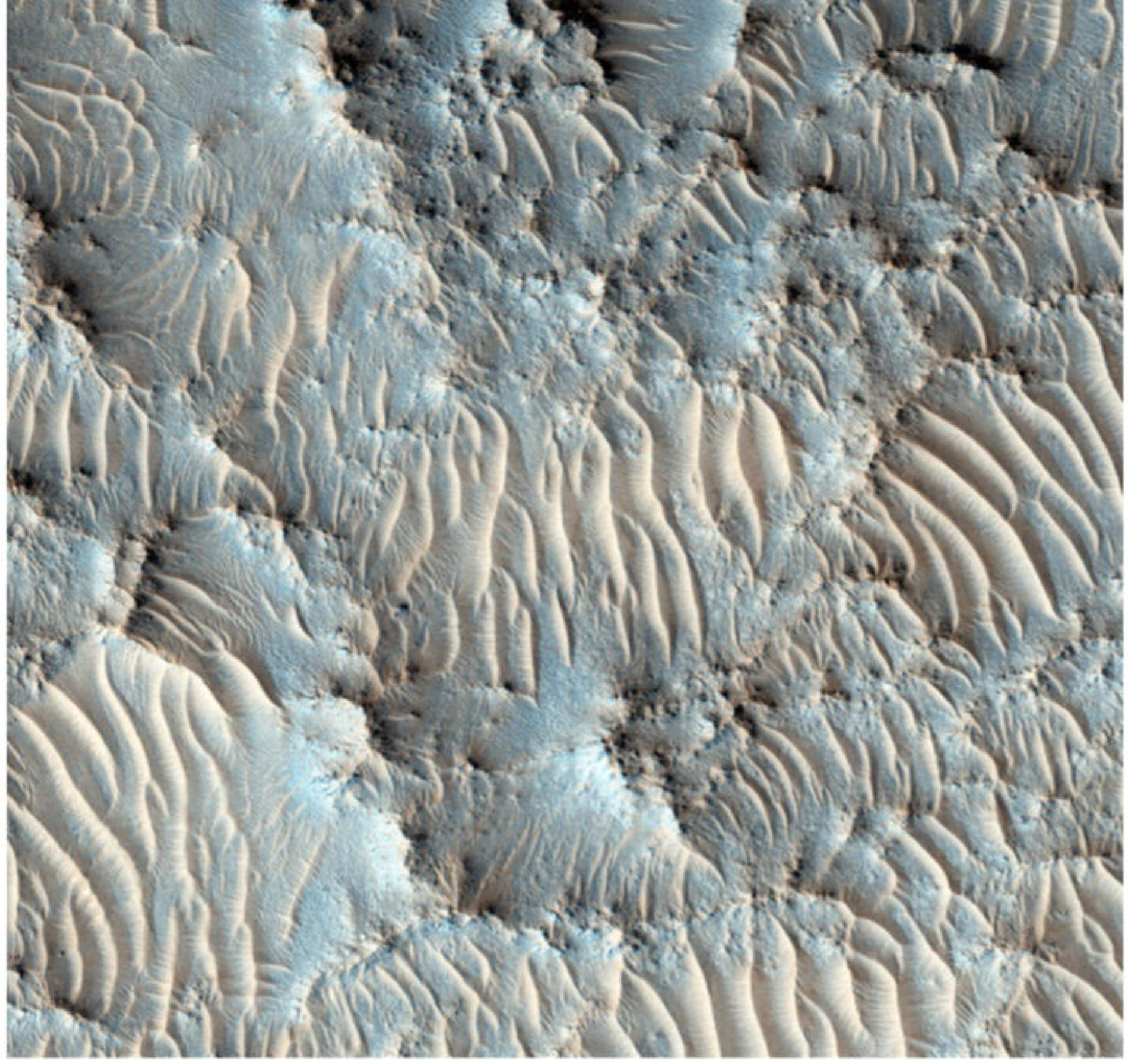
Those discoveries have amplified the importance of the close-up lander and rover studies conducted at six additional landing sites since the two Vikings set down in 1976. Of particular relevance to the search for life have been the incredible journeys of three NASA rovers — Spirit, Opportunity, and Curiosity — each of which found minerals occurring as layers of sandstones or other fine-grained sedimentary rocks that point to the intimate interactions between these rocks and surface water and/or groundwater.

For example, after several years of exploring the primarily bone-dry volcanic plains of Gusev Crater, the Spirit rover spent more than four additional years discovering evidence of water-altered iron oxides, carbonates, and hydrated sulfates and silica in places associated with a probable hydrothermal environment. Scientists think these places are similar in some ways to the hot springs around Yellowstone National Park in Wyoming. With liquid water, ample heat and energy sources, and possibly organic molecules (at least from the constant rain of cometary and asteroidal organics that pummel all the planets), Gusev Crater certainly qualifies as having been a potentially habitable environment. Still, no direct evidence exists that the surface or subsurface is inhabited today.

The Opportunity rover made related discoveries during its more than 14-year traverse across the flat, cratered plains of Meridiani Planum. Scientists found evidence that abundant surface water and groundwater altered the pre-existing volcanic rocks, and the specific minerals identified showed that the water varied from somewhat acidic to more typical freshwater along the rover's path. Using crater walls as probes into the subsurface, the rover team found the record of Meridiani's watery past extends many tens to hundreds of meters underground,



NASA'S OPPORTUNITY ROVER captured this view of Burns Cliff, which forms the southeastern wall of Endurance Crater. Most of the layered bedrock here formed in liquid water — one of three key ingredients for life as we know it. This wide-angle mosaic includes a photorealistic model of the rover for scale. NASA/JPL-CALTECH/CORNELL

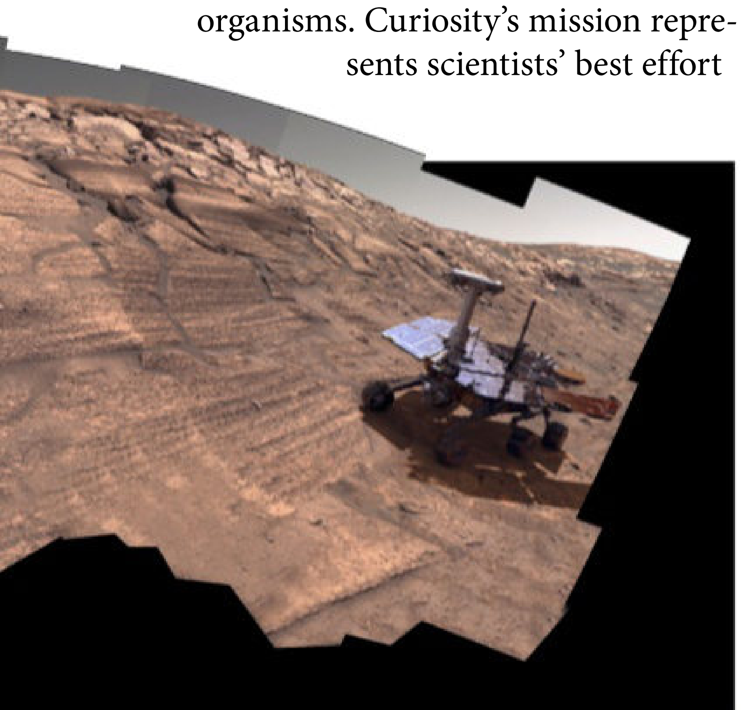


SAND DUNES PACK this tiny section of Jezero Crater, the landing site for NASA's next rover, which is set to launch in summer 2020 and land in February 2021. Scientists will use high-resolution images like this one from the Mars Reconnaissance Orbiter to choose a safe, but scientifically interesting, landing site. NASA/JPL/UNIVERSITY OF ARIZONA

suggesting the environment would have been habitable over significant amounts of geologic time. Again, however, Opportunity uncovered no specific evidence of extinct or existing life. Like Spirit, it did not carry any instruments capable of making a detailed analysis of organic molecules.

The Curiosity mission is in the middle of perhaps the most ambitious effort yet to search for evidence of life on the surface and shallow subsurface of Mars. Since 2012, this rover has been exploring an enormous mound of sedimentary deposits containing clays, sulfates, and iron oxides in Gale Crater. Curiosity carries sophisticated chemical, mineralogic, and organic detection instruments as well as a drill that can penetrate the uppermost 2 inches (5 centimeters) of the subsurface. The rover is exploring an eroding landscape in which some of the sedimentary layers have been buried for perhaps billions of years before being exposed relatively recently. As such, drilling and sampling these layers provides a way to study materials that have been protected from much of the harmful ultraviolet radiation and oxidizing perchlorates for much longer than many other places on Mars.

Indeed, Curiosity's instruments have discovered relatively simple indigenous organic molecules — though they could be related to organics delivered by meteorite falls or atmospheric processes that can create small amounts of organic molecules from ultraviolet radiation. Still, every time Curiosity drills a hole, the science team could discover stunning evidence of preserved *complex* organic molecules from living or once-living organisms. Curiosity's mission represents scientists' best effort yet to systematically search for evidence of life on Mars.



The future of life on Mars

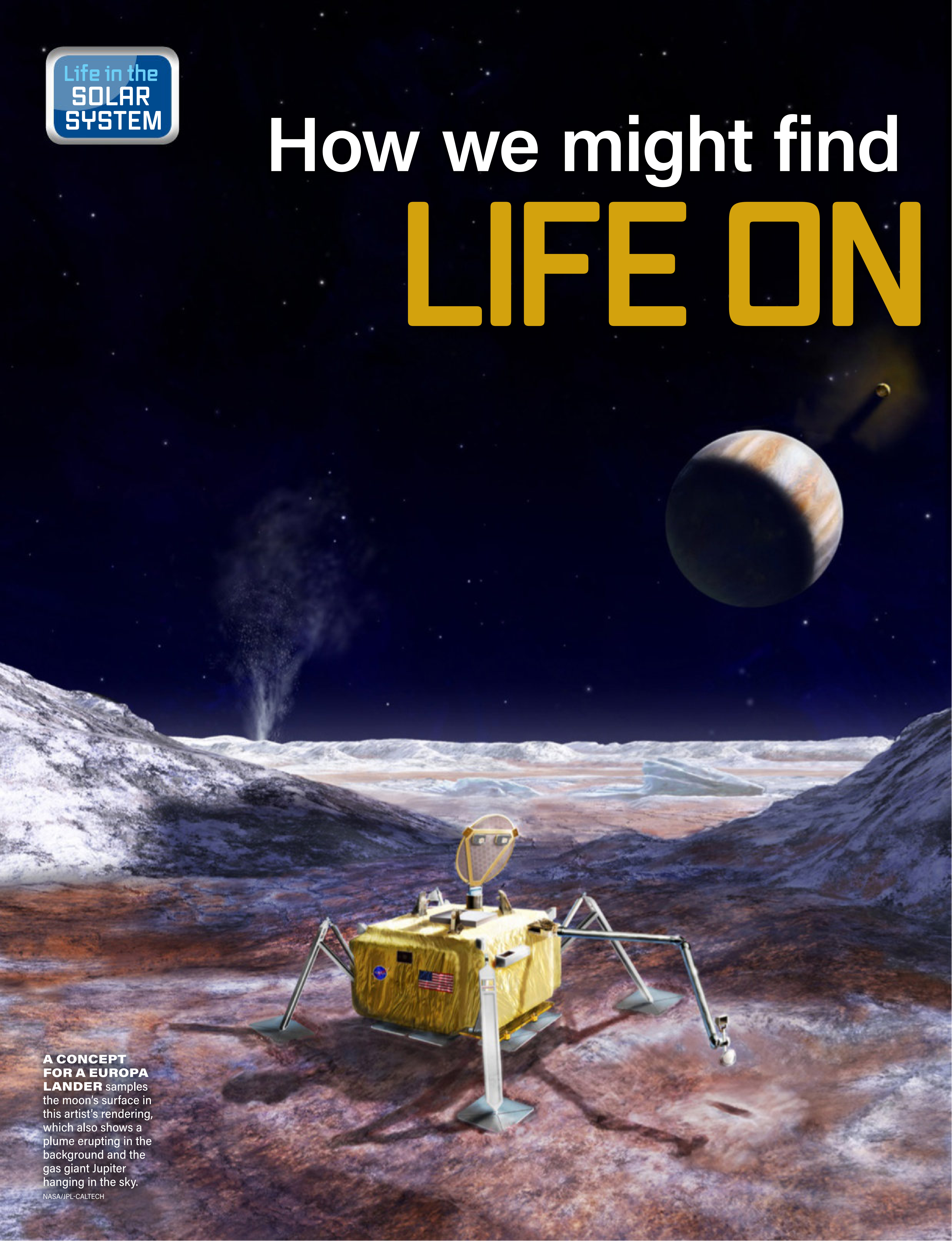
The next best effort will begin in 2020, when NASA will launch a still-unnamed rover toward Jezero Crater, an ancient basin where a beautifully preserved river delta once flowed its sediments into a shallow sea. On Earth, such deltas are excellent environments for preserving organic materials and even fossils transported by gentle downstream currents. By exploring such an environment and drilling into the delta's layers, scientists will maximize their chances of finding evidence of past or present life on Mars.

Even better, NASA intends to store the Jezero drill samples in a few dozen core tubes that will be cached on the surface. Then, later in the 2020s, a future rover will collect and launch them in a capsule to Mars orbit, where another orbiter will capture the capsule and deliver it to Earth. Back here, in laboratories much more sophisticated than any we could currently deploy on Mars, those samples will be interrogated for the subtlest signs of complex organic molecules or other potential chemical or isotopic biosignatures. Such a Mars sample return mission would be the next step in searching for life on the Red Planet.

Beyond the 2020s, NASA and SpaceX are contemplating human missions to Mars. Such ventures would likely target mid-latitude regions where there's enough sunlight to provide adequate power and where ground ice could be mined most easily to help sustain a small initial settlement. The presence of ground ice, and the potential for past or present associated groundwater, means such places also could be habitable. Bringing human explorers — with their associated expertise, intuition, and expanded capabilities for accessing the subsurface — into those kinds of environments could represent the next giant leap in the search for life on Mars.

Jim Bell *is a planetary scientist in Arizona State University's School of Earth and Space Exploration and president of The Planetary Society, the world's largest public space advocacy organization. He has written a number of space photography books, including* Postcards from Mars *and* The Space Book*.*

How we might find LIFE ON



A CONCEPT FOR A EUROPA LANDER samples the moon's surface in this artist's rendering, which also shows a plume erupting in the background and the gas giant Jupiter hanging in the sky.
NASA/JPL-CALTECH

EUROPA

Jupiter's icy moon is a great candidate for habitability. But life's best chance to exist is beneath the crust.

BY MARA JOHNSON-GROH

THE GALILEO SPACECRAFT captured Europa in great detail. This shot shows the largest portion of the moon imaged at the highest resolution, offering a close-in view of several features, including regions that researchers believe formed when the icy crust melted and refroze. Although the image has slightly enhanced color, it largely approximates how the moon would look to the naked eye. NASA/JPL-CALTECH/SETI INSTITUTE

EUROPA, ONE OF JUPITER'S four Galilean moons, is not the most welcoming place. On the surface, daytime temperatures barely surpass –260 degrees Fahrenheit (–160 degrees Celsius), and a fractured, icy shell blankets the landscape. Giant geysers occasionally blast water vapor 125 miles (200 kilometers) above the surface — the equivalent of about 20 stacked Mount Everests. If these conditions weren't enough to deter visitors, intense radiation from Jupiter would doom any living thing on the surface.

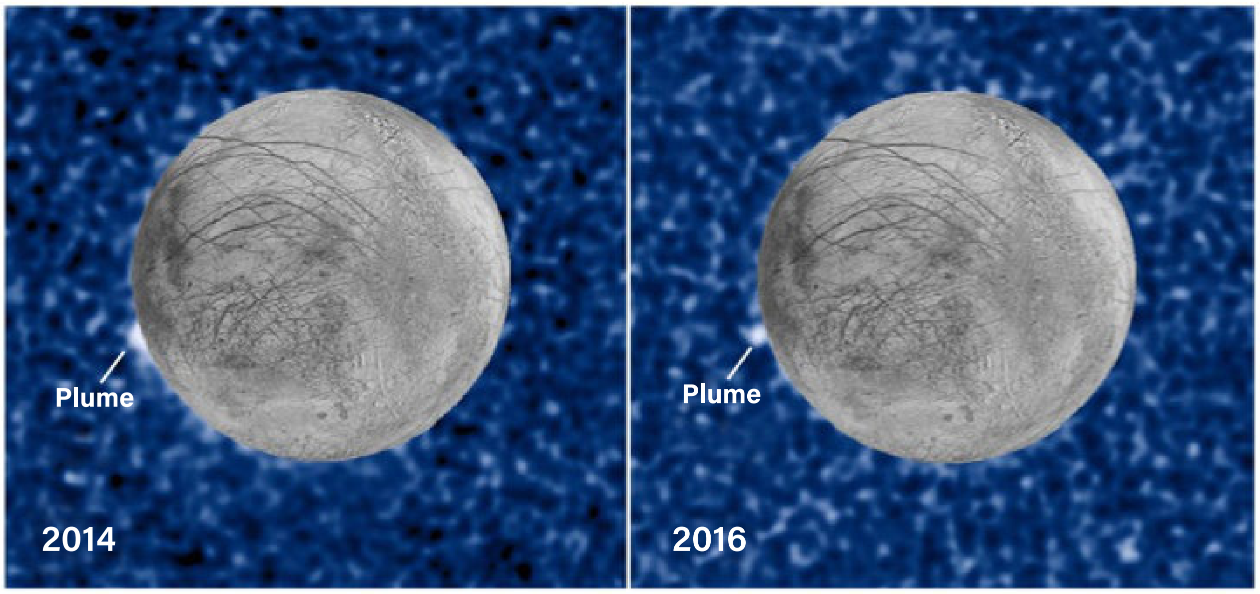
Yet Europa is considered one of the best candidates to sustain life in the solar system. Despite its extreme conditions, the moon hits the trifecta of requirements for life as we know it: water, energy, and chemical building blocks. Although Europa is just one-quarter the diameter of our planet, it harbors a subsurface ocean twice the volume of the oceans on Earth. This aquatic environment, which has been stable for billions of years, may be a reservoir for life — and scientists want to find out whether it lurks beneath the surface.

Subsurface oceans

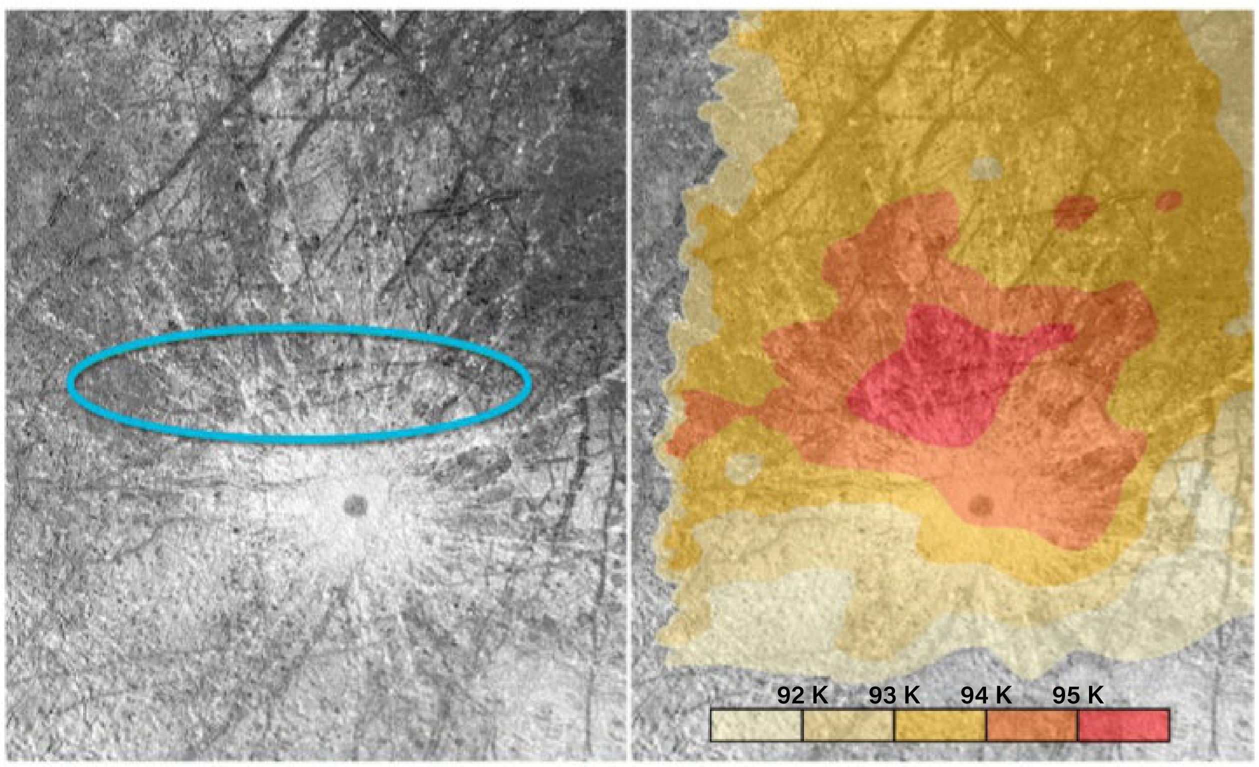
Life on Earth originated at sea, so it's not a stretch to imagine life on Europa starting in a similar environment. The moon's subzero temperatures prohibit surface oceans like ours, but scientists in the 1970s discovered an icy shell covering Europa. Studies of the surface ice show it is largely water ice with a smattering of related compounds like hydrogen peroxide, carbon dioxide, and sulfur dioxide. While the shell's thickness is uncertain — best estimates range up to dozens of miles — scientists are certain that a liquid ocean circulates beneath.

Voyager 1 and 2 took the first close-up images of Europa when they flew through the Jupiter system in 1979. The images showed a relatively smooth surface with few craters or mountains, but scratched with bands and ridges. The lack of large impact craters, which build up as meteorites strike a planetary body over millions or billions of years, meant that some process was erasing them. Separated ridges, where it looked as if icy material had gushed up between the walls, also suggested a geologically active world. Scientists observed long linear features that they determined could be created if the surface was disconnected from the moon's interior — for example, with a liquid ocean sandwiched between them.

At about 485 million miles (780 million km) from the Sun, Europa does not receive enough heat to keep an ocean liquid. But it has its own heat source: Jupiter. As Europa travels in an eccentric orbit around its host planet, differences in the force of gravity from one side of the moon to the other squish and squeeze it. This friction is enough to heat up the moon's solid interior in a process known as tidal heating. The heated rocky ocean floor could then maintain a liquid ocean and induce circulation below the crust of ice. If the ice shell is sufficiently thin in places, the heated water might even seep



IN 2014 AND 2016, the Hubble Space Telescope spotted plumes spouting from Europa's surface, visible in infrared wavelengths. The 2014 plume (left) was estimated to reach about 30 miles (50 km) above the surface; in 2016, a plume rose from the same location to about 62 miles (100 km). The detailed images of the moon are composites of Galileo photos, superimposed over the Hubble data. NASA/ESA/W. SPARKS (STScI)/USGS ASTROGEOLOGY SCIENCE CENTER



THESE IMAGES OF EUROPA target a warm region (enclosed by the blue oval) spotted by Galileo and identified as the location where plumes erupted in 2014 and 2016. At right, color indicates temperature in kelvins, with the warmest areas in red. The presence of the plumes and their eruption from a warm area on the surface support the idea that the moon hosts a relatively warm, liquid subsurface ocean. NASA/ESA/W. SPARKS (STScI)/USGS ASTROGEOLOGY SCIENCE CENTER

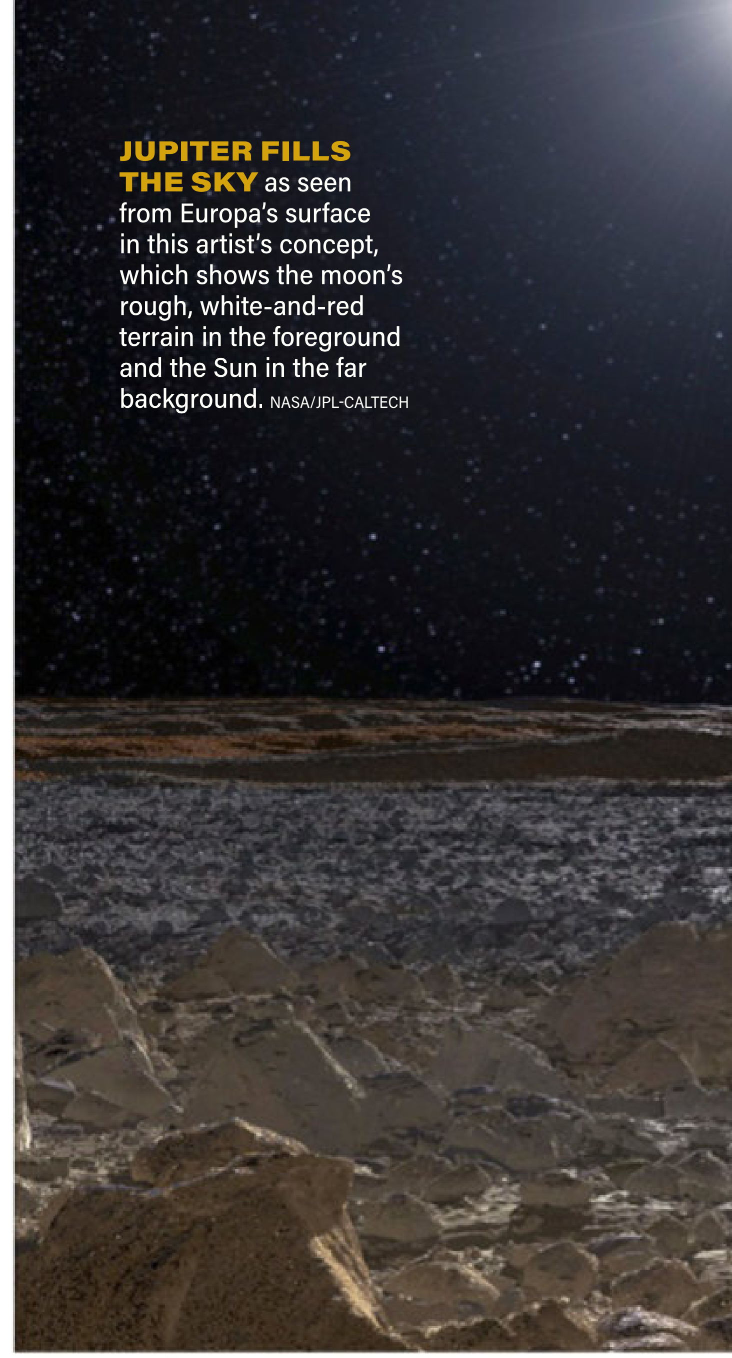
though, creating the jumbled surface of broken ice blocks astronomers see in images. Such heating could also generate the geysers blasting from the surface.

In 1989, NASA launched its Galileo mission to study Jupiter and the four Galilean moons — Io, Europa, Ganymede, and Callisto — in greater detail. With 12 close flybys, the mission took new measurements that increased scientists' certainty of a liquid ocean on Europa. Perhaps the most conclusive data from Galileo were the magnetic field measurements. As the spacecraft approached Europa, it observed a slight "bend" in Jupiter's magnetic field, indicating that a second magnetic field is being created, or induced, within the moon. The most likely cause, researchers believe, is the circulation of an electrically conductive global saltwater ocean beneath the surface.

Microbial energy bars

In addition to water, life needs energy. Most life on Earth derives its energy from the Sun. Plants use the Sun's energy directly, while we — and other animals — use the products they create. However, Europa's harsh conditions likely relegate life below the surface, where the distant Sun doesn't shine.

On Earth, microbes can live near deep-sea vents where warm, chemical-rich material bubbles up. Although no hard evidence yet exists, some scientists suspect that Europa's tidal heating



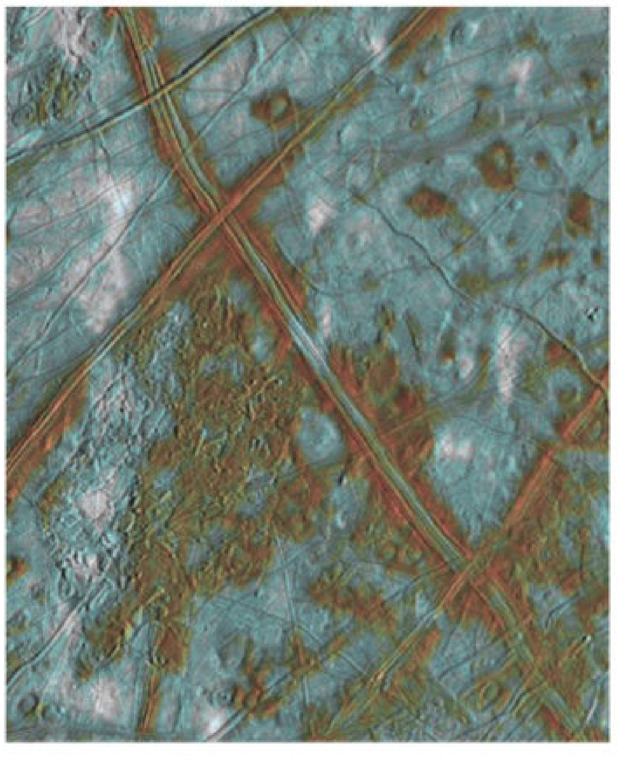
JUPITER FILLS THE SKY as seen from Europa's surface in this artist's concept, which shows the moon's rough, white-and-red terrain in the foreground and the Sun in the far background. NASA/JPL-CALTECH

creates volcanoes and hydrothermal vents on the ocean floor, just as tectonic activity does on Earth. Providing more than just a heat source, any volcanoes or vents would also offer an important source of nutrients. The heat and activity in the interior would drive chemical reactions and bring up new material into the ocean. If Europa's interior is highly active, there could be a large exchange of material, which would provide a steady flow of nutrients and even the chemical building blocks for life. Thus, determining just how active Europa is remains a key question for scientists investigating the moon's potential habitability.

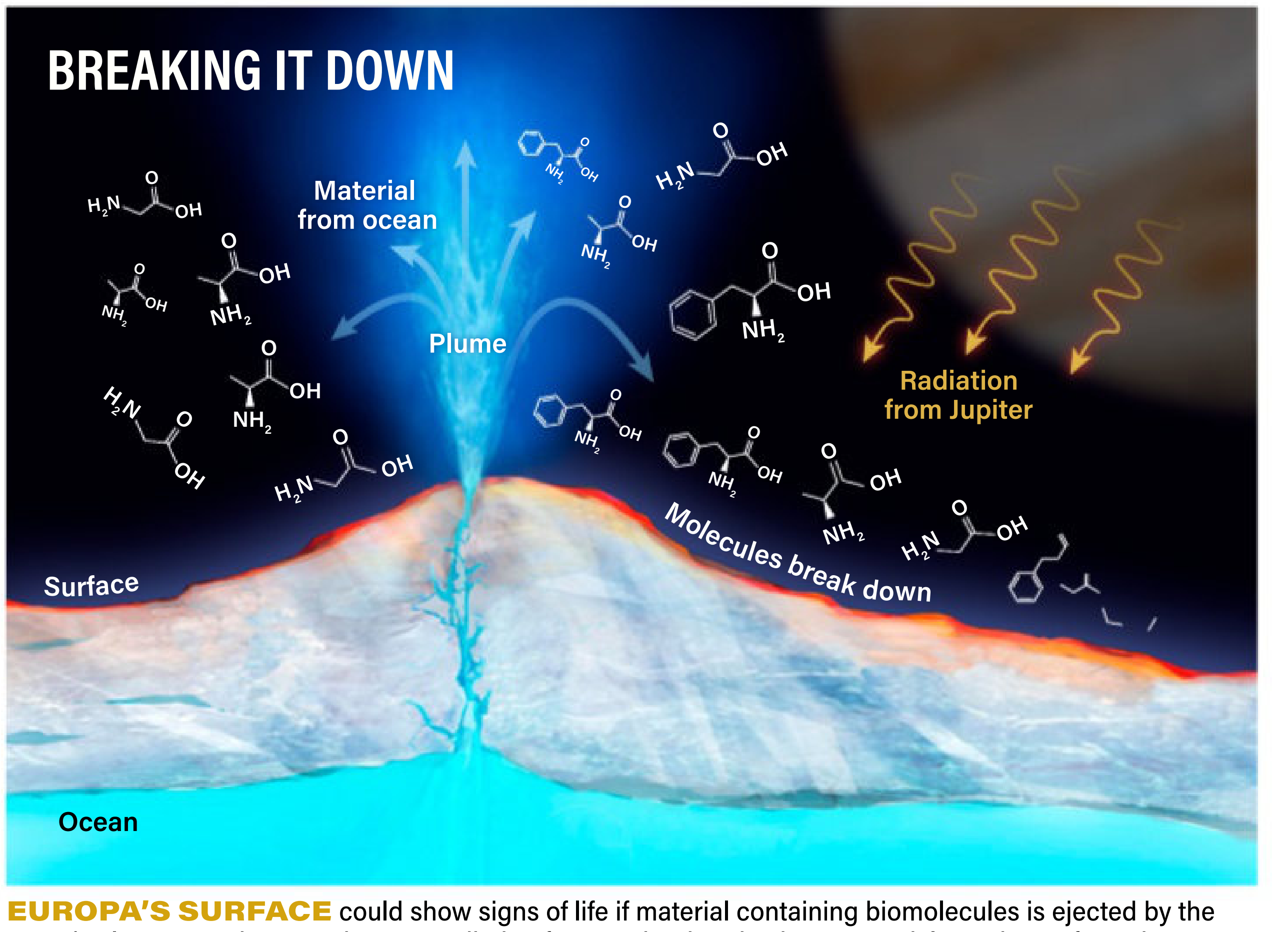
Above the surface, intense radiation from Jupiter also helps break down molecules. These chemical bits and pieces can then reform to create new compounds that could also be useful to microbial life. Open fissures on the surface might allow these compounds to eventually circulate below.

Gathering intel

Finding hard evidence of life is difficult — particularly on Europa, where it would likely lie under layers of ice.



EUROPA'S ICY CRUST contains a wealth of interesting topography that hints at the moon's geologic past. This close-up image of the terrain, taken by the Galileo spacecraft, shows ridges, domes, and a jumbled area of "ice rafts" that scientists think broke away from their original locations. The smashed-up blocks of terrain are a compelling sign that the moon once had a liquid ocean. NASA/JPL/UNIVERSITY OF ARIZONA

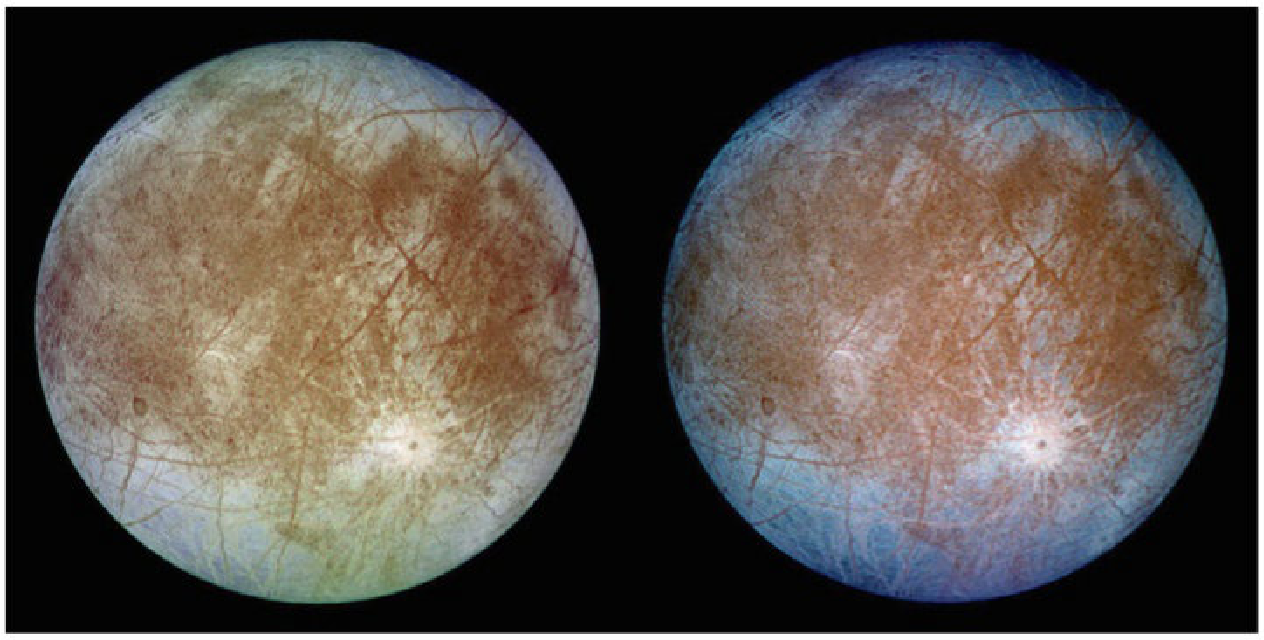


EUROPA'S SURFACE could show signs of life if material containing biomolecules is ejected by the moon's plumes. But because intense radiation from Jupiter breaks down materials on the surface, those signs could be erased, which is why researchers hope to take a direct picture of life rather than detect it through surface composition. *ASTRONOMY*: ROEN KELLY

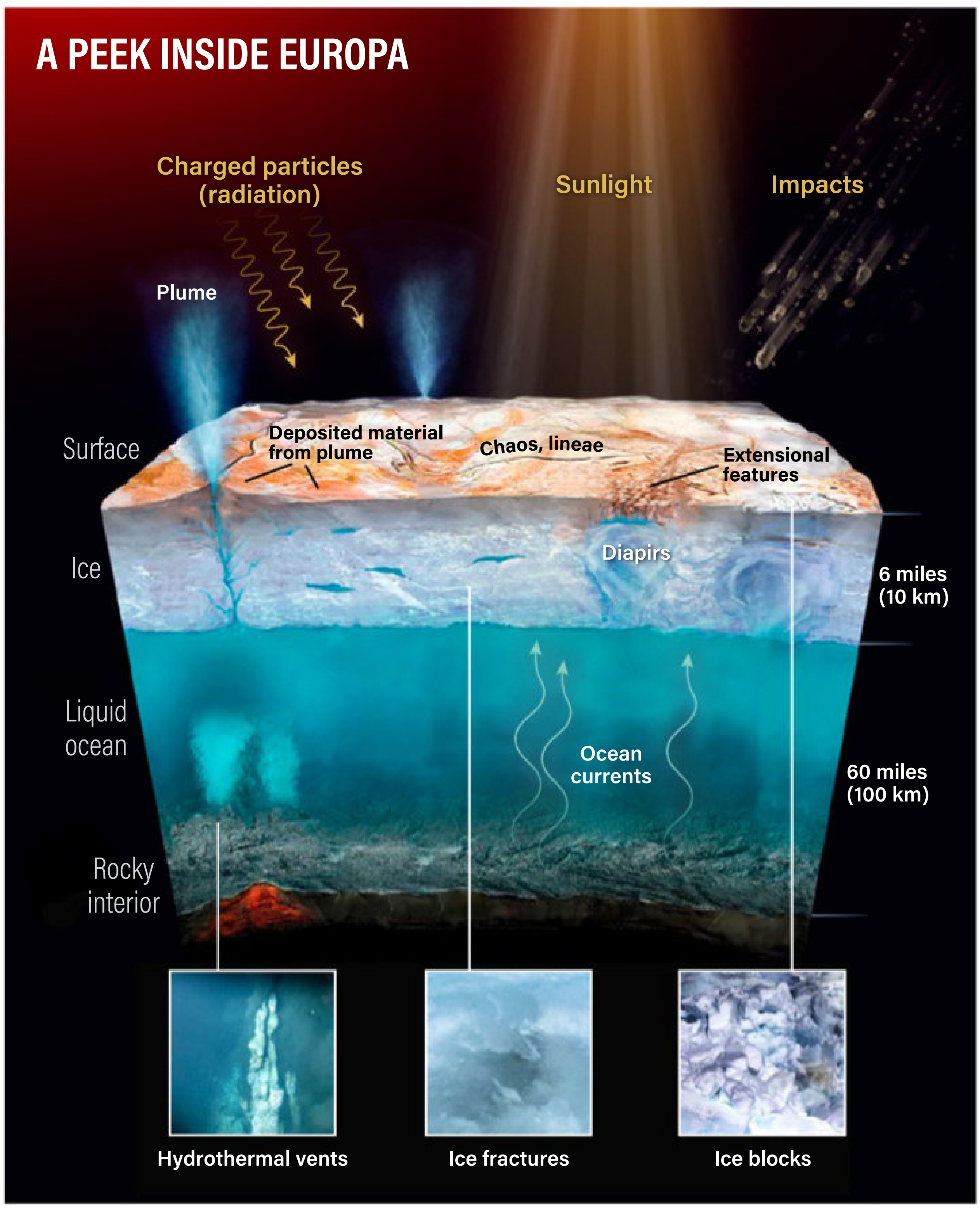
"Biologists still struggle to put a definition on what is alive and what is not alive," says Curt Niebur, a scientist at NASA Headquarters in Washington, D.C. "It's hard enough [searching for life] on Earth, so doing that halfway across the solar system with a robotic spacecraft is even more difficult, more complicated, and more challenging."

Because of the seemingly uninhabitable surface conditions, any probe sent to the moon would theoretically have to drill down some unknown distance before sampling for life. Scientists are working on ways to achieve this, but in the near future, they'll only be able to take measurements remotely.

Niebur is working on just that as the program scientist for NASA's Europa Clipper mission, which aims to launch in 2023. By studying the moon in detail, the mission will determine whether Europa has conditions suitable for life.



THESE TWO VIEWS of Europa's trailing side show the moon in natural color (left) and false color to enhance variations in the terrain. Bluer and whiter regions are covered in particles of water ice; redder areas are contaminated by minerals from the moon's interior or delivered by impacts. Several long, thin fractures — some more than 1,850 miles (3,000 km) long — are visible across the surface. Also easy to distinguish on the moon's lower half is the bright Pwyll crater, a 31-mile-wide (50 km) scar left by a recent impact. NASA/JPL/DLR



HEAT AND MATERIALS from Europa's interior might be released through hydrothermal vents on the moon's ocean floors. Warm water rising toward the base of the icy shell could cause cracks and other features, such as diapirs, while large chunks of the surface — ice rafts — may detach and float to new locations. Plumes could spout the ocean's contents high above the moon, while radiation, impacts, and sunlight can all cause changes on the ice from above. *ASTRONOMY*: ROEN KELLY

Entering orbit around Europa, the craft will use nine instruments to investigate the moon's surface and interior. At closest approach, Europa Clipper will speed by just 3 miles (5 km) above the surface, low enough to fly through geyser bursts. A mass spectrometer and dust mass analyzer will study particles ejected in the bursts, while an ultraviolet spectrograph will image the plumes from afar and identify their composition. Other instruments will look for thermal signatures on the surface to detect new bursts, while ice-penetrating radar will measure the thickness of the icy shell. A magnetometer will measure the strength of the moon's magnetic field to probe its interior. These data will help scientists determine how deep the ocean might be, as well as its salinity.

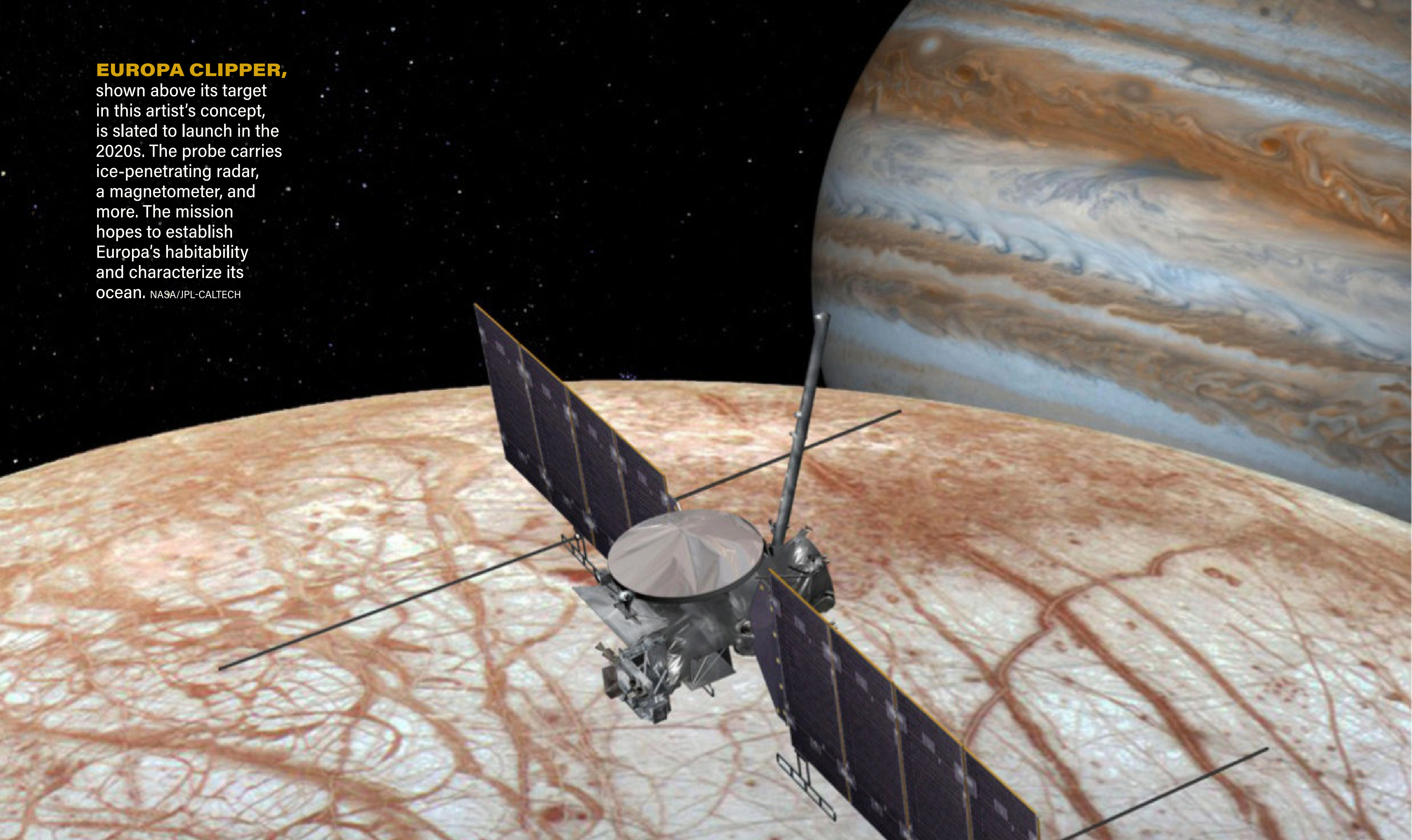
Proof in pictures

Ultimately, Europa Clipper will likely be able provide proof of habitability, but not signs of life. If selected, NASA's proposed Europa Lander will follow after Europa Clipper and complement its mission by searching directly for biosignatures on the surface, as well as sampling the local composition of the moon.

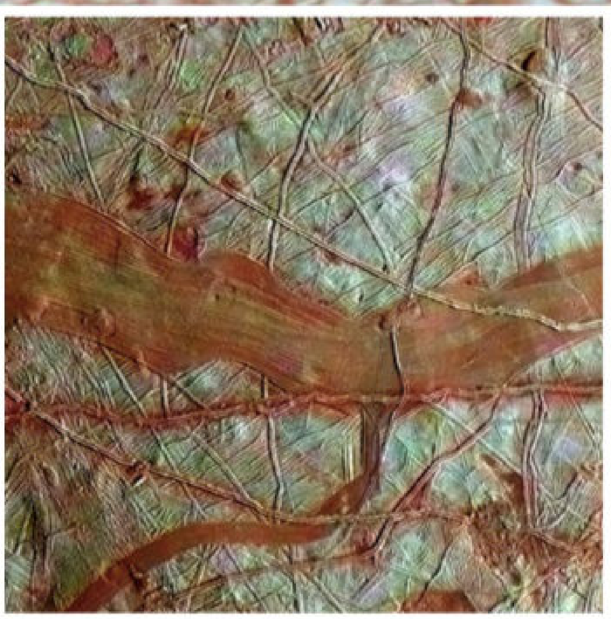
Perhaps the best way to capture conclusive evidence of life on Europa is to take a photo. Scientists think their best bet is to equip the Europa Lander with a microscope for imaging water and ice samples.

Jay Nadeau, a biophysicist at Portland State University, and her collaborators are testing autonomous microscopes robust enough to withstand an interplanetary journey. They're also developing a method of creating 3D images, similar to a hologram, with a camera that can simultaneously focus at multiple distances to avoid blurry images. However, such images generate a lot of data, and the proposed lander's power supply and communications bandwidth for sending information back to Earth is limited. With multiple instruments vying for those necessities, Nadeau suspects they'll have enough bandwidth to send back only a few 3D pictures. "There's not much data you can send back from the mission, so we're going to need a computer algorithm to say, 'This picture is actually interesting and we'll send it back to Earth,'" Nadeau says.

The first missions will likely only be able to take surface samples, which would show life that has been preserved



EUROPA CLIPPER, shown above its target in this artist's concept, is slated to launch in the 2020s. The probe carries ice-penetrating radar, a magnetometer, and more. The mission hopes to establish Europa's habitability and characterize its ocean. NASA/JPL-CALTECH



THIS ZOOMED-IN, FALSE-COLOR view of bands on Europa's surface shows an area about 101 by 103 miles (163 by 167 km). Bluer regions represent purer water ice; red areas indicate water mixed with contaminants such as magnesium sulfate and sulfuric acid. NASA/JPL-CALTECH/SETI INSTITUTE

in ice. To that end, Nadeau and her team have taken their test instruments to extreme locations in the Arctic. Through studying microbial life in 100,000-year-old glaciers, Nadeau is trying to understand what they might be able to see on Europa. These types of studies are helping her create better computer algorithms to look for life, dead or alive.

"Sometimes cells [in glacial ice] can survive, but a lot of times they don't, and you get dead microbes," Nadeau says. But dead microbes can look a lot like inorganic specs of dust, so it's more challenging to prove they were once alive.

But how would we get at life below the surface? Some researchers have proposed a nuclear-powered drill that could melt its way down to an area shielded from the damaging radiation above the ice. According to recent calculations, protected locations could exist a foot (30 centimeters) or less below the surface. At higher latitudes, where the radiation is less intense, biomaterials could be preserved at depths as shallow as 0.4 inch (1 cm).

Along with a microscope and potentially a drill, the Europa Lander mission would carry other instruments, including seismometers to investigate subsurface structure and spectrometers to analyze surface material composition.

While it's difficult to speculate whether life will be found on Europa, there is certainly cause to think it's a habitable place. If the planned and proposed missions stay on track, we may have an answer within a decade. Regardless of whether Europa is habitable or not, our observations will turn up new and interesting aspects of the moon to study.

"If life didn't arise [on Europa], that makes life on Earth all the more special," Niebur says. "But if we find that life did arise, that frankly makes the universe all the more special."

Mara Johnson-Groh, *a freelance writer and photographer interested in topics on Earth and beyond, is a frequent contributor to* Astronomy *magazine.*

THE SOLAR SYSTEM'S CHANGING LANDSCAPE AS IT APPEARS IN EARTH'S SKY.

BY MARTIN RATCLIFFE AND ALISTER LING

September 2019

Neptune peaks in Aquarius

Neptune's distinct color shows up in amateur scopes, though the cloud features that Voyager 2 saw in 1989 are out of reach. NASA/JPL

The giants of the solar system take center stage this month. While Jupiter and Saturn stand out every September evening and deserve the lion's share of your attention, Neptune ranks a close third as it reaches peak visibility. The distant world skims past a relatively bright star, making it easier to find than usual. Uranus lies farther east and makes a worthy morning object. Finally, Mercury and Venus appear in evening twilight at the end of the month.

Let's start our tour in the evening sky with the toughest targets. Both **Mercury** and **Venus** make fleeting appearances in bright twilight as September draws to a close. On the 30th, Venus stands 1° above the western horizon 30 minutes after sunset. Gleaming at magnitude –3.9, it shows up only because it shines so brightly. You might see magnitude –0.2 Mercury one binocular field to Venus' upper left.

The inner planets fare poorly because the ecliptic — the path of the Sun and planets across the sky — makes a shallow angle to the western horizon after sunset from mid-northern latitudes. Thus, the angular separation of a planet from the Sun translates mostly into distance along the horizon and not into altitude.

You won't have to strain at all to see **Jupiter**. The giant planet shines brilliantly in southern Ophiuchus. It stands 25° high in the south-southwest an hour after sunset in early September and 20° high in the southwest at the same time as the month closes. During the same period, Jupiter fades from magnitude –2.2 to –2.0. This makes the planet some 20 times brighter than Antares, the red supergiant star that lies 8° to Jupiter's lower right. The First Quarter Moon stands 4° to Jupiter's right and 7° above Antares on September 5.

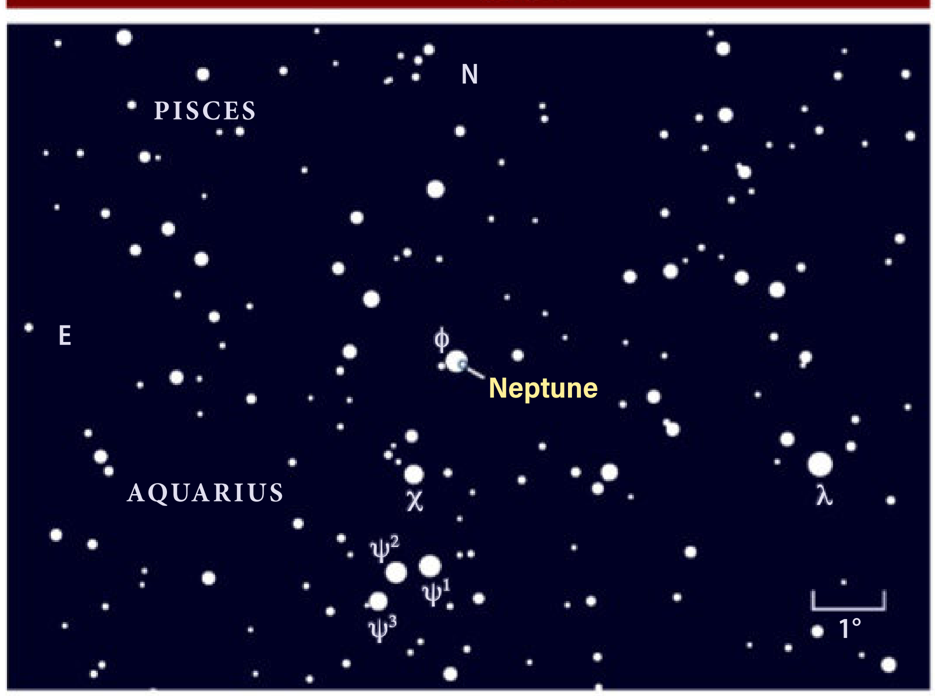
Jupiter appears best through a telescope starting in late twilight, when the planet is high enough to avoid the poor seeing conditions that typically interfere with objects near the horizon. This gives you a couple of hours of prime observing in early September and at least an hour of good views as the month winds down.

Jupiter reveals a wealth of detail through any scope. Even an untrained eye will notice two dark equatorial belts, one on either side of a brighter zone coinciding with the equator. The gas giant's disk measures 37.4" across the equator and 35.0" through the poles at midmonth, an obvious difference once you know to look for it.

Lower-contrast details pop into view along the edges of the equatorial belts during moments of steady seeing. Jupiter's fast spin drives these features. The giant planet's equatorial regions rotate once every 9 hours 50 minutes, taking five minutes less than at higher latitudes.

Any telescope also reveals Jupiter's four bright moons. All four typically show up against the blackness of space near the planet, but occasionally one or more hides in plain sight as it crosses in front of the planet. Watching these transits, and the far easier shadow transits

A distant world's close encounter



Neptune lies in eastern Aquarius at opposition the night of September 9/10, just 6' from 4th-magnitude Phi (ϕ) Aquarii. ALL ILLUSTRATIONS: *ASTRONOMY*: ROEN KELLY

OBSERVING HIGHLIGHT

NEPTUNE reaches its 2019 peak September 9/10, when the planet glows at magnitude 7.8 and spans 2.4" when viewed through a telescope.

that follow close on their heels, can be a riveting experience.

With Jupiter on display for only a few hours each evening, however, only a limited number of events are visible. Your first good look comes September 4, when Io transits Jupiter. The innermost moon first touches the planet's limb at 8:04 P.M. EDT, and its shadow follows at 9:21 P.M. Both moon and shadow take about 130 minutes to transit the jovian disk.

Giant Ganymede's shadow crosses Jupiter's north polar region starting at 11:22 P.M. EDT on September 5. Although the gas giant is setting along the East Coast, observers farther west will get nice views of the shadow's 153-minute transit.

Jupiter's four bright moons all orbit in the planet's equatorial plane, so they usually line up. But this symmetry breaks down once in a while. Watch the evening of September 19, and you'll see Ganymede pass 30" due north of Callisto.

Saturn lies 30° east of Jupiter and trails some two hours behind its sister world. This lag is great news for Saturn watchers because it places the planet at its highest in the south as darkness falls and keeps it on view past midnight. Saturn lies in Sagittarius, just south of the constellation's Teaspoon asterism. The magnitude 0.4 ringed world shines nearly four times

— *Continued on page 42*

RISING MOON | A terrific trio of terraced craters

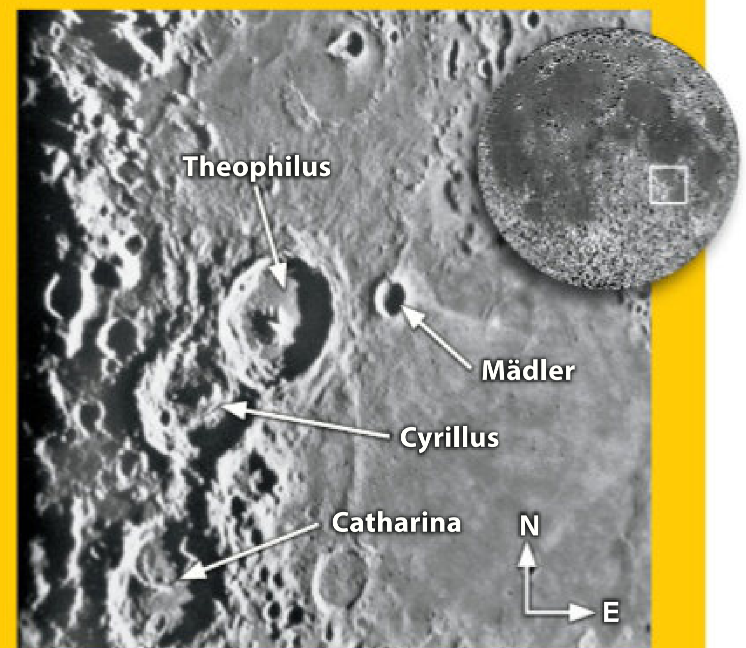
THE WAXING CRESCENT MOON offers a smorgasbord of fantastic views. From the slenderest of arcs to First Quarter phase, Luna shows off rolling seas bordered by craters with towering peaks and aprons of debris blasted out during the impacts that created them. The best detail appears along the terminator, where the Sun is rising and encroaches on the dark lunar night.

Let's focus on the scene the evening of September 4. If you look just south of the lunar equator, three magnificent craters will grab your attention. Northernmost Theophilus has the most classic shape of the trio: It showcases a sharp, almost perfectly circular rim with a dramatic multiple peak at its center. Because it is much bigger and deeper than the crater Mädler immediately to its east, Theophilus' walls have slumped into terraces that appear most noticeable on its western flank.

You can make some educated guesses as to the relative ages of lunar features even without the tools of a geologist. Theophilus must be younger than neighboring Cyrillus to the southwest because it overlays the latter crater's ragged rim. Although Cyrillus also has a complex peak and slumped walls, the impacts of smaller objects over the ages have degraded them. Also note that the debris apron surrounding Theophilus partially fills Cyrillus. The apron's rough texture is obvious at this phase. Under a high Sun at Full Moon, this topographic detail vanishes. Mädler seems to shelter the terrain to its east from this debris, hinting at its intermediate age.

The southernmost member of the crater trio is Catharina. Once upon a time, it must have been sharp-featured like Theophilus, but billions of years of bombardment have erased the central peak and left its walls lower and softer.

Theophilus, Cyrillus, and Catharina



These three large craters form a stunning group when the Sun first lights them up the evening of September 4. *CONSOLIDATED LUNAR ATLAS*/UA/LPL; INSET: NASA/GSFC/ASU

METEOR WATCH | Catch the false dawn

The zodiacal light shines on autumn mornings

Solar system dust particles cast an eerie glow into the predawn sky in late September and early October. BARRY BURGESS

THE ECLIPTIC'S LOW ANGLE to the western horizon after sunset, which keeps Mercury and Venus immersed in bright twilight all month, has a favorable flip side — the ecliptic stands nearly straight up from the eastern horizon before sunrise. This solar system geometry affords observers great views of the false dawn, or zodiacal light, on September mornings.

This faint, cone-shaped glow has a broad base in Leo and tapers as it climbs through Cancer and Gemini into Taurus. The glow arises from sunlight reflecting off fine dust particles in the plane of the solar system, which is why it aligns with the ecliptic. To see the light, you need to observe from a dark site shortly before twilight begins. Catch the false dawn's ethereal glow on moonless mornings, which run from September 27 to October 11 this year.

STAR DOME

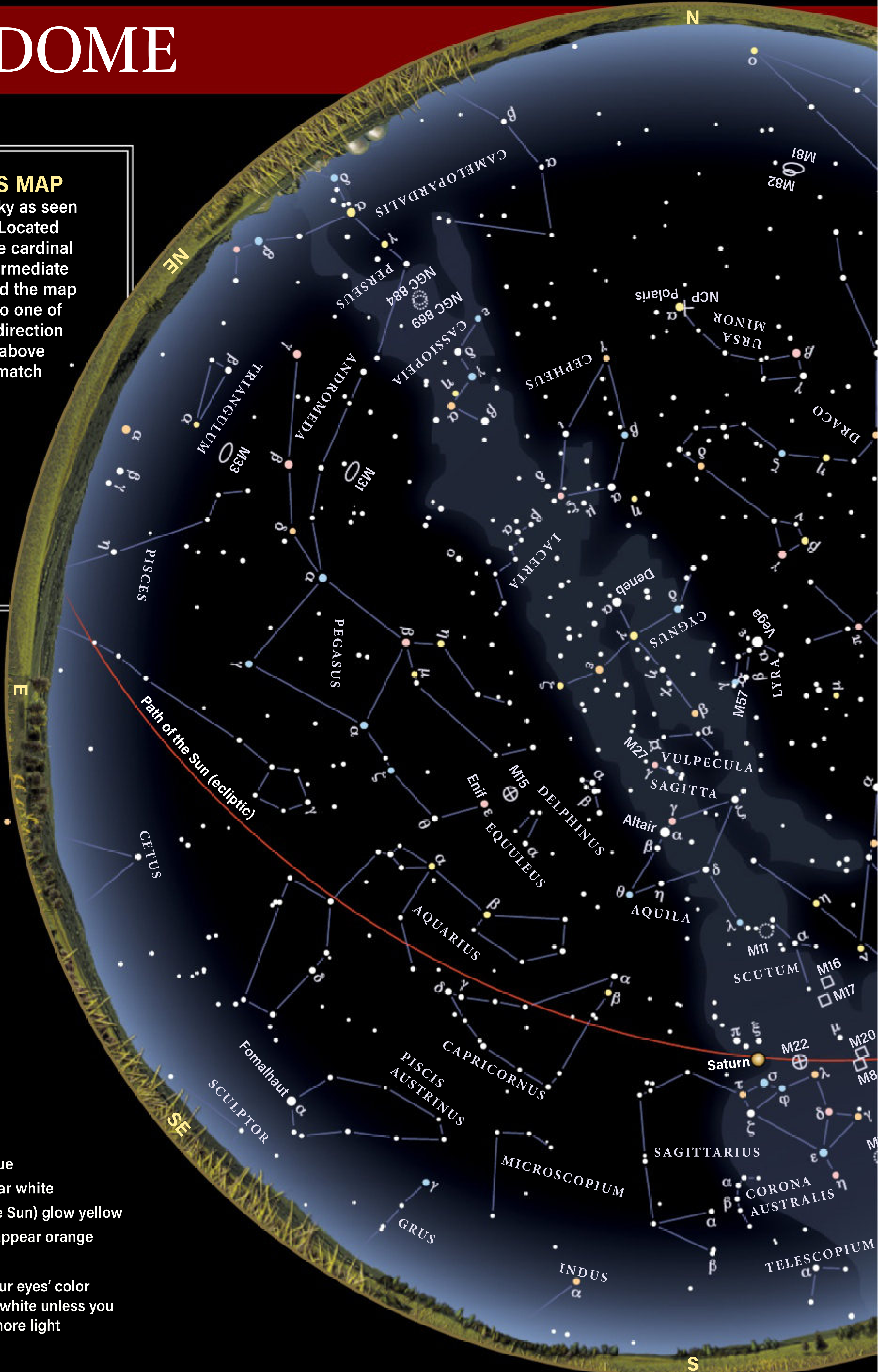
HOW TO USE THIS MAP

This map portrays the sky as seen near 35° north latitude. Located inside the border are the cardinal directions and their intermediate points. To find stars, hold the map overhead and orient it so one of the labels matches the direction you're facing. The stars above the map's horizon now match what's in the sky.

The all-sky map shows how the sky looks at:

10 P.M. September 1
9 P.M. September 15
8 P.M. September 30

Planets are shown at midmonth



MAP SYMBOLS

- Open cluster
- Globular cluster
- Diffuse nebula
- Planetary nebula
- Galaxy

STAR MAGNITUDES

- Sirius
- 0.0
- 1.0
- 2.0
- 3.0
- 4.0
- 5.0

STAR COLORS

A star's color depends on its surface temperature.

- The hottest stars shine blue
- Slightly cooler stars appear white
- Intermediate stars (like the Sun) glow yellow
- Lower-temperature stars appear orange
- The coolest stars glow red
- Fainter stars can't excite our eyes' color receptors, so they appear white unless you use optical aid to gather more light

BEGINNERS: WATCH A VIDEO ABOUT HOW TO READ A STAR CHART AT **www.Astronomy.com/starchart.**

SEPTEMBER 2019

SUN.	MON.	TUES.	WED.	THURS.	FRI.	SAT.
1	2	3	4	5	6	7
8	9	10	11	12	13	14
15	16	17	18	19	20	21
22	23	24	25	26	27	28
29	30					

ILLUSTRATIONS BY *ASTRONOMY*: ROEN KELLY

Note: Moon phases in the calendar vary in size due to the distance from Earth and are shown at 0h Universal Time.

CALENDAR OF EVENTS

2 Mars is in conjunction with the Sun, 7 A.M. EDT

3 Mercury is in superior conjunction, 10 P.M. EDT

5 First Quarter Moon occurs at 11:10 P.M. EDT

6 Asteroid Hertha is at opposition, 2 A.M. EDT

The Moon passes 2° north of Jupiter, 3 A.M. EDT

8 The Moon passes 0.04° south of Saturn, 10 A.M. EDT

The Moon passes 0.08° north of Pluto, 11 P.M. EDT

10 Neptune is at opposition, 3 A.M. EDT

13 The Moon is at apogee (252,511 miles from Earth), 9:32 A.M. EDT

The Moon passes 4° south of Neptune, 2 P.M. EDT

14 Full Moon occurs at 12:33 A.M. EDT

17 The Moon passes 4° south of Uranus, 4 P.M. EDT

18 Saturn is stationary, 2 A.M. EDT

21 Last Quarter Moon occurs at 10:41 P.M. EDT

23 Autumnal equinox occurs at 3:50 A.M. EDT

25 Asteroid Vesta is stationary, 1 A.M. EDT

27 The Moon is at perigee (222,328 miles from Earth), 10:24 P.M. EDT

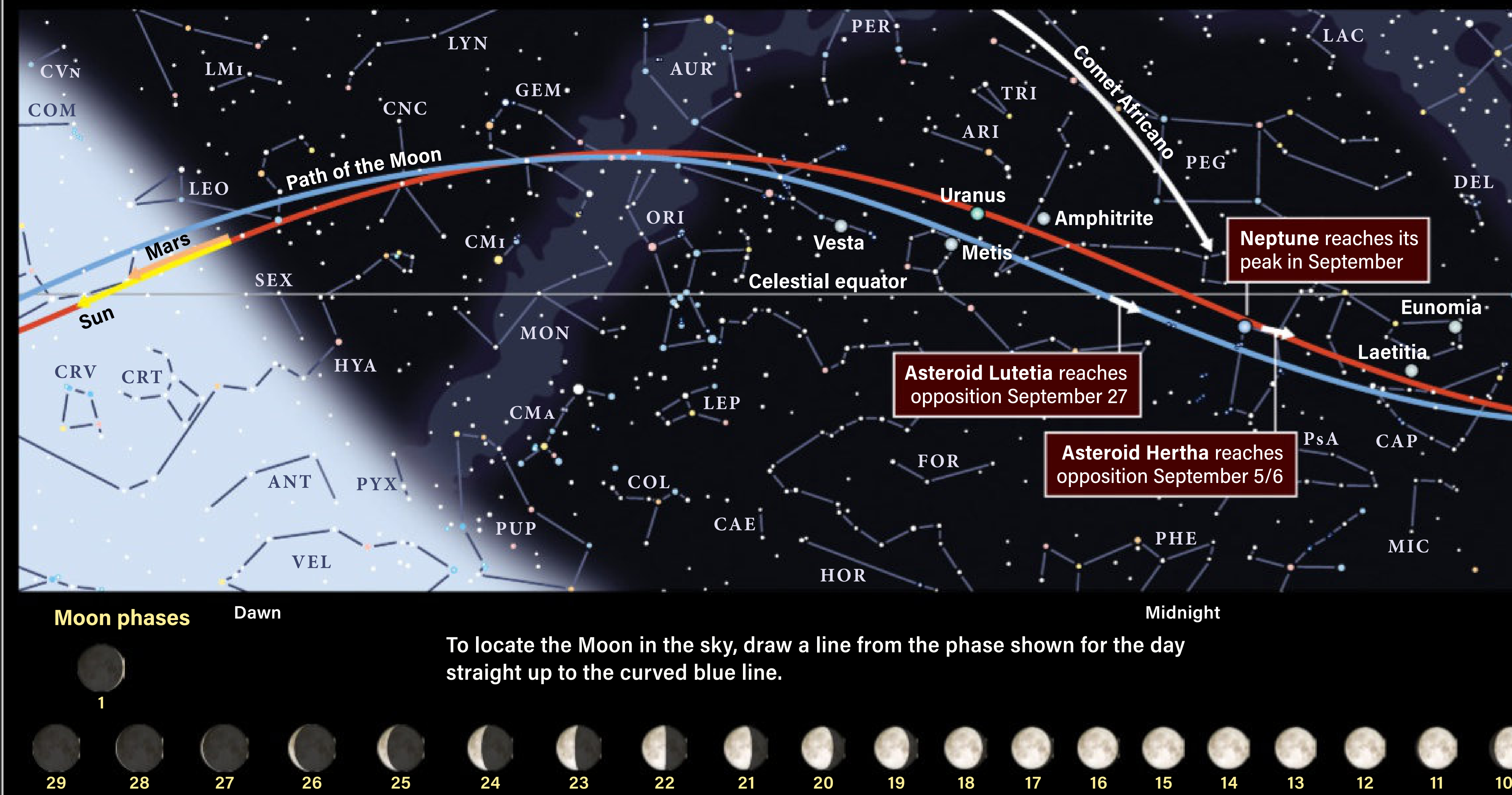
Asteroid Lutetia is at opposition, midnight EDT

28 New Moon occurs at 2:26 P.M. EDT

Mercury passes 1.4° north of Spica, 7 P.M. EDT

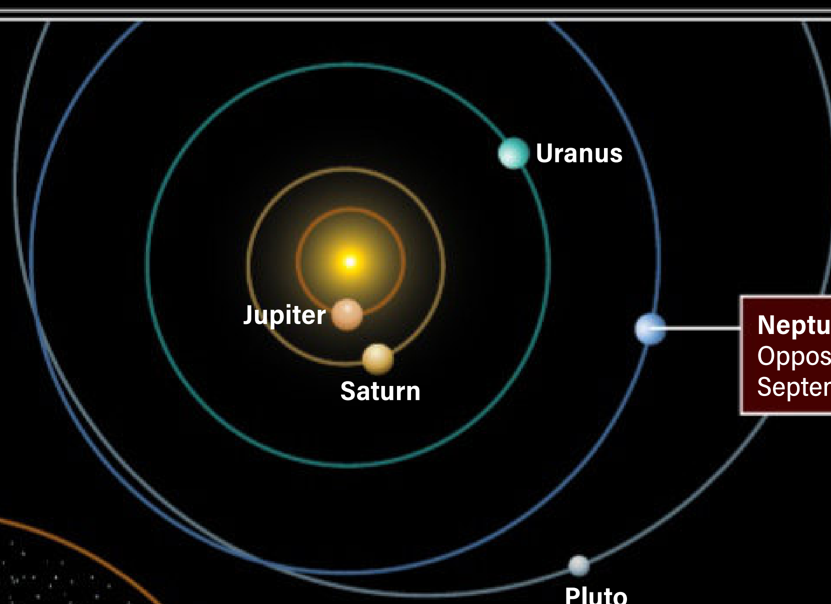
29 The Moon passes 6° north of Mercury, 6 P.M. EDT

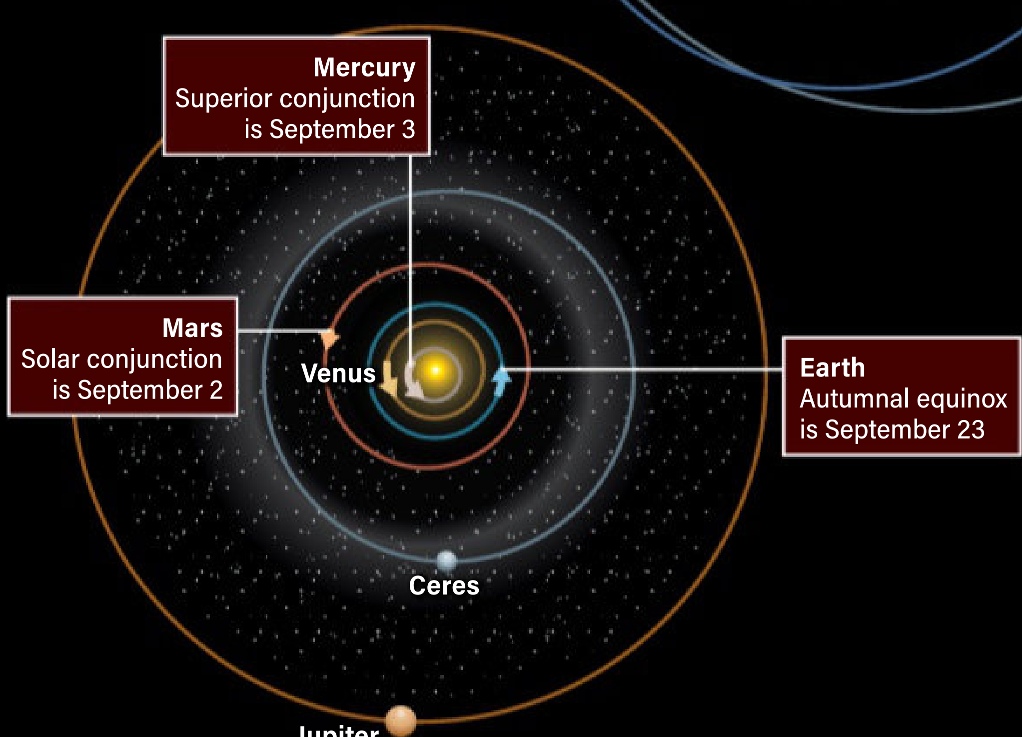
PATHS OF THE PLANETS



THE PLANETS IN THEIR ORBITS

Arrows show the inner planets' monthly motions and dots depict the outer planets' positions at mid-month from high above their orbits.





THE PLANETS IN THE SKY

These illustrations show the size, phase, and orientation of each planet and the two brightest dwarf panets at 0h UT for the dates in the data table at bottom. South is at the top to match the view through a telescope.

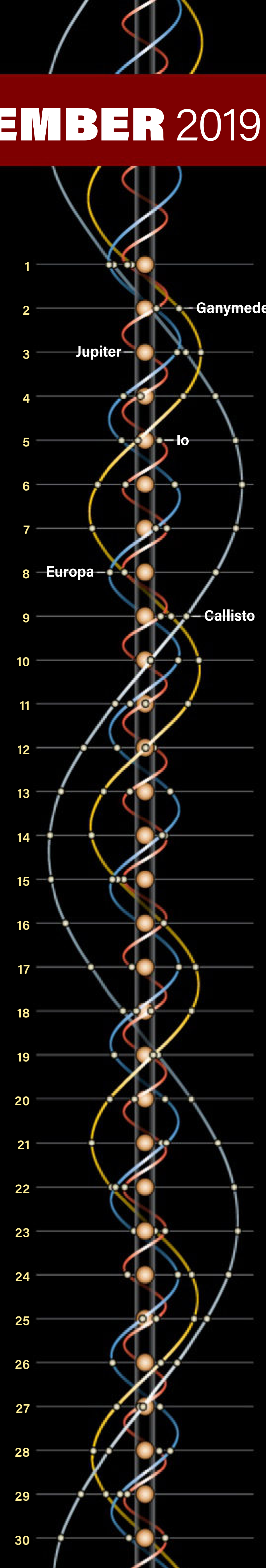
PLANETS	MERCURY	VENUS
Date	Sept. 30	Sept. 30
Magnitude	–0.2	–3.9
Angular size	5.2"	10.0"
Illumination	86%	98%
Distance (AU) from Earth	1.287	1.666
Distance (AU) from Sun	0.465	0.723
Right ascension (2000.0)	13h30.9m	13h11.2m
Declination (2000.0)	–10°27'	–6°32'

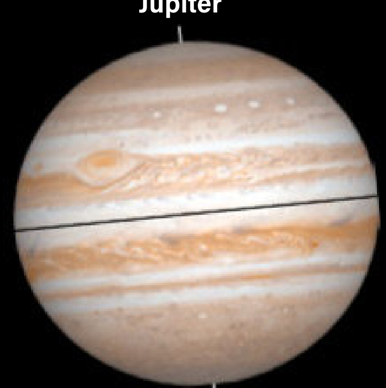
This map unfolds the entire night sky from sunset (at right) until sunrise (at left). Arrows and colored dots show motions and locations of solar system objects during the month.

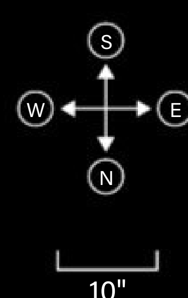
SEPTEMBER 2019

JUPITER'S MOONS

Dots display positions of Galilean satellites at 11 P.M. EDT on the date shown. South is at the top to match the view through a telescope.

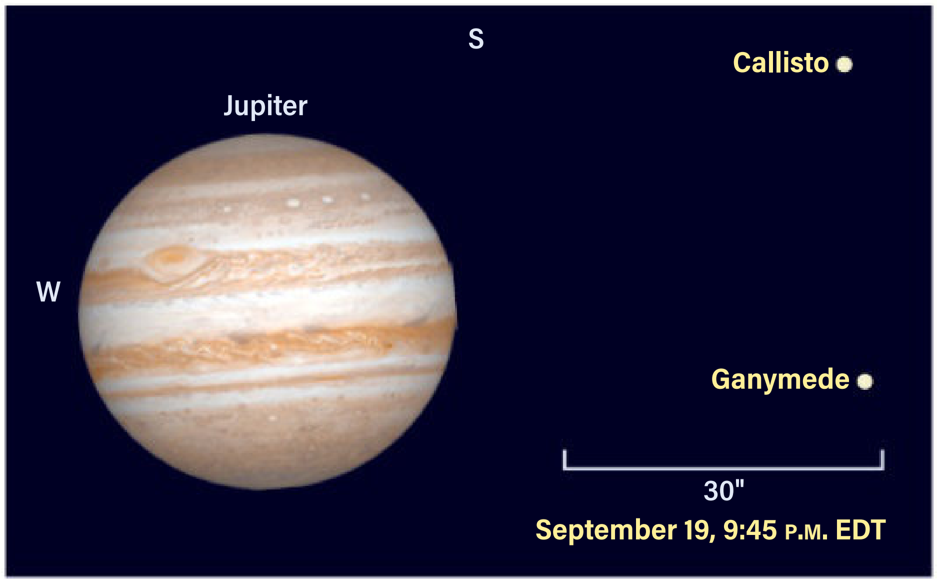






MARS	CERES	JUPITER	SATURN	URANUS	NEPTUNE	PLUTO
Sept. 15	Sept. 15	Sept. 15	Sept. 15	Sept. 15	Sept. 15	Sept. 15
1.8	9.0	–2.1	0.4	5.7	7.8	14.3
3.5"	0.5"	37.4"	17.3"	3.7"	2.4"	0.1"
100%	97%	99%	100%	100%	100%	100%
2.665	2.889	5.268	9.623	19.099	28.932	33.383
1.664	2.847	5.266	10.044	19.832	29.935	33.880
11h15.4m	16h28.7m	16h59.3m	18h59.2m	2h15.0m	23h13.5m	19h28.8m
5°55'	–23°27'	–22°24'	–22°32'	13°00'	–6°09'	–22°23'

Ganymede and Callisto pass in the night



Jupiter's two biggest moons line up north-south of each other September 19. You can see them change relative positions in as little as five minutes.

brighter than any of the Archer's stars.

Viewing Saturn through a telescope is always a thrill. Only a handful of celestial objects look like their photographs, and Saturn ranks at the top. In mid-September, the planet's disk measures 17" across while the rings span 39" and tilt 25° to our line of sight. Because Saturn reached opposition in July, its shadow now hides the far side of the rings just east of the planet's disk. The effect gives the world a dramatic 3D appearance.

The large tilt of the rings provides exquisite views of their structure. Any scope shows the outer A ring, the brighter B ring, and the dark Cassini Division that separates the two. The ghostly C ring lies closest to Saturn and appears through larger instruments under good viewing conditions.

Amateur telescopes also reveal six saturnian moons. The brightest, 8th-magnitude Titan, shows up through any scope. It takes 16 days to complete an orbit; you can find it due south of Saturn on September 7 and 23 and due north of the planet September 16.

Three 10th-magnitude moons — Tethys, Dione, and Rhea — orbit closer to Saturn than Titan and appear through 4-inch and larger scopes. You'll need a bigger instrument to see 12th-magnitude Enceladus. This satellite orbits so close to the rings' outer edge that it is often lost in the glare. Look for it September 4 when it lies 5" southwest of Tethys.

Iapetus brightens and fades as it orbits Saturn because it has one bright and one dark hemisphere that turn toward

WHEN TO VIEW THE PLANETS

EVENING SKY
Mercury (west)
Venus (west)
Jupiter (southwest)
Saturn (south)
Neptune (east)

MIDNIGHT
Saturn (southwest)
Uranus (east)
Neptune (south)

MORNING SKY
Uranus (southwest)
Neptune (west)

COMET SEARCH | A speedy visitor grows an anti-tail

AFTER A SEEMINGLY ENDLESS STRING of months without a decent comet, the tide starts to turn in September. Comet Africano (C/2018 W2) gets us started as it brightens to 9th magnitude this month. Africano does need time to flourish, however. Our first taste of the comet comes in early September, when it glows at 11th magnitude against the backdrop of Perseus. It remains visible all night, climbing nearly overhead shortly before dawn.

The comet grows brighter and more intriguing when it comes closest to Earth at New Moon in September's final week. Our planet passes through the comet's orbital plane on the 24th. To see why this matters, imagine a comet's picture etched into a glass door, and look at it as you walk past the door edge-on. The comet's curved dust tail appears as a thin knife to the north while its southern flank sports a short anti-tail. It seems to poke out the other side simply because we see it from below.

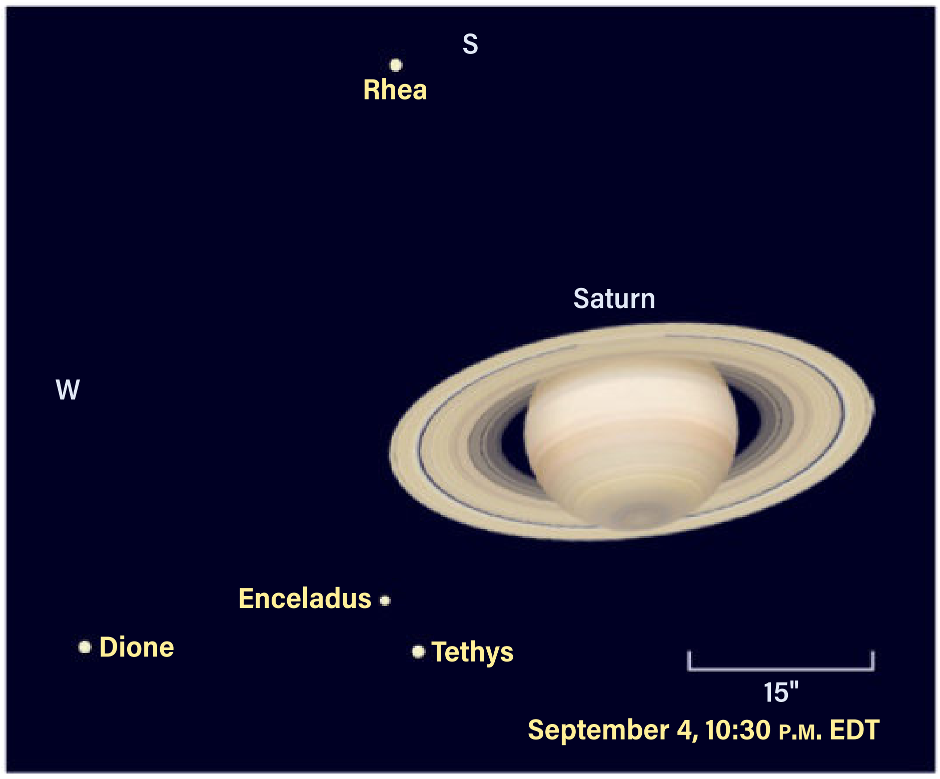
On September 28, Africano shares the same low-power field as the 11th-magnitude spiral galaxy NGC 7743 in southern Pegasus. Both objects should be brighter in the middle, but their shapes will be quite different. The galaxy appears nicely symmetric, while the comet looks more angular and shows a sharper southern edge. Use as much power as the objects can take in order to see these details more clearly.

Astronomers Brian Africano and Hannes Groeller discovered this comet within minutes of each other November 27, 2018. It's moving in the opposite direction from Earth's orbital motion, which causes it to zip across nearly 70° of sky this month. Its hyperbolic trajectory suggests it might have originated outside the solar system, but it could just as easily have received a boost from another Oort Cloud comet long ago.

Comet Africano (C/2018 W2)

Late September finds this 9th-magnitude dirty snowball at its closest to Earth. It then resides among the background stars of southern Pegasus.

Bashful Enceladus comes into view



Although Saturn's sixth-largest moon glows dimly not far from the planet's bright rings, it shows up nicely near brighter Tethys on September 4.

Earth in phase with its orbit. It glows at 11th magnitude when it passes 1.4' south of Saturn on September 11. It brightens as it heads west in the following weeks, reaching 10th magnitude when it lies 8.5' from the planet at the end of the month.

You won't find a better time to track down **Neptune**. The ice giant planet reaches opposition the night of September 9/10, when it lies closest to Earth and remains visible all night. Even better, it passes within 1' of magnitude 4.2 Phi (ϕ) Aquarii this month, so finding the right field is a snap.

You'll need binoculars or a telescope to capture the fainter glow of magnitude 7.8 Neptune. First, locate Phi in eastern Aquarius. The star appears 30° high in the southeast by 11 P.M. local daylight time on the 1st and reaches a similar altitude by 9 P.M. at month's end.

Once you have Phi in focus, Neptune will be in the same low-power field. The planet lies 7' east of the star September 1, but the gap closes with each passing night. At 11 P.M. EDT on the 5th, Neptune stands 42" east of Phi, and the separation narrows by about 4" with each passing hour. They come closest — 13" apart — shortly after daybreak on the 6th. The two make a lovely contrast all night, with Phi a ruddy point of light and blue-gray Neptune showing a 2.4"-diameter disk.

Neptune's westward motion carries it 6' west of Phi at opposition and 40' away by the end of September. Still, the two appear within the same low-power field.

Although magnitude 5.7 **Uranus** shines significantly brighter than Neptune, it's harder to find because it lacks a nearby star to guide you. Uranus rises among the background stars of southern Aries by 10 P.M. local daylight time in early September and two hours earlier by month's end, though it proves much easier to find once it climbs high in the south after midnight.

To locate Uranus, start at 2nd-magnitude Hamal (Alpha [α] Arietis), the Ram's brightest star. The planet lies 11° south of Hamal in a sparse region slightly south of 6th-magnitude 19 Ari. Uranus appears less than 2.5° south of this star throughout September. To verify your planet sighting, target the object with a telescope; only Uranus shows a blue-green disk that spans 3.7".

Mars is too close to the Sun to see. It will return to view before dawn in late October.

Martin Ratcliffe *provides planetarium development for Sky-Skan, Inc., from his home in Wichita, Kansas.* **Alister Ling**, *who lives in Edmonton, Alberta, has watched the skies since 1975.*

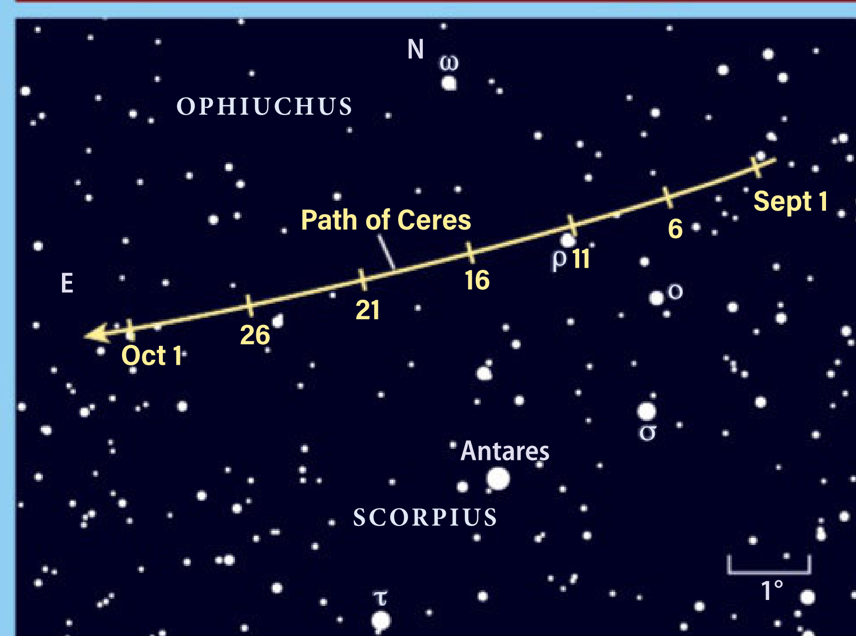
LOCATING ASTEROIDS |
Catch Ceres among colorful clouds

EVEN IF YOU'RE STUCK IN THE SUBURBS, you'll be able to spot a 9th-magnitude dwarf planet through a 3-inch telescope this month. Ceres has faded some since its late May peak, so it will be a challenge to see through binoculars. Several bright stars in the vicinity make the hunt easier, however, so it's a good time to take another look at Ceres.

The dwarf planet lies near 1st-magnitude Antares, the ruddy supergiant that marks the heart of Scorpius the Scorpion. More importantly, the darkness behind Ceres helps it stand out. In August, Ceres floated in front of fields swarming with stars belonging to the Milky Way's central bulge. But in September, it traverses star-poor dust lanes. What makes the journey even better for imagers are the super-photogenic swaths of red, blue, and yellow clouds of gas and dust that form the Rho (ρ) Ophiuchi complex.

On September 15, Ceres passes 2.9° north of Antares, and the closest star that outshines the asteroid lies 1° away. Identifying Ceres will be easy, but detecting its motion from night to night will be nearly impossible. For that, you need some nice reference stars. The best is Rho Oph itself, which stands 12' south of Ceres on the 11th, though a few field stars perform admirably on September's last few evenings. Simply sketch the positions of three or four stars and then add a dot for Ceres as it moves hour by hour.

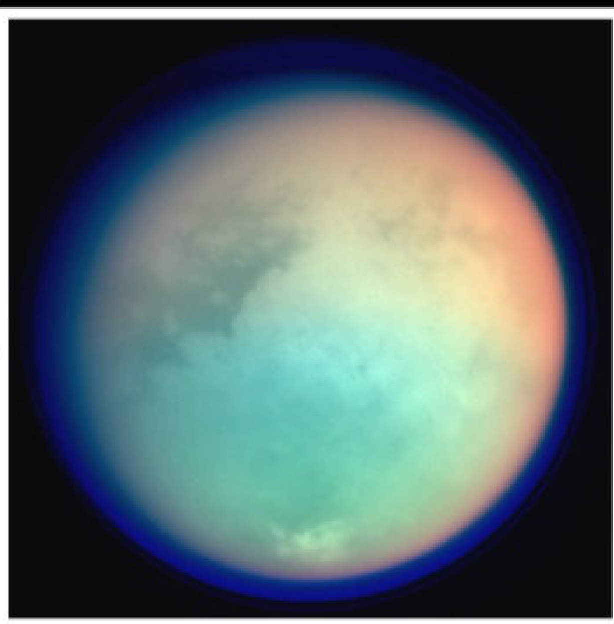
A dwarf planet meets the Scorpion's heart



Use 1st-magnitude Antares as a guide to Ceres this month. The 9th-magnitude asteroid passes within 3° of this star in mid-September.

Searching for life on SATURN'S BIG MOON

Titan's soupy skies drizzle complex hydrocarbons onto the moon's surface, potentially providing the building blocks of life. BY MICHAEL CARROLL



DESPITE ITS FRIGID temperature, Titan is a tantalizing target for further exploration because it hosts a dense atmosphere (blue haze) and maintains an active rain cycle. NASA/JPL-CALTECH/SPACE SCIENCE INSTITUTE

IN 1908, WHEN PERCIVAL LOWELL PUBLISHED *Mars as the Abode of Life*, he saw the Red Planet as surely teeming with life. Today, we know that's not the case — but the search for life in the solar system continues, and with far more tantalizing targets.

We have since learned a great deal about the icy ocean moons of the outer solar system. We've seen cryovolcanoes erupting from Enceladus and witnessed nitrogen glaciers sliding across the face of Pluto.

Titan experiences rainfall. But instead of water, Titan's clouds dump liquid methane from above.

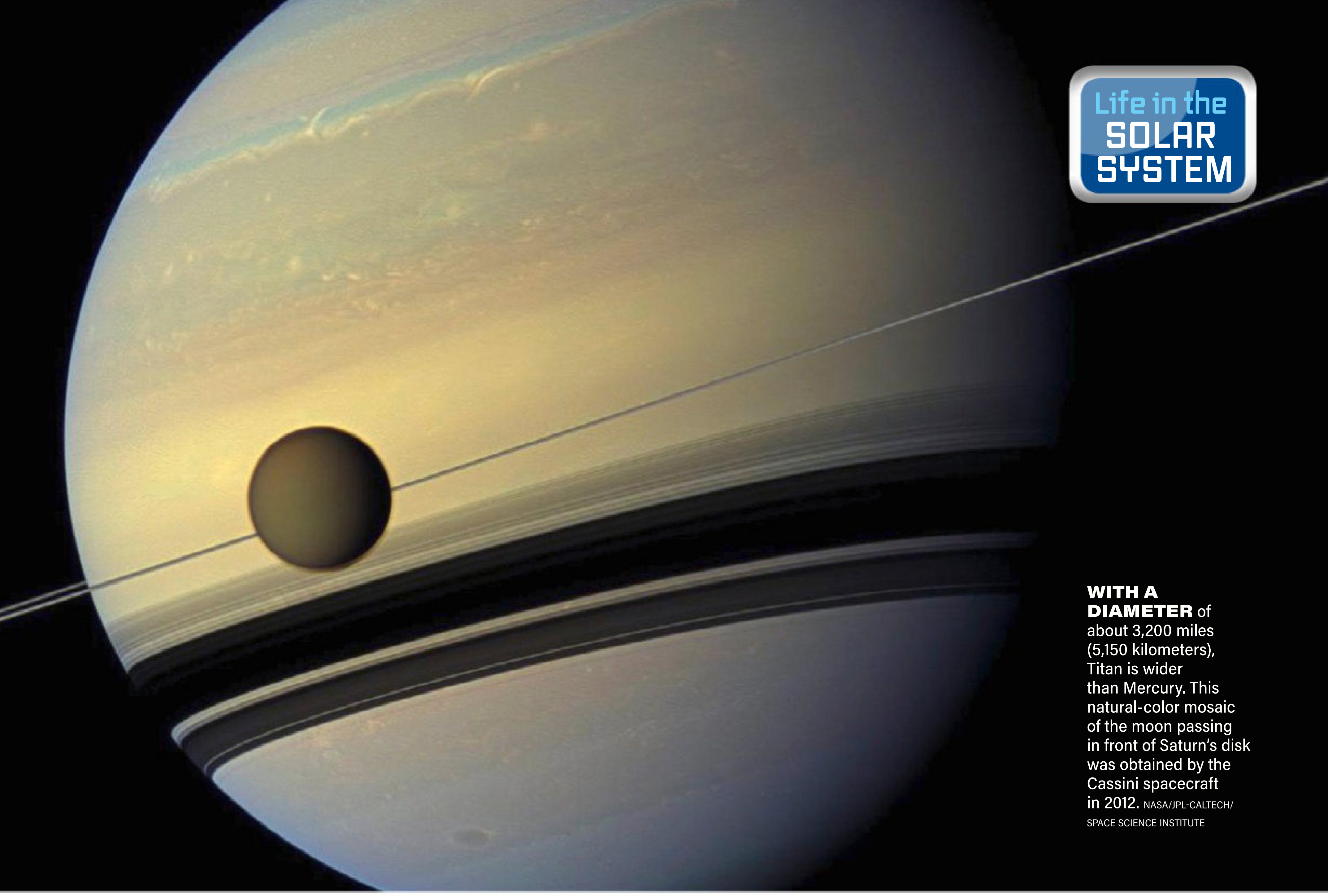
But still we wonder: What life might be out there? If biomes have secured a foothold on the distant worlds of our solar system, what form do they take?

These days, astrobiologists are turning their sights to another alien world, nearly the size of Mars and far more distant: Saturn's largest moon, Titan.

A different kind of life

At first blush, Titan seems an inhospitable place for an active biosphere. Its opaque nitrogen-methane cocoon is the second-densest atmosphere among all the solid bodies of the solar system, after Venus. Its atmospheric blanket sustains surface temperatures of –290 degrees Fahrenheit (–178 degrees Celsius). Still, these chilly temperatures are much warmer than the moon's smaller sibling Enceladus, whose daytime temperatures hover nearly 80 F (27 C) below Titan's. Yet despite such frigid temperatures, Titan has other features that might make it more conducive to life.

Titan experiences rainfall. But instead of water, Titan's clouds dump liquid methane, which is chemically similar to the natural gas that many of us heat our homes with. No matter what the rain is made of, the great moon is the only world besides Earth confirmed to have an active rain cycle fed by evaporation from surface lakes and rivers. Its river valleys



WITH A DIAMETER of about 3,200 miles (5,150 kilometers), Titan is wider than Mercury. This natural-color mosaic of the moon passing in front of Saturn's disk was obtained by the Cassini spacecraft in 2012. NASA/JPL-CALTECH/SPACE SCIENCE INSTITUTE

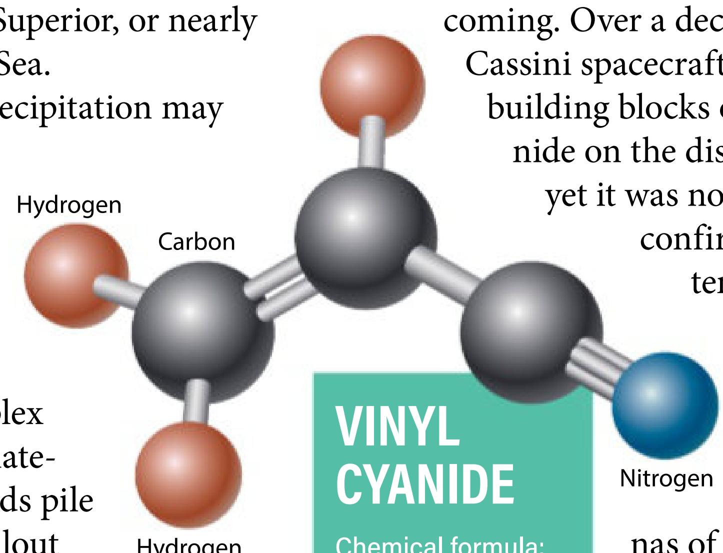
drain into liquid-filled basins, some as large as the terrestrial seas. Titan's largest sea, Kraken Mare, covers about 154,000 square miles (400,000 square kilometers), making it roughly five times the area of North America's Lake Superior, or nearly the size of Asia's Black Sea.

A second kind of precipitation may have even more bearing on the search for life on Titan: a steady drizzle of hydrocarbons. This organic "soot" combines with methane to form complex compounds, the raw materials of life. Titan's winds pile up the hydrocarbon fallout into vast sand seas.

But methane and hydrocarbons aren't the only things falling from Titan's soupy skies. Sunlight and radiation from Saturn break up nitrogen and methane molecules in Titan's atmosphere. When these fragments recombine, they create a compound called vinyl cyanide. Vinyl cyanide is important in the search for life because it tends to assemble into membranes like those found in terrestrial living cells.

This news has exciting implications for life on Titan, but it was a long time coming. Over a decade ago, the Cassini spacecraft detected the building blocks of vinyl cyanide on the distant moon, yet it was not equipped to confirm its existence. Later, in 2014, astronomers calibrating the 66 antennas of the Atacama Large Millimeter/submillimeter Array in Chile happened to use Titan as their target. As luck would have it, their data contained the fingerprints of vinyl cyanide. We now know that thousands of tons of the stuff float high in Titan's upper atmosphere, and an astounding 10 billion tons may have accrued in Titan's largest methane seas, Ligeia Mare and Kraken Mare.

The ability to form cell membranes is certainly not a guarantee of life. However, it is likely one of the prerequisites. Plus, Titan has even more to offer, says planetary scientist and engineer Ralph Lorenz of Johns Hopkins University's Applied Physics Laboratory, who was part of the team that landed Cassini's Huygens probe on Titan. Lorenz believes Titan is interesting for several key reasons. "There are processes going on there that we don't see at Mars today: the formation of clouds and rain, the pooling of liquids on the surface, their movement by tides and presumably by wind as well, the formation of waves. You have a much more astrobiologically interesting chemistry at Titan because of the methane being processed into literally hundreds of other compounds," he says.



ASTRONOMY: ROEN KELLY

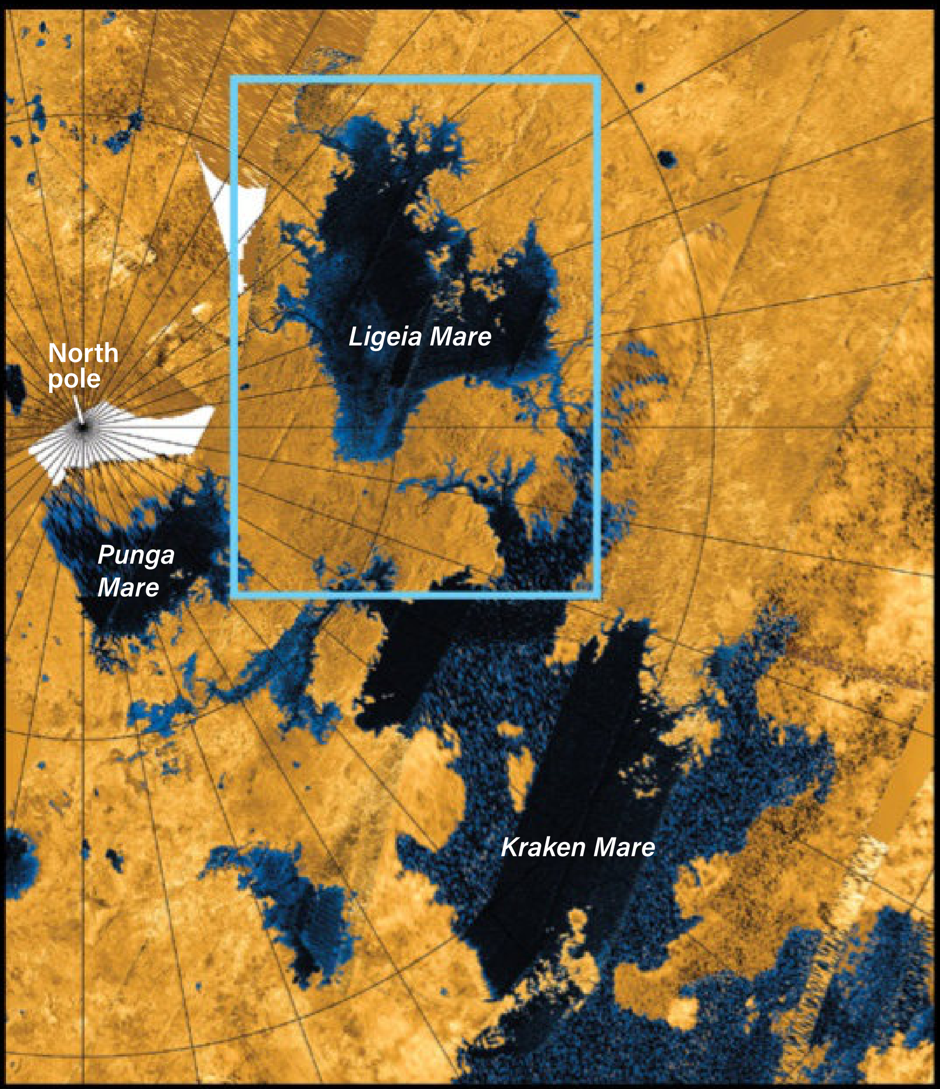
VINYL CYANIDE

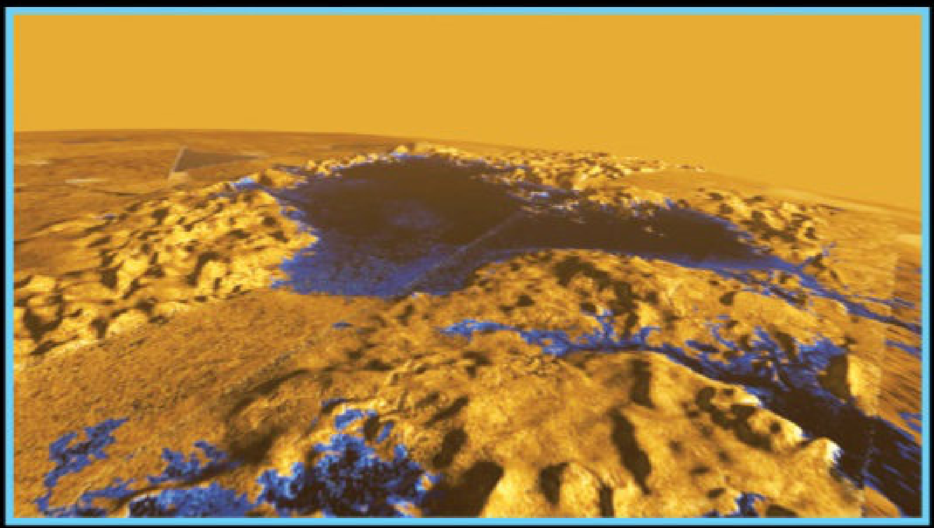
Chemical formula: C_2H_3CN

First detection in space: 1975

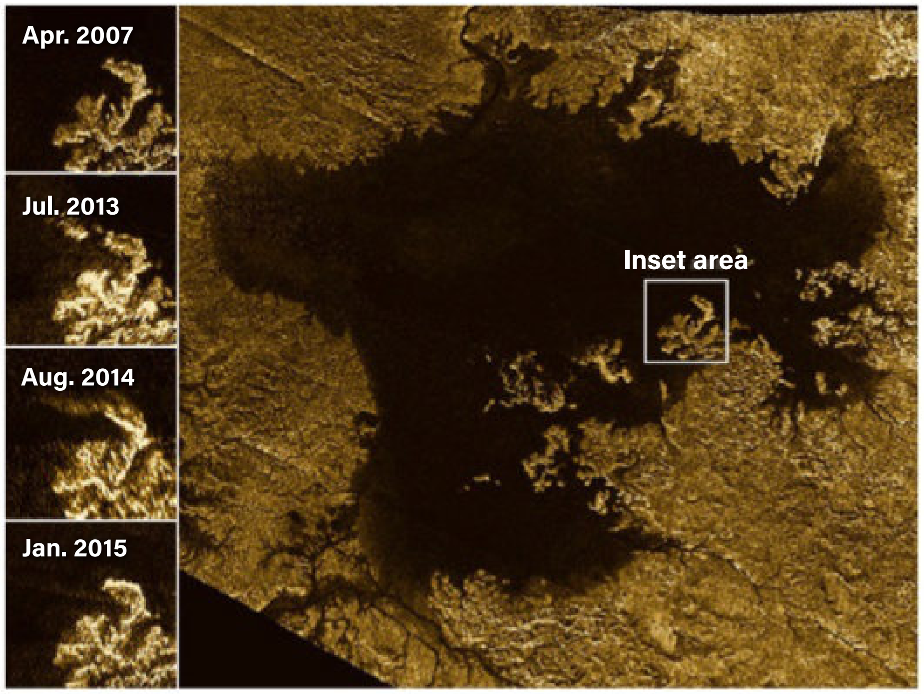
First clear detection on Titan published: 2017

Estimated availability in Ligeia Mare alone: Enough for 10 million cell membranes per cubic centimeter





THIS FALSE-COLOR VIEW of the seas near Titan's north pole at left was created using radar images from the Cassini spacecraft. Ligeia Mare, seen in the 3D reconstruction above, spans about 250 miles (400 km) and reaches depths of more than 500 feet (165 m). It appears quite placid, likely due to a dearth of wind at the time of observation. LEFT: NASA/JPL-CALTECH/ASI/USGS; ABOVE: H. ZEBKER



BY SCOURING CASSINI IMAGES, researchers uncovered transient features (insets) in Ligeia Mare they dubbed "Magic Islands," which are thought to be waves or bubbles in the hydrocarbon sea. NASA/JPL-CALTECH/ASI/CORNELL

Overcoming the cold

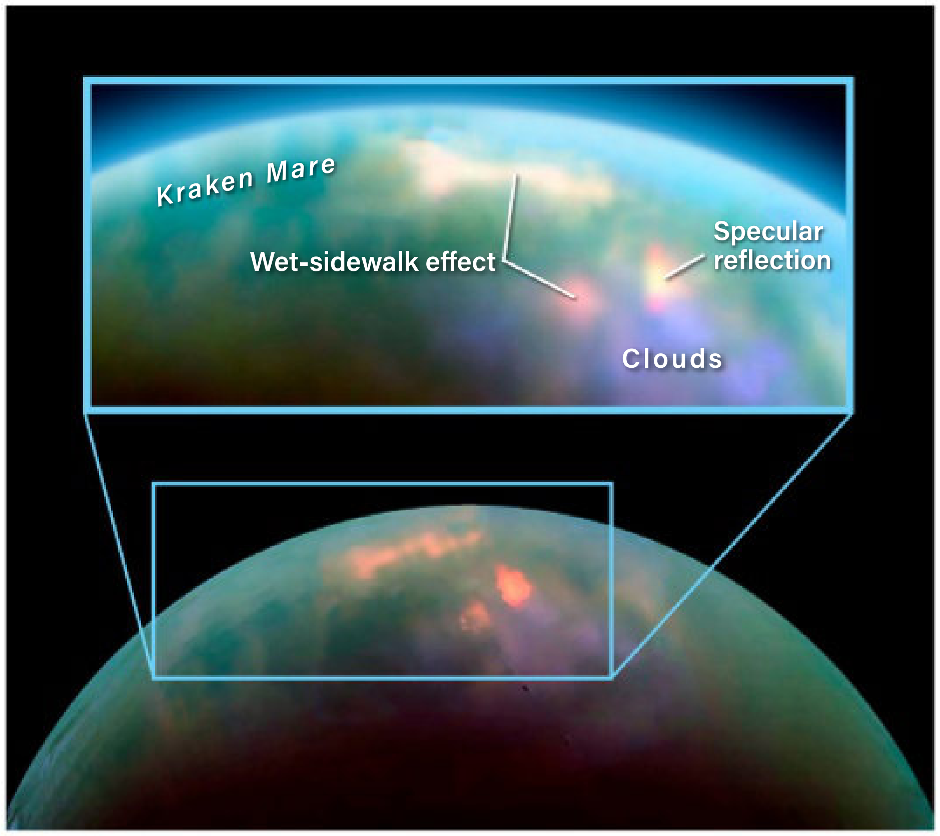
The primary roadblock to life on Titan remains its cold temperature. Chemical reactions of any kind (including biological ones) are sluggish. So how could all those organic compounds — called tholins — dissolve in Titan's methane lakes, combining into life-friendly mixes? NASA Ames astrobiologist Christopher McKay is trying to find out by experimenting in the laboratory with the solubility of organic material in liquid methane and ethane. "If you put the gunk in the water, the water will turn brown like tea, because things are dissolving in it. If you take that same tholin and put it in liquid methane and ethane, nothing happens. The problem is that it's freezing cold." To overcome this, McKay says they immerse tholins in isopentane, which is similar to methane, but can dissolve tholins at room temperature.

As part of their experiments, McKay and his team chill down isopentane, adding liquid methane and ethane to the mix. As the process continues, all the isopentane solidifies, separates out, and is gradually replaced by methane and ethane. But the concoction still exhibits some solubility. Using this process, the team "tricks" the mechanism keeping the tholins from dissolving into the methane, allowing them to mix in. "Titan may be able to do that with time. It could be that in the low temperatures, it just takes a lot of time. In my lab, we can't do an experiment that lasts for a million years, but Titan can," he says.

Low temperatures may actually be an advantage for Titan life, McKay asserts. On the one hand, cold temperatures can slow down or entirely prevent reactions from occurring. "On the other hand," he says, "low temperatures can be good because everything is slow; you don't have to work very hard. You don't need a lot of energy. Being slow is a feature if you don't have very much energy."

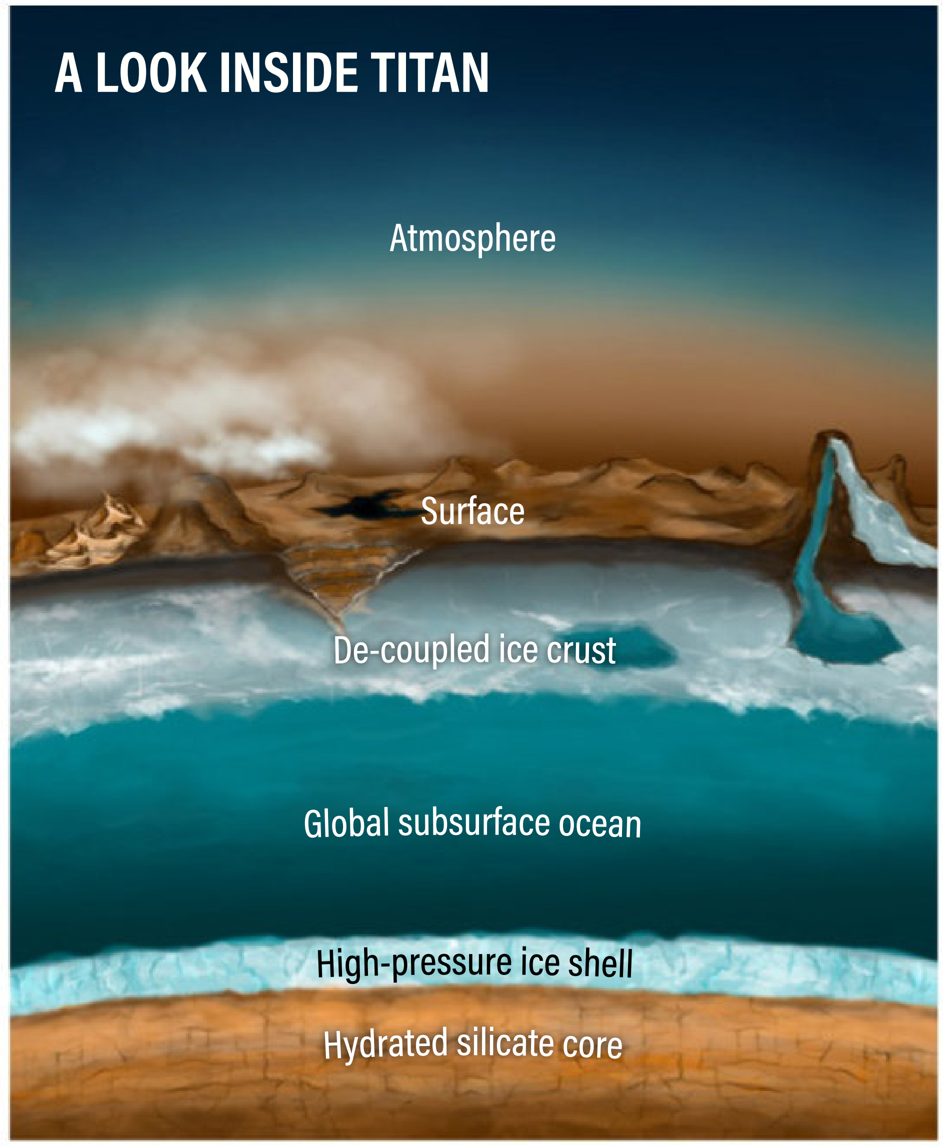
> "Low temperatures can be good because everything is slow; you don't have to work very hard. You don't need a lot of energy."

Yet some biologists are skeptical that such slow biological processes can occur. It's possible that biotic forms may have developed weaker chemical bonds than those found in terrestrial life, so the chemical reactions might not be so limited. But this has not, as yet, been seen in nature. Additionally, biochemists have failed to find models that they can point to as possible genetic molecules (those that can store information like RNA and DNA) for Titan. Unlike the diverse structures of protein molecules, hydrocarbons are limited in the way their physical structures can interact with each other and compounds in their environment. In other words, Titan's a tough place to live.



THE SURFACE near Titan's north pole, imaged above by Cassini's Visual and Infrared Mapping Spectrometer, displays a "wet-sidewalk effect" on its surface after seasonal methane rains. The inset view highlights the effect, as well as the mirrorlike (or specular) reflection of sunlight off one of Titan's lakes, named Xolotlan Lacus. NASA/JPL/UNIVERSITY OF ARIZONA/UNIVERSITY OF IDAHO

A CROSS SECTION OF TITAN at right shows the subsurface global ocean that likely hides beneath the moon's rocky surface. *ASTRONOMY*: ROEN KELLY, AFTER ATHANASIOS KARAGIOTAS AND THEONI SHALAMBERIDZE



Life beneath

Although Titan's surface conditions may make biology a difficult prospect, the world likely has a gentler subsurface ocean — a sea of saltwater 60 miles (100 km) beneath the ice. Careful study of features on Titan's surface shows that the moon's crust has wandered over time, shifting the positions of mountains and other landmarks by as much as 19 miles (30 km). Cassini orbital measurements also revealed bulges in the moon's surface, further suggesting that Titan's interior has a layer of liquid beneath its frozen surface. The water is likely rich in salts with dissolved sulfur, sodium, and potassium, elements common in the outer solar system. Titan's briny depths, locked in eternal darkness, seem cut off from any external energy source and separated from the world's mineral-rich, rocky core. But studies of ice fields show that diapirs — slowly rising masses of solid ice — can transport material from the base of glaciers upward within the ice. It may well be that minerals from Titan's core have migrated upward to mix with its isolated water ocean, providing life-empowering minerals. Additionally, cryovolcanic surface activity and its organic fallout likely interact with this ocean. Along with the ever-present hydrocarbon soot, this forges another source of biomaterials that may be channeled into the subsurface ocean.

TO HELP SCIENTISTS investigate Titan's subsurface ocean, NASA is exploring the development of a submarine that could search for hydrothermal vents on the ocean's floor, as seen in this artist concept. NASA

Water has another advantage: It can dissolve a whole host of life-friendly compounds, far more than either methane and ethane. Water is the great enabler of most biological operations we understand, often serving as a bridge between important chemicals that are necessary to life.

But how could we find out if, in fact, Titan has an active, alien biome?

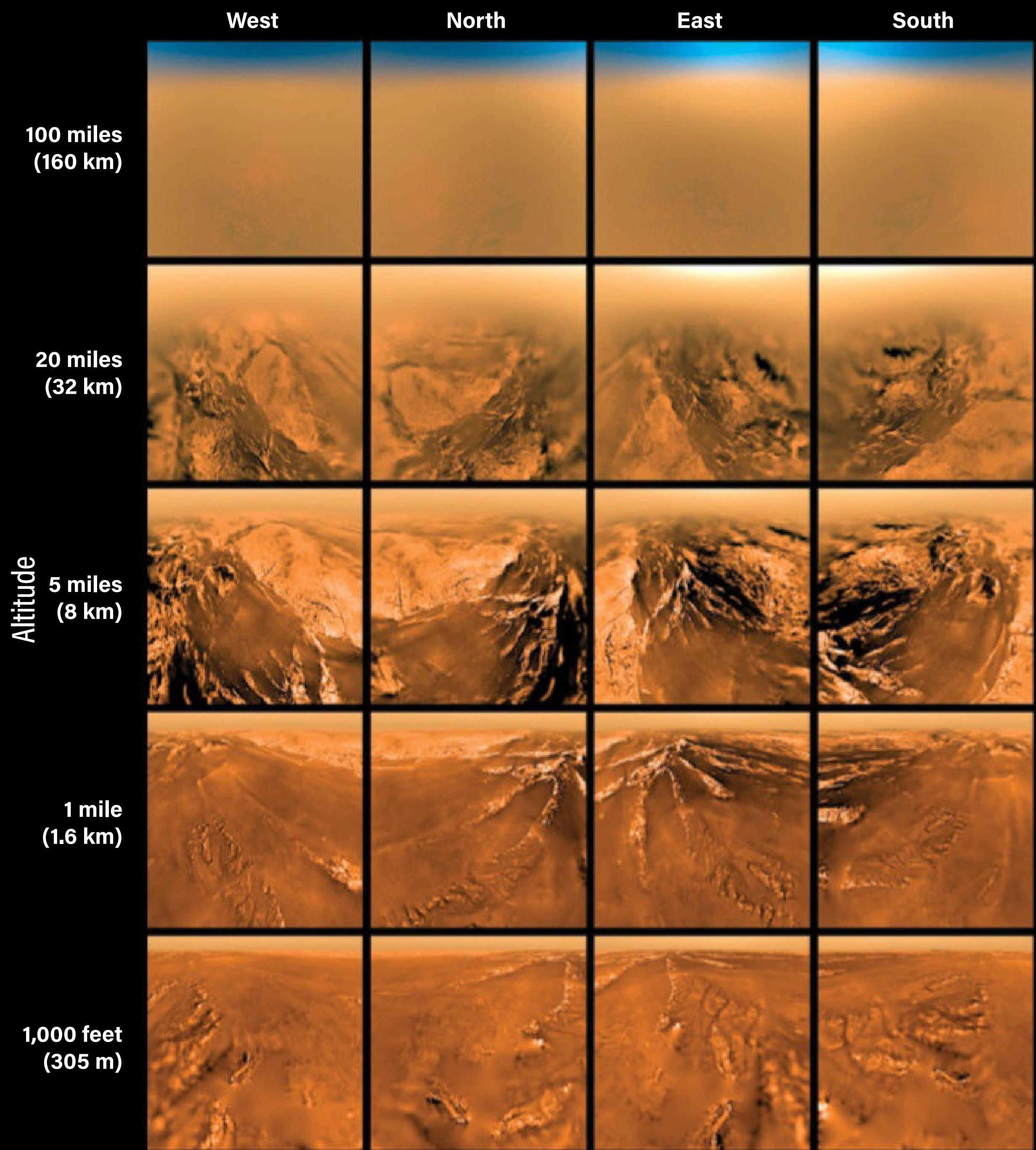
The search is on

For Lorenz, Titan provides a multitude of possibilities: "There's plenty to discover in Titan's seas, even if they are just methane, nitrogen, and ethane. There is the very exciting astrobiological potential of 'Can you have a whole different chemistry of life in that different solvent?' There are a whole set of functions like metabolism, information storage, and replication, and you need to figure out how to make the molecular toolbox to do those things. Nobody really knows how well that works there."

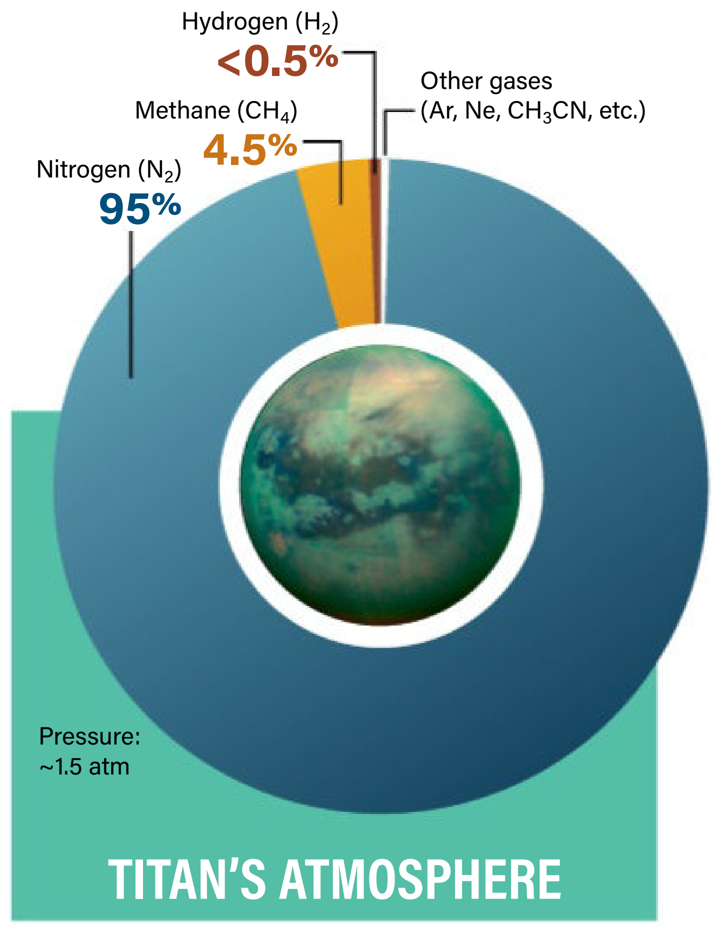
"The story of life on Titan is really the story of energy," says McKay. "Life is going to need energy no matter what it does or how it's built; it may or may not need membranes or a particular type of membrane, but it's going to need energy." But what energy sources might be available for biological processes?

Solar energy is one available energy source (although it is much lower on Titan than on Earth). Another energy source is hydrogen — in fact, just about every organic on Titan can react with hydrogen to release energy. To astrobiologists like McKay, "That's interesting in terms of the energy requirement for life, but it's also interesting in terms of a biosignature."

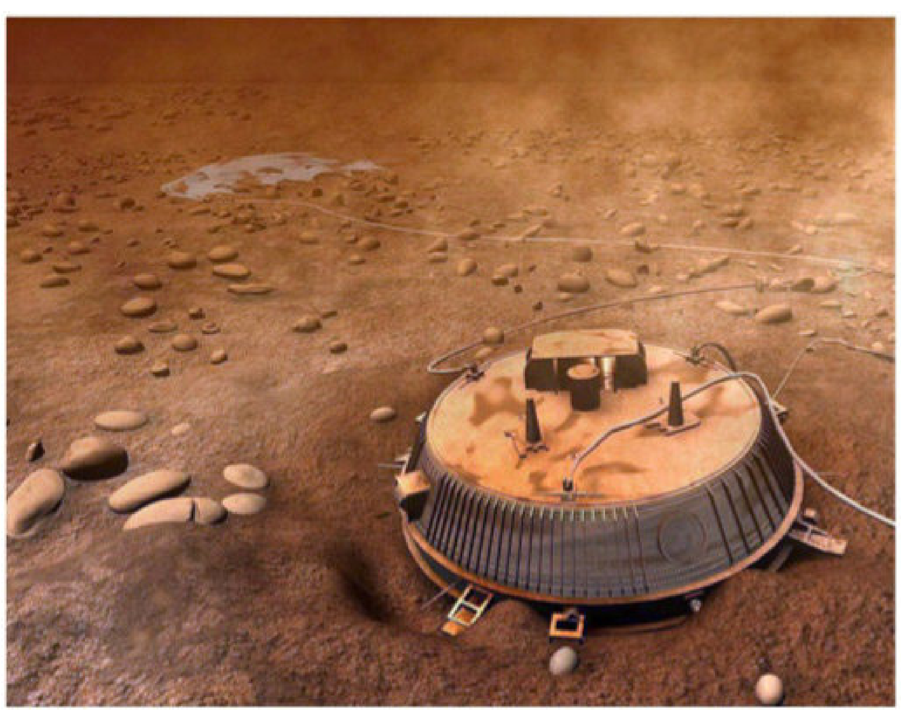
HUYGENS DESCENDS TO TITAN'S SURFACE



THIS SET OF IMAGES was captured by the ESA's Huygens probe as it descended to Titan's surface on January 14, 2005. ESA/NASA/JPL-CALTECH/UNIVERSITY OF ARIZONA



ABOVE: ASTRONOMY: ROEN KELLY, AFTER COMPOUNDCHEM.COM

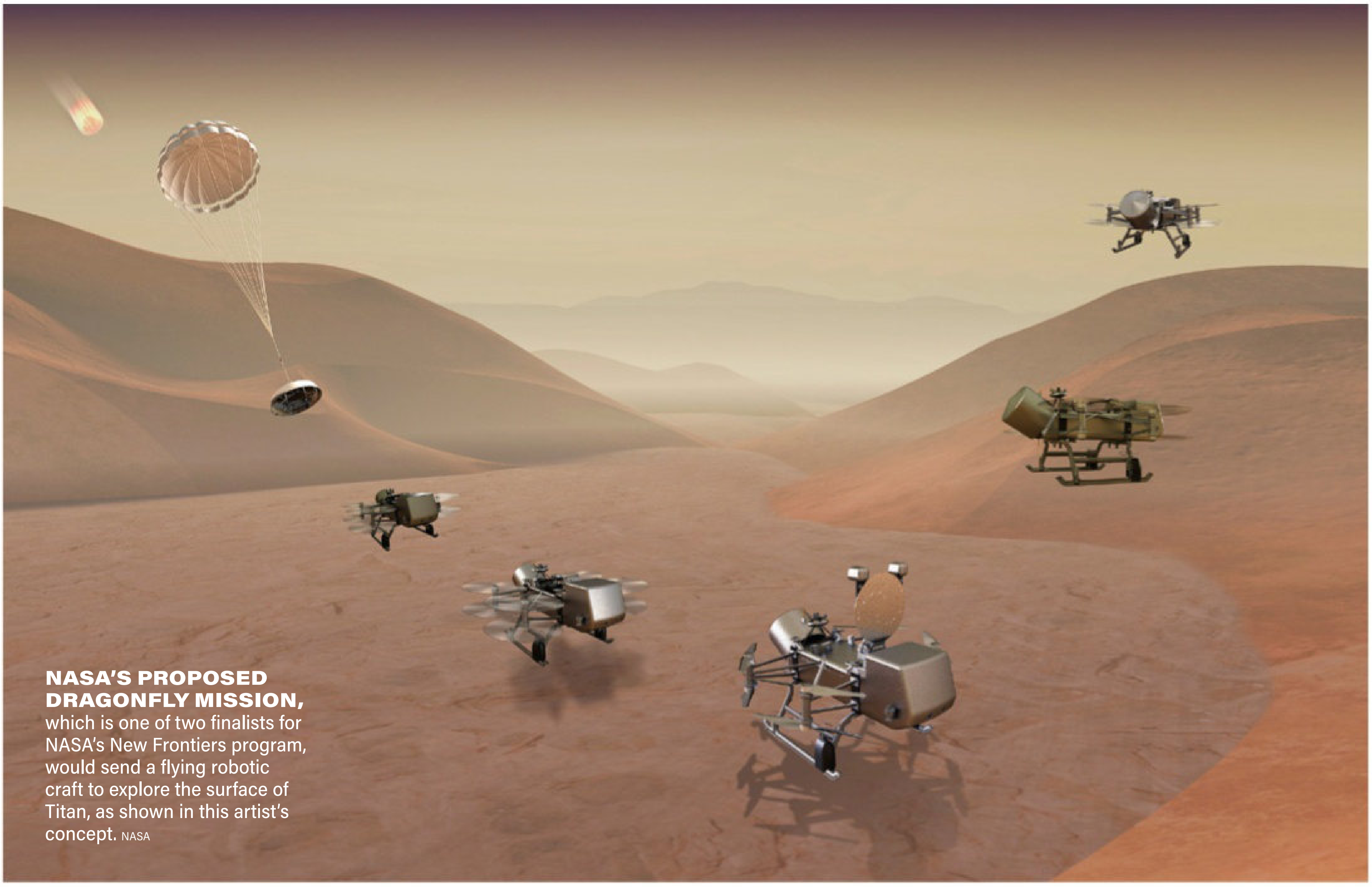


THE HUYGENS PROBE, seen in this artist's concept at left, lasted about 90 minutes on Titan's surface before running out of battery power. After landing, it captured the color-enhanced image of the moon's rock-strewn surface pictured at right. ILLUSTRATION: ESA. PHOTO: ESA/NASA/JPL/UNIVERSITY OF ARIZONA

Biosignatures — fingerprints of active biology — are markers for which future probes will search. For example, one of the biosignatures of life on Earth is the presence of oxygen. But while life both creates and consumes oxygen, this gas would not confirm the existence of terrestrial life, McKay says. That's because Earth's atmosphere is roughly 21 percent oxygen, enough that variations due to life are tiny compared with the total amount of oxygen in the air.

But carbon dioxide is a different matter. Because this gas makes up only 0.04 percent of Earth's atmosphere, "If you measured carbon dioxide [on Earth], you would find that it was highly variable," McKay says. The life-caused variation in carbon dioxide is large enough to affect the total. On Titan, carbon dioxide's analogue might be molecular hydrogen, which makes up less than 0.5 percent of the moon's atmosphere. If biological processes on Titan consume hydrogen, this gas may fluctuate, offering researchers a sign of life.

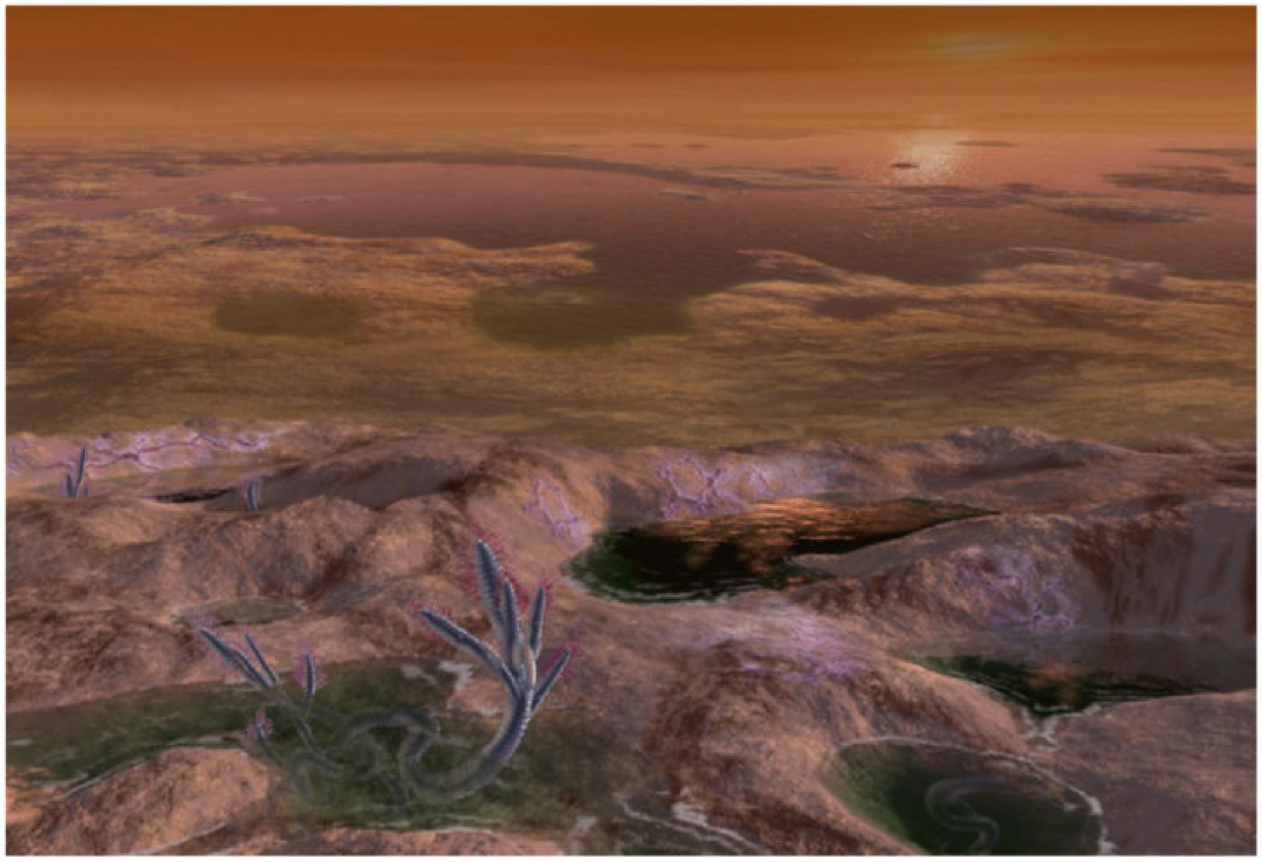
Actively searching for living organisms on any other world is difficult. This is especially true in an environment as alien as Titan. Unlike Mars and Enceladus, where we know that Earth-like life will operate with analogs of terrestrial metabolism, detecting life on Titan will require many different approaches. First, a probe would need to search for biomarkers in the



NASA'S PROPOSED DRAGONFLY MISSION, which is one of two finalists for NASA's New Frontiers program, would send a flying robotic craft to explore the surface of Titan, as shown in this artist's concept. NASA

environment, such as imbalances or cycles of gas levels. Second, in examining surface materials, a lander would go on to search for new structures or unfamiliar, repeating, non-geological patterns. Boats or submarines could sniff out biosignatures in Titan's methane seas. Orbiters also could detect biosignatures from above. One probe under consideration, a drone called Dragonfly, aims to chart hydrogen levels by scooping up material around it. It will then study the material with an advanced gas chromatograph mass spectrometer, which will separate and analyze specific types of molecules within the sample. On Mars and Enceladus, scientists are looking for water-based life, so they will search for molecules that work well in water like amino acids and lipids. But on Titan, we have no idea which molecules to look for. So researchers will be looking for anything that sticks out and makes them say, "Huh, that's odd."

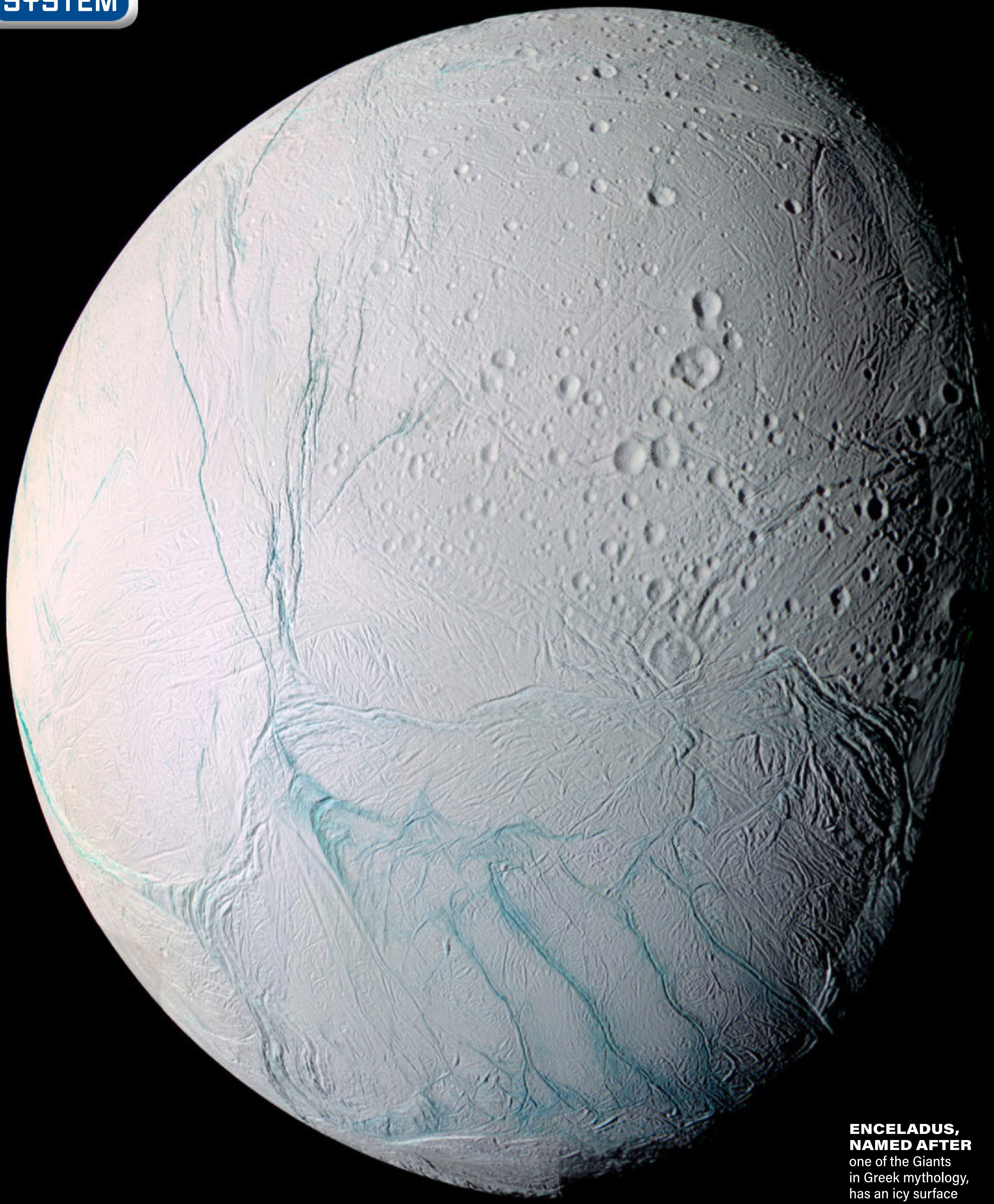
The discovery of life on Titan would be a watershed moment in the biological sciences. Though life on Mars or Enceladus will likely be chemically similar to that found on Earth, on Titan, any life capable of surviving in liquid methane will tell us that more than one kind of life exists in the universe. As McKay puts it, the news would tell us, "Not only do we have neighbors, but they are strange, or we are strange, we don't know which. It would be remarkable."



THIS SPECULATIVE ILLUSTRATION shows what the surface of Titan may look like if a completely unique form of life exists based on hydrocarbons like methane and ethane. MICHAEL CARROLL

When not painting or writing about space science, **Michael Carroll** *writes novels. His latest,* Lords of the Ice Moons*, published by Springer, takes place on Enceladus.*

Life in the SOLAR SYSTEM



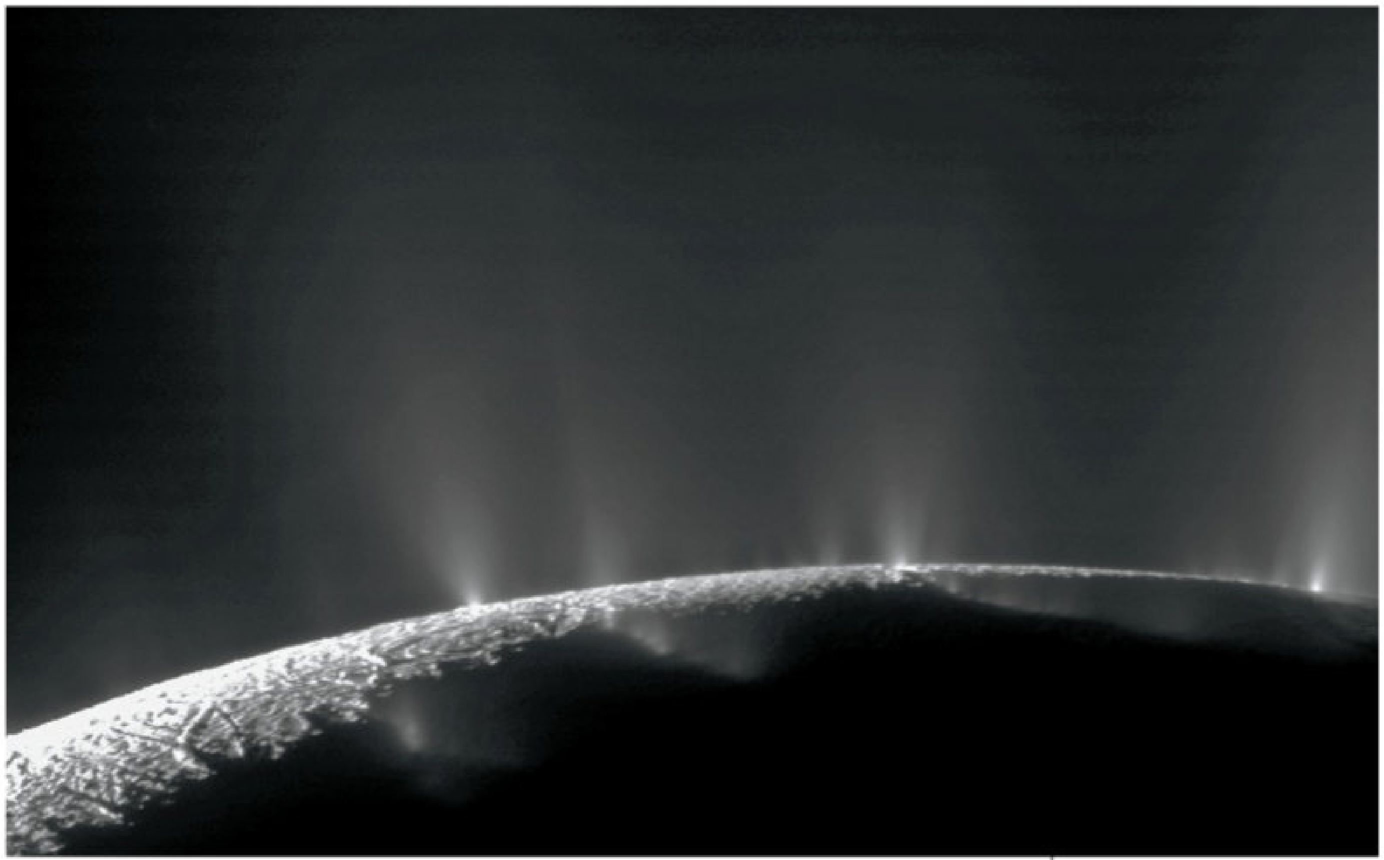
ENCELADUS, NAMED AFTER one of the Giants in Greek mythology, has an icy surface that reflects 81 percent of the light falling on it.
CASSINI IMAGING TEAM/JPL/ESA/NASA

The enigma of ENCELADUS

This tiny saturnian moon may be, pound for pound, the most valuable piece of real estate in the solar system. BY MORGAN L. CABLE AND LINDA J. SPILKER

"In the old time Pallas [Athena] heaved on high Sicily, and on huge Enceladus dashed down the isle, which burns with the burning yet of that immortal giant, as he breathes fire underground."

— Quintus Smyrnaeus, *The Fall of Troy*



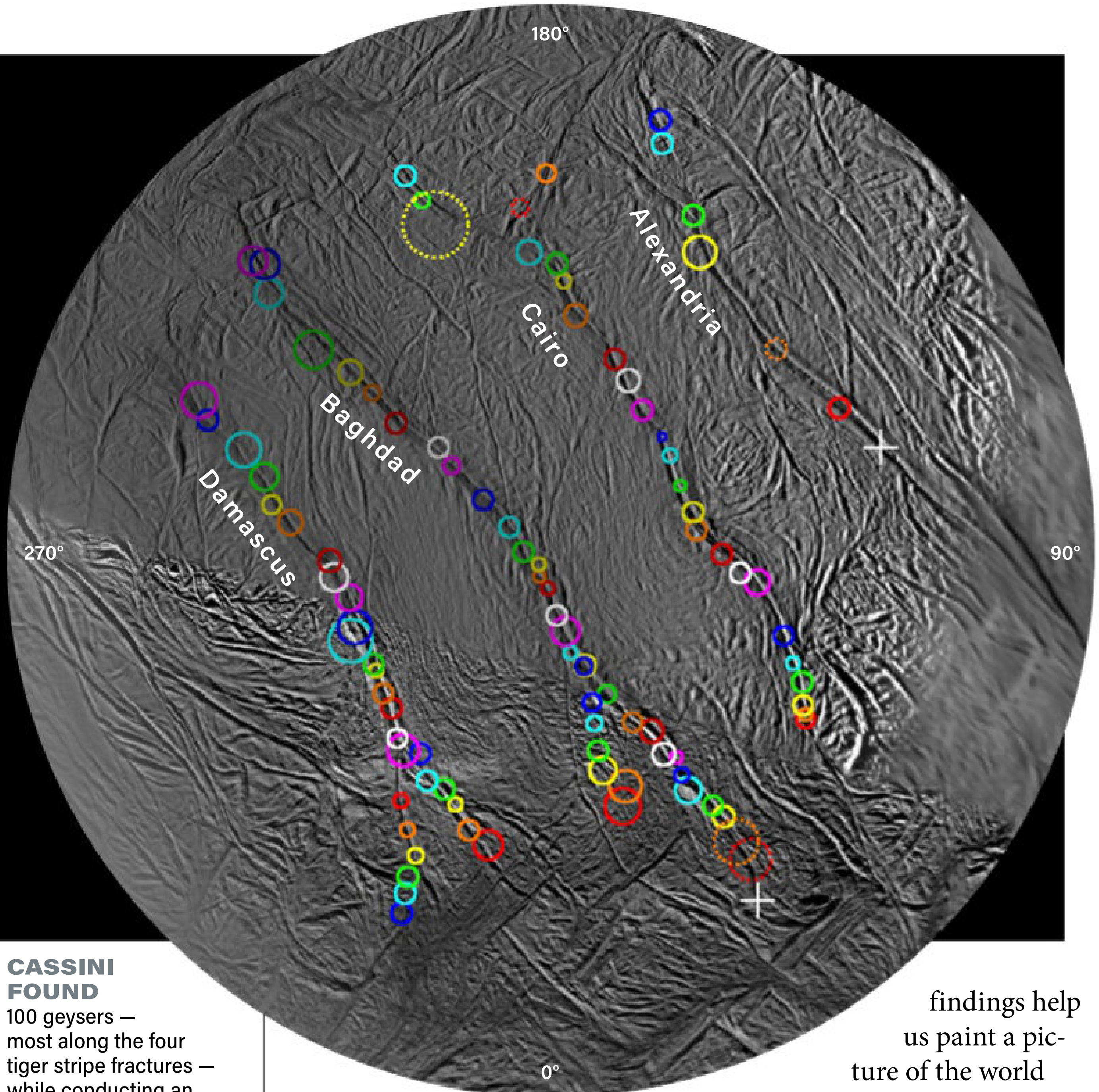
PLUMES SPRAY WATER ICE and vapor from many locations along the so-called "tiger stripes" crossing Enceladus' south polar terrain. The four prominent fractures are about 84 miles (135 kilometers) long. This two-image mosaic of the moon shows the curvilinear arrangement of geysers, erupting from the fractures. NASA/JPL/SPACE SCIENCE INSTITUTE

Saturn's sixth-largest moon, Enceladus has a diameter of only 310 miles (500 kilometers), and a mass less than 1⁄50,000 that of Earth. When it comes to places to look for life, however, Enceladus is at the top of the list, and it's right in our cosmic backyard.

A bit ignored at first

English astronomer William Herschel discovered Enceladus in 1789, but it remained an enigma until the Cassini mission began orbiting Saturn in 2004. Prior to Cassini, Enceladus was a bit ignored. We didn't know liquid water could exist that far out in the solar system, so why would anyone be that interested in another boring, dead ball of ice?

That all changed one year later, when Cassini's magnetometer (think: fancy compass) detected something strange in Saturn's magnetic field near Enceladus. This suggested the moon was active. Subsequent passes by Enceladus revealed four massive fissures — dubbed "tiger stripes" — in a hot spot centered on the south pole. And emanating from those cracks was a massive plume of water vapor and ice grains. Enceladus lost its label of being a dead relic of a bygone era and leaped to center stage as a dynamic world with a subsurface ocean.



CASSINI FOUND 100 geysers — most along the four tiger stripe fractures — while conducting an imaging survey of Enceladus' south polar region. Researchers plotted them on this polar stereographic map to compare geyser activity with enhanced thermal emission observed by Cassini's heat-measuring instruments and with the distribution of tidal stresses across the region. Those comparisons produced clues that helped explain how the geysers work. In this image, the more precise a geyser location is known, the smaller the circle representing it. These four sulci (the large fractures) are named for ancient cities on Earth. NASA/JPL-CALTECH/SPACE SCIENCE INSTITUTE

But was it really an underground ocean, or more of a local southern sea? Thankfully, Cassini could answer this question, too. By verifying excess wobble over Enceladus' orbital period, the imaging cameras confirmed that the icy crust is not connected to the world's rocky core. This could only be possible if the crust is floating on a global, subsurface, liquid-water ocean.

And Cassini didn't stop there. Mass spectrometers aboard the spacecraft analyzed the gas and grains during multiple fly-throughs of the plume. These instruments, the Ion and Neutral Mass Spectrometer (INMS) and Cosmic Dust Analyzer (CDA), found the plume contains mostly water, but also salts, ammonia, carbon dioxide, and small and large organic molecules. These findings help us paint a picture of the world underneath the ice: a possibly habitable ocean that's slightly alkaline, with access to chemical energy in the water and geothermal energy at the rocky seafloor.

Possible energy sources

One of the greatest legacies of the Cassini mission is that it established Enceladus as possessing all three ingredients for life as we know it: water, chemistry, and energy. Water in the ocean — check. Chemistry in the simple and complex organics detected in the plume — check. These could be utilized to form the molecular machinery of life.

Energy takes a bit more explaining.

It is likely that hydrothermal vents are present at the seafloor of Enceladus. We know this because of three lines of evidence. First, INMS detected methane in the plume, at higher concentrations than would exist if sourced from clathrates (water-ice cages at high pressure with methane trapped inside) or other reservoirs in the ice. Methane is a key product of hydrothermal systems.

Second, CDA discovered silica nanograins of a particular size and oxidation state traced to the ocean. These only could have formed where liquid water is touching rock at temperatures of at least 194 degrees Fahrenheit (90 degrees Celsius), in the range of hydrothermal vents like "white smokers" here on Earth.

And third, the recent confirmation of molecular hydrogen in the plume by the INMS team strongly suggests interaction of liquid water with a rocky core.

On Earth, hydrothermal vents at the base of the Mid-Atlantic Ridge host teeming ecosystems, living as far removed as one can imagine from photosynthesis. These habitats survive off of geothermal and chemical energy. A similar community might exist near a hydrothermal vent at the seafloor of Enceladus.

IT IS LIKELY THAT HYDROTHERMAL VENTS ARE PRESENT AT THE SEAFLOOR OF ENCELADUS.

So, we have water, chemistry, and energy. Let's say they have mixed together long enough for life to form. (Your guess is as good as anybody's here — estimates range from 100,000 to 25 million years.) How might we detect it?

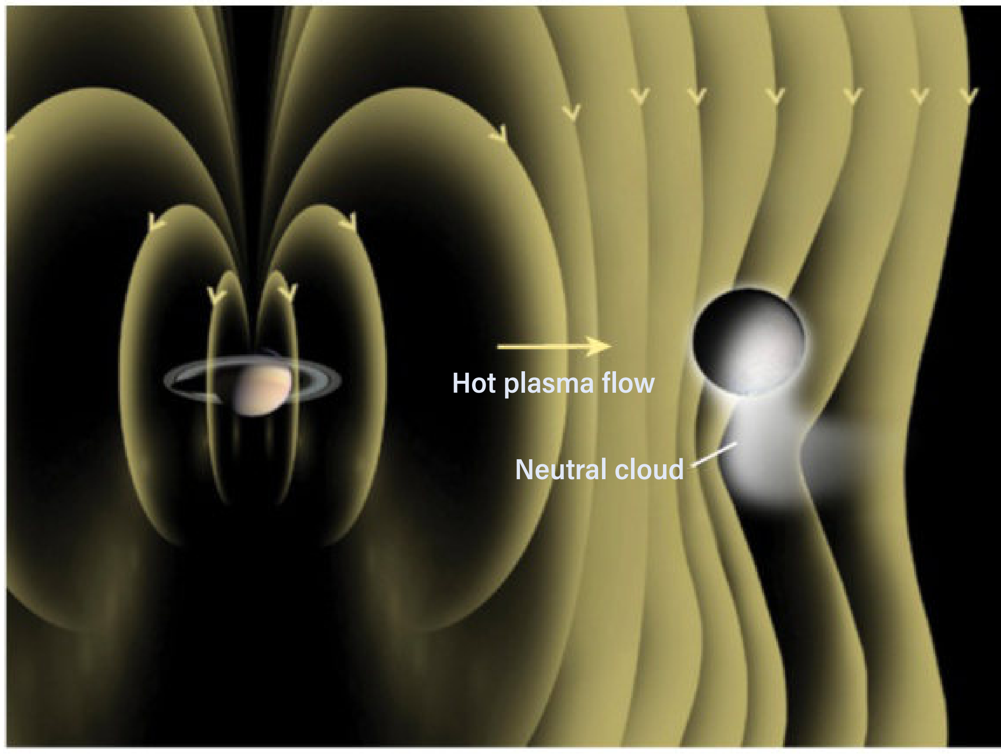
Assuming an energy-limited scenario (a good analog is Lake Vostok, a body of water in

Antarctica that's been covered with ice for the last 35 million years), we are probably looking at cell densities in the range of 100–1,000 cells per milliliter of ocean water. For reference, Earth's oceans have about 1 million cells or more per milliliter.

We assume this life would use readily available building blocks — such as amino acids, which are abundant in carbonaceous chondrites and likely present all over the saturnian system — in numbers on par with Earth-based life.

This assumption is reasonable because life needs chemical complexity to carry out the reactions that keep cells functional. Then we are looking at concentrations of biomarkers on the order of less than 1 part per billion. That's tough for current instruments to achieve, without some kind of concentration step.

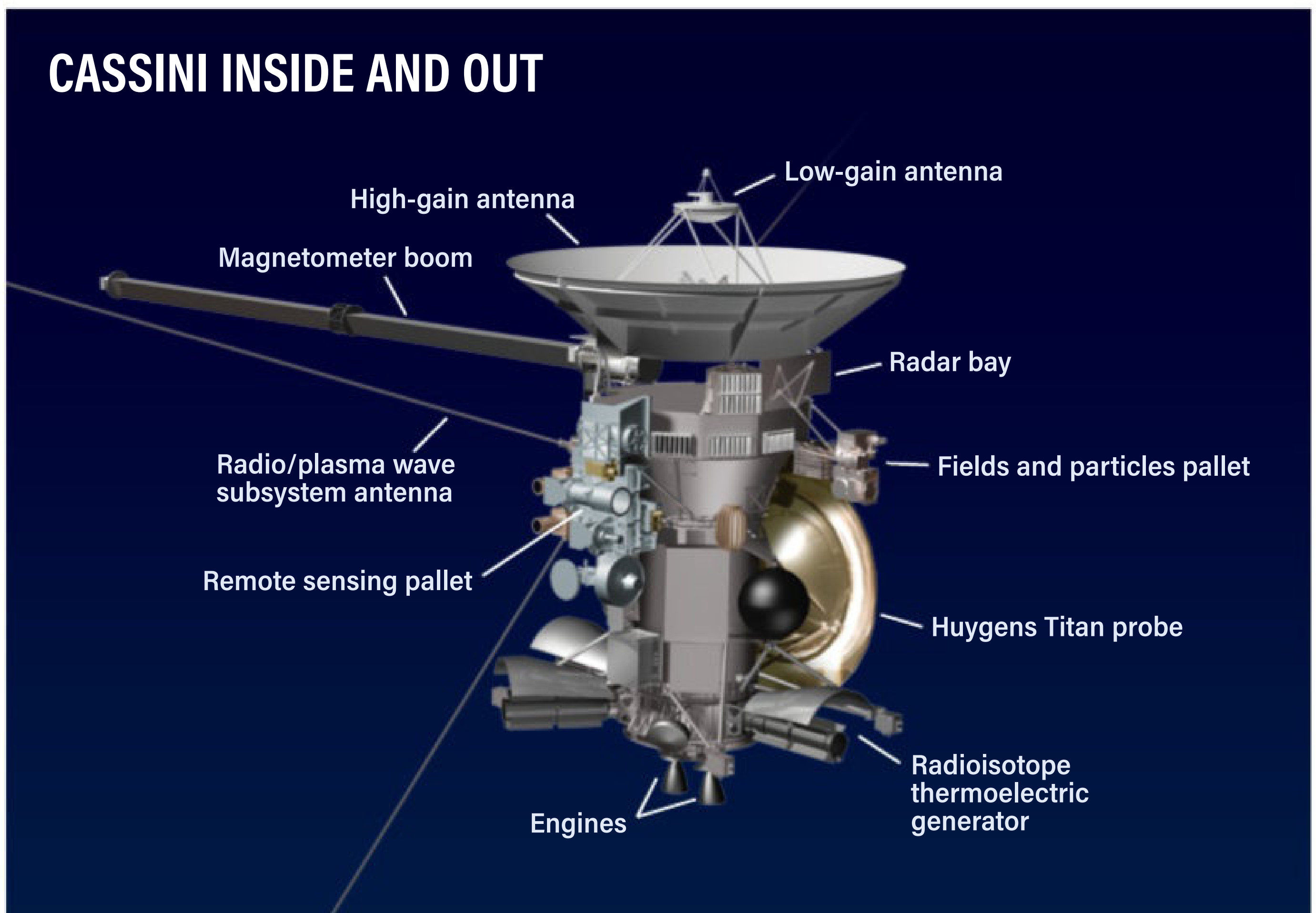
Does this mean we have to wait for more advanced instruments before we search for life? Nope.



MAGNETIC DISTORTION

AS CASSINI FLEW BY ENCELADUS, its magnetometer, which measures the magnetic field in its area, detected an anomaly scientists later confirmed as plumes coming from the moon's south polar region. This illustration shows the bending of the planet's magnetic field caused by Enceladus. NASA/JPL-CALTECH

CASSINI INSIDE AND OUT



Organic enrichment in the plume

Of all the ice grains detected by the CDA instrument, a fraction had a high concentration of organic molecules, something the CDA team calls high mass organic cations (HMOC). While the instrument couldn't specifically identify the structures of the HMOCs, a thorough analysis led to some educated guesses, such as aromatics (carbon-containing ringed structures) and oxygen- and nitrogen-bearing species. Within Enceladus' ocean, there may be a complex organic soup of molecules.

The best theory for how these organic-rich ice grains might form is due to something called "bubbles bursting." The grains were not only organic-rich, but also salt-poor, suggesting they came from an organic layer at the ice-ocean interface.

On Earth we have something similar floating at the surface of our ocean. It's a film called an "organic microlayer," as it's not very thick and is typically made up of organics from biological activity (i.e., bits of cells) and from other sources, too.

The organic molecules like to hang out together and aren't huge fans of salts or water, so they push these things out of the microlayer. Then, wave activity causes bubbles in this microlayer to burst, generating aerosols that are organic-rich and salt-poor.

A similar process may be happening on Enceladus. Organic molecules in the ocean may be concentrated at the ocean-ice boundary, and, just like on Earth, may force out the water and salts from this film. As the liquid surface at the base of the plume boils into vacuum, bubbles might burst and disperse the organic film, producing some grains that have a lot of organics inside, and little salt.

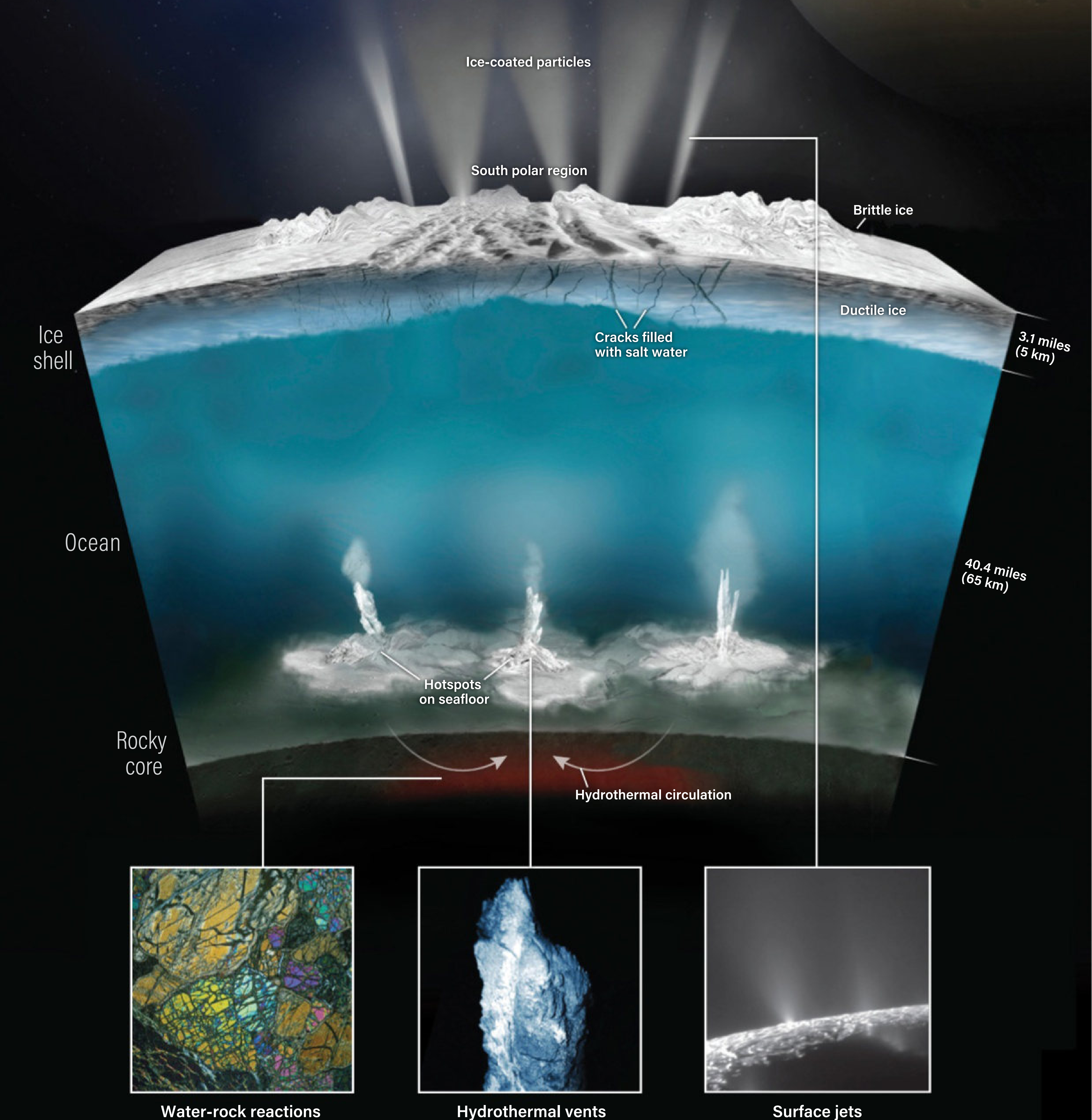
The result of all of this? Enceladus may be helping to concentrate the very things astrobiologists want to study the most: organic molecules.

CASSINI WAS A COOPERATIVE project of NASA, the European Space Agency, and the Italian Space Agency. The spacecraft spent more than 13 years studying Saturn, its rings, and its moons. It captured some 450,000 images and returned 635 gigabytes of science data. NASA/JPL-CALTECH

POWERING THE GEYSERS

THE CASSINI SPACECRAFT detected hydrogen in the plume of gas and icy material spraying from Enceladus during its final, deepest dive through the plume October 28, 2015. By studying the plumes, researchers hope to determine the composition of this moon's subsurface ocean. This graphic illustrates a theory on how water interacts with rock at the bottom of the ocean, producing hydrogen.

NASA/JPL-CALTECH/SOUTHWEST RESEARCH INSTITUTE



Aerosols on Earth boast organic molecules enriched hundreds to thousands of times over typical ocean concentrations. If we collect samples by flying through the plume or by landing on the surface, we may have a greater chance of detecting evidence of life on Enceladus, if it exists.

Future mission concepts

Enceladus has captivated us and given us more than enough reasons to go back. Many possible missions would do the job, and a few have been proposed in the post-Cassini era, although not yet selected by NASA to proceed.

Some would do as Cassini did — fly through the plume and analyze the gas and grains — but with upgraded instruments capable of much more sensitive and effective tests for life. Others would land on Enceladus' south polar terrain, sampling fresh snow deposited onto the surface from the plume.

Even more ambitious concepts include a sample return mission (although with a round-trip time of 14 years, we would have to wait awhile to get that sample) or various climbing or melting robots to descend the 1.2 to 6.2 miles (2 to 10 km) through the ice shell and reach the ocean itself.

Whatever we send, the next mission to Enceladus — if indeed astrobiology is its main objective — will need a well-designed suite of instruments capable of searching for multiple, independent lines of evidence for life. Our understanding of life's characteristics has advanced greatly since the Viking era, the last time NASA openly stated the search for life as the primary goal.

ENCELADUS HAS CAPTIVATED US AND GIVEN US MORE THAN ENOUGH REASONS TO GO BACK.

Back when the two Viking landers touched down on Mars in 1976, for example, we knew only two of the three branches of life. (Archaea, the third and most primitive branch of the tree of life, was discovered in 1977.) The Viking landers had three biological experiments designed to search for life in the martian regolith. One test result was positive, one was negative, and one was ambiguous. Since then, we have learned a great deal about how to design experiments such that an ambiguous result is much less likely.

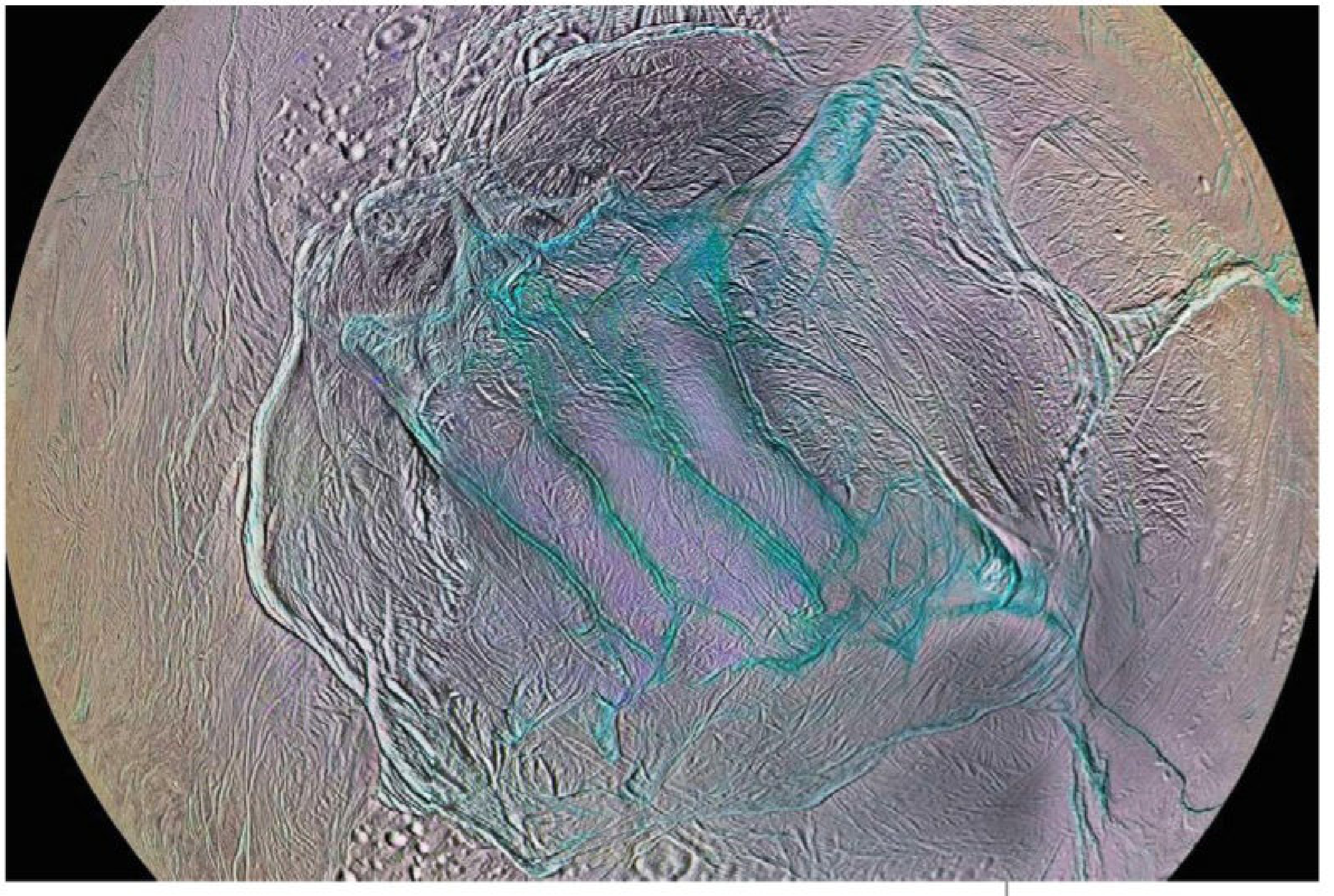
We are also getting better at searching for biosignatures that are as agnostic to Earth life as possible. For example, a future mission to Enceladus might not target DNA, which is Earth-life-specific, but it might look for a molecule that could serve the same function for alien life: a large molecule with repeating subunits (akin to an alphabet) capable of storing information, such as the blueprints to build an alien cell. If such a molecule is detected, along with positive identification of multiple other biosignatures, a strong case could be made for the first detection in human history of life on another world.

Active, accessible, and relevant

Enceladus is not the only place that could host life. Europa has an even larger liquid water reservoir, and Titan's ocean may entertain an unimaginably rich organic chemistry.

But Enceladus is the one place where researchers know for certain that they can access material from the ocean without the need to dig or drill (or even land). We can use technology available right now to test the hypothesis of whether life may be present somewhere else in the solar system.

Enceladus may be a tiny moon, but good things often come in small packages. The time is now to answer the key question that has driven us since we first looked up: Are we alone?

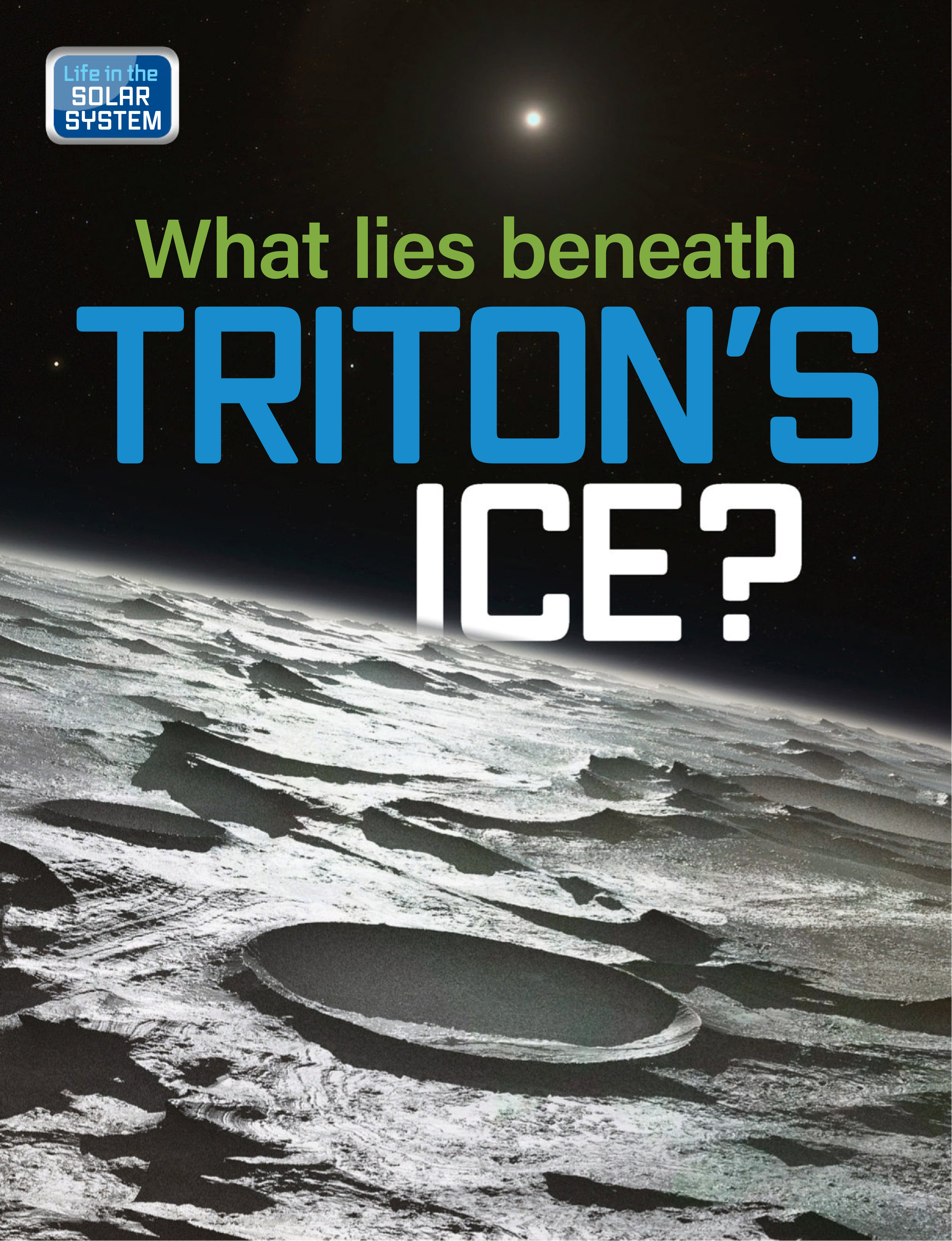


RESEARCHERS CREATED this enhanced view of Enceladus' south polar region by combining Cassini images taken through infrared, green, and ultraviolet filters. The tiger stripe fractures, the source of the plumes venting gas and dust into space, are prominently visible at center. NASA/JPL-CALTECH/SSI/LUNAR AND PLANETARY INSTITUTE/PAUL SCHENK (LPI, HOUSTON)

Morgan L. Cable *is a research scientist and supervisor of the Astrobiology and Ocean Worlds Group at JPL.* **Linda J. Spilker** *is a planetary scientist, ring researcher, and Cassini project scientist at JPL.*

Life in the SOLAR SYSTEM

What lies beneath TRITON'S ICE?



Neptune's moon Triton shows tantalizing evidence of water beneath its jumbled crust, making it a high-priority target in the search for life. BY NOLA TAYLOR REDD

WHEN VOYAGER 2 FLEW BY NEPTUNE and its largest satellite, Triton, in 1989, it revealed a moon with never-before-seen terrain and plumes spurting from the surface. At the time, scientists attributed the plumes to heating from the Sun. But recent advances in understanding ocean worlds such as Jupiter's moon Europa and Saturn's moon Enceladus have raised the possibility that Triton's plumes may indicate it, too, harbors an ocean under its icy crust — a place where life may have managed to evolve.

Ocean worlds abound in the solar system. Europa and Enceladus may be the best known after Earth, but dwarf planets Pluto and Ceres are also candidates for hosting liquid water beneath their surface. Two of Jupiter's other large moons, Callisto and Ganymede, may also have subsurface oceans, but thick crusts make access a challenge. Even some of the largest chunks of ice at the edge of the solar system could have water under the surface.

"These are not just solid rock-and-ice bodies in the outer solar system," says Kathy Mandt, a planetary scientist at Johns Hopkins Applied Physics Laboratory. "The subsurface liquid water could have the potential for hosting life based on what we see in the depths of our own oceans."

TRITON'S ICY SURFACE and thin atmosphere appear as they might look from several miles above the moon in this artist's impression. A crescent Neptune hangs in the background, while the Sun appears as only a bright star in the upper left. ESO/L. CALÇADA

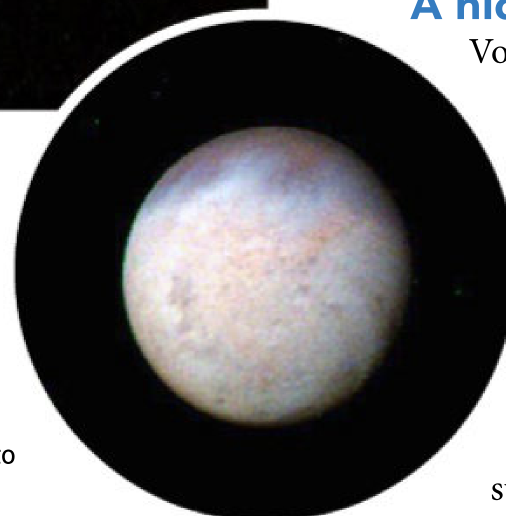
Longtime Triton researcher Candice Hansen of the Planetary Science Institute in Arizona agrees that ocean worlds may be key sites for life to evolve. "On Earth, if you have liquid water, you've got life," she says. Several years ago, at a meeting of planetary scientists, she recalls that many of the Earth-focused oceanographers present were confident that an extraterrestrial ocean would lead to the discovery of life. "They [said], 'You'll find life, we'll find it all over,'" Hansen says.

A hidden ocean

Voyager glimpsed Triton only briefly, but that glimpse was tantalizing enough. The spacecraft revealed that the moon's surface is young, with some estimates setting its age as low as 10 million years. The reshaping and repaving of the terrain suggest that something is happening beneath the surface.

Whether that process comes from the movement of rocks or the effect of an ocean remains unclear.

One of the moon's most intriguing



ABOVE: **TRITON, NEPTUNE'S LARGEST MOON,** seems to hang beneath its ice giant parent. Both appear as crescents in this image taken by Voyager 2 just over three days after its closest approach to the system. NASA/JPL

RIGHT: **VOYAGER SNAPPED THIS COLOR IMAGE** of Triton, constructed from three separate images through different filters, on August 23, 1989. Features down to a size of about 29 miles (47 km) across are visible on the moon's surface. NASA/JPL

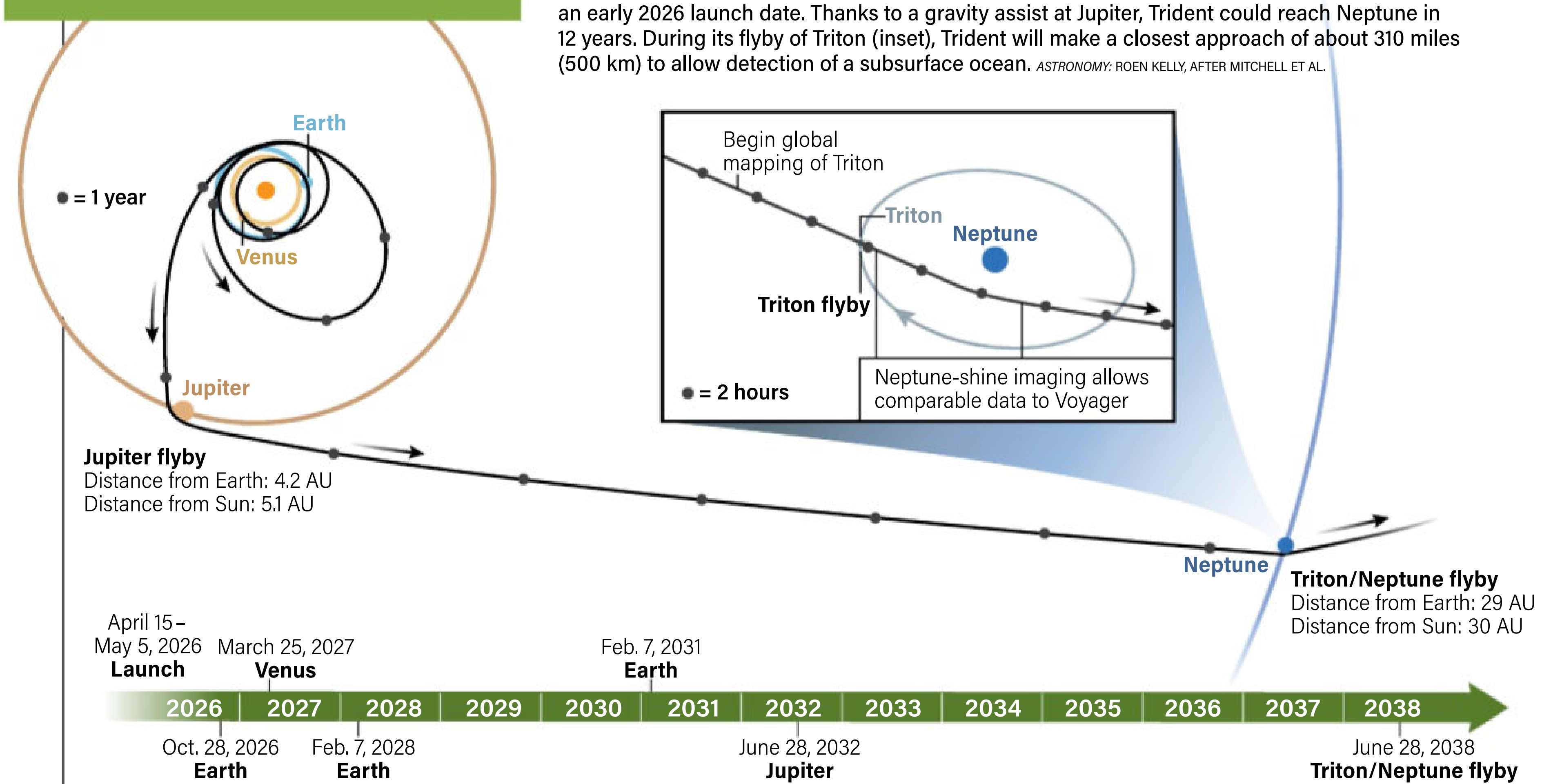
STUDYING TRITON FROM AFAR

Since the Voyager flyby, scientists have continued to study Triton using Earth-based instruments, but the results are global rather than local. Neptune orbits the Sun more than 30 times farther than Earth, making it a challenge to discern details. Planetary scientists can gather information about Triton's composition as a whole, revealing the presence of material like carbon and hydrogen, but that doesn't offer insights into individual regions, such as the cantaloupe terrain.

Background stars also offer insights about the moon. As Triton passes in front of a star, researchers can study the way the starlight shines through the moon's thin, tenuous atmosphere, revealing clues about its composition as well. — *N.T.R.*

TRIDENT: MISSION TO TRITON

THIS PROPOSED TIMELINE indicates how the Trident mission would proceed, given an early 2026 launch date. Thanks to a gravity assist at Jupiter, Trident could reach Neptune in 12 years. During its flyby of Triton (inset), Trident will make a closest approach of about 310 miles (500 km) to allow detection of a subsurface ocean. *ASTRONOMY:* ROEN KELLY, AFTER MITCHELL ET AL.



ABOVE: **TWO SALT DOME DIAPIRS** in Iran (the white feature in the middle of the image, as well as the mound to its left), as imaged from orbit by astronauts, create an Earth analog of Triton's terrain. These features were formed by blobs of salt, rather than ice, rising to the surface. NASA

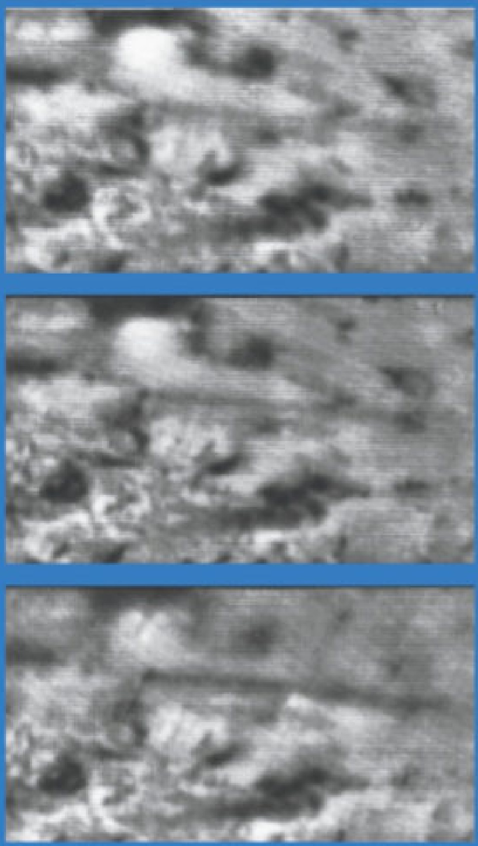
LEFT: **PLANETARY SCIENTISTS BELIEVE** Triton's unique cantaloupe terrain (foreground) was formed by rising blobs of ice called diapirs as the entire surface underwent a refresh in the past. Most of these craggy mounts are a few hundred feet high and a few miles across. (Vertical relief has been exaggerated by a factor of 25.) NASA/JPL/UNIVERSITIES SPACE RESEARCH ASSOCIATION/LUNAR & PLANETARY INSTITUTE

features is its cantaloupe terrain — rugged surface features that resemble the skin of the fruit whose name it bears. Planetary scientists think that rising blobs of ice, known as diapirs, cause this terrain as they are pushed upward through the more brittle surface by heating from below.

Voyager also glimpsed plumes of material shooting a few miles above the surface. "At the time, we developed a whole theory about solar-driven nitrogen geysers," says Hansen, who was on the Voyager team. She describes some of the reasoning as circumstantial, because the geysers appeared where the Sun was nearly directly overhead. As sunlight heated the ices, nitrogen could have jumped from solid to gas to become the plumes.

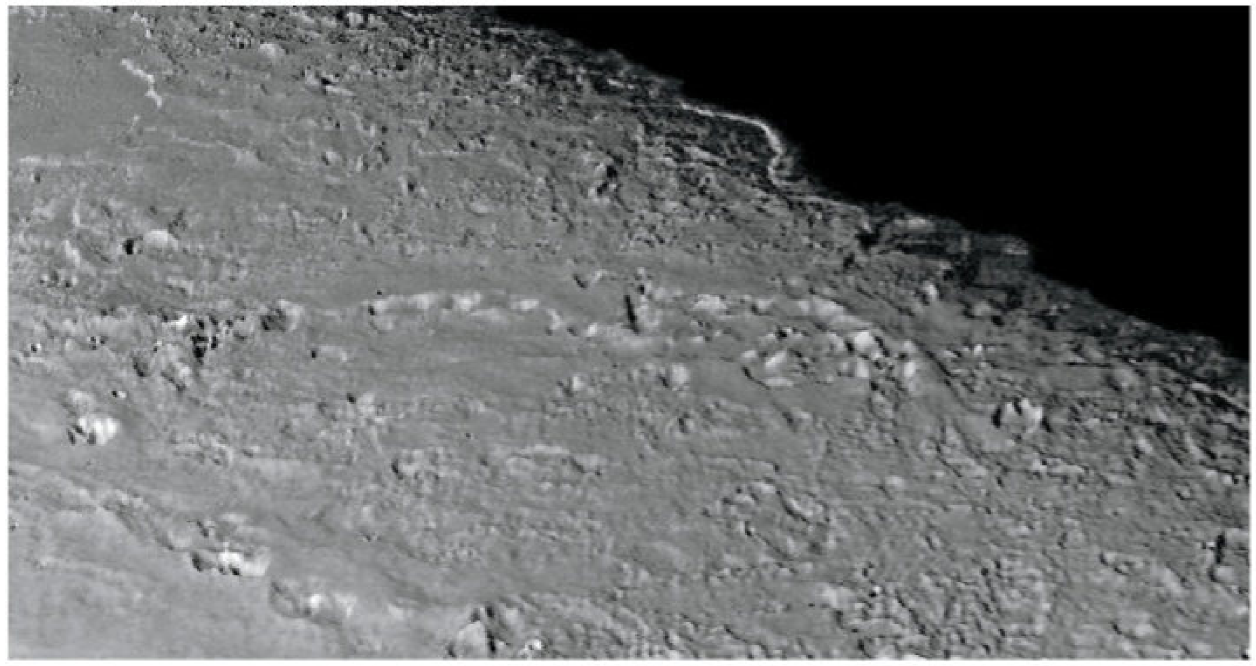
With the discovery of geysers spouting water from Enceladus and Europa, scientists are taking another look at Triton's plumes. "Maybe Triton is like Enceladus and Europa, and there could actually be water plumes coming from an interior ocean," says Mandt.

Material from the plumes has recolored Triton's surface: Voyager spotted streaks suggesting material fell from previously or currently active geysers. If the geysers draw water from a liquid



IN THESE SEQUENTIAL IMAGES captured by Voyager 2 August 26, 1989, a dark volcanic plume reaching about 5 miles (8 km) high stretches to the right across Triton's landscape as time progresses from top to bottom. In the last image, the plume has drifted about 100 miles (150 km). NASA/JPL

A study of Triton could increase understanding of the various paths life does — or does not — travel to evolve.



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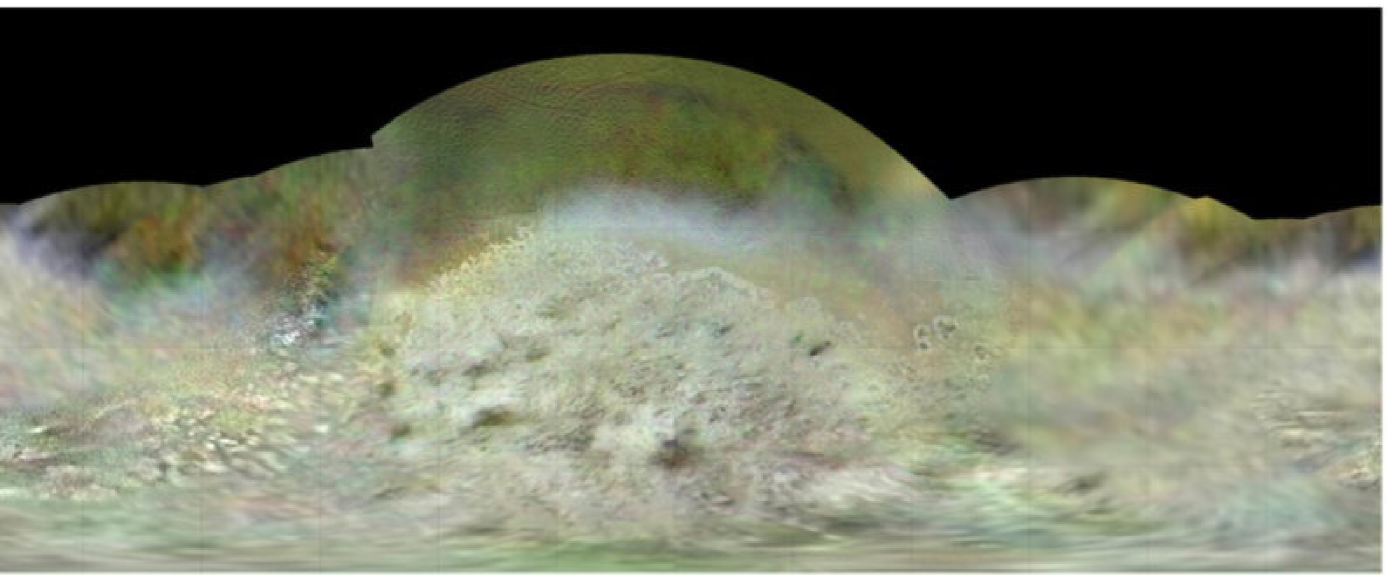


ABOVE: **THE CHAIN OF CRATERS** marching across the volcanic plains in the center of this Voyager shot were likely created by cryovolcanoes similar to their basaltic cousins on Earth. (Vertical relief has been exaggerated by a factor of 25.)

LEFT: **THIS GLOBAL COLOR MAP** of Triton, created by Lunar and Planetary Institute researcher Paul Schenk, shows the moon's surface down to features about 1,970 feet (600 m) across. Though the colors have been slightly stretched for contrast, the map provides a close approximation of the moon's true appearance. NASA/JPL-CALTECH/LUNAR & PLANETARY INSTITUTE

ocean, samples of the interior may lie on the moon's surface, ripe for the taking.

Together, these studies suggest the possibility that Triton may be hiding liquid beneath its surface, making it a potentially habitable site in the solar system. "We've got some tantalizing clues that it is an ocean world," says Amanda Hendrix, also of the Planetary Science Institute.

Heating an ocean

Triton was born in the Kuiper Belt, the ring of icy rocks orbiting the Sun beyond the planets. Early in their lifetimes, Neptune and Uranus likely engaged in an intricate dance that moved them, and the Kuiper Belt, to their present locations. This cosmic shuffle also allowed Neptune to capture at least one Kuiper Belt object as a moon: Triton.

Triton's surface probably felt the first tremors of activity during that violent grab. Tidal heating caused by energy dissipation during its capture and the slow circularization of its orbit likely caused geologic activity on the surface. Ices may have moved or melted, and its interior structure may have been briefly affected.

But that one event billions of years ago isn't enough to keep Triton's surface fresh. Something else must be warming its interior today to create a liquid ocean. On Europa, the varying gravitational tug from Jupiter and its fellow moons may be helping to maintain an ocean, but Triton is Neptune's only large moon.

Instead, it's Triton's orbital tilt that may enable a liquid ocean. Although the moon always keeps the same face toward its planet, its orbit ducks above and below Neptune's equator, allowing its poles to experience a change in seasons. As the moon orbits the ice giant, its tilt means that different parts of its interior are kneaded by the planet's gravity. That could be enough to keep a liquid ocean from freezing solid, Hansen says.

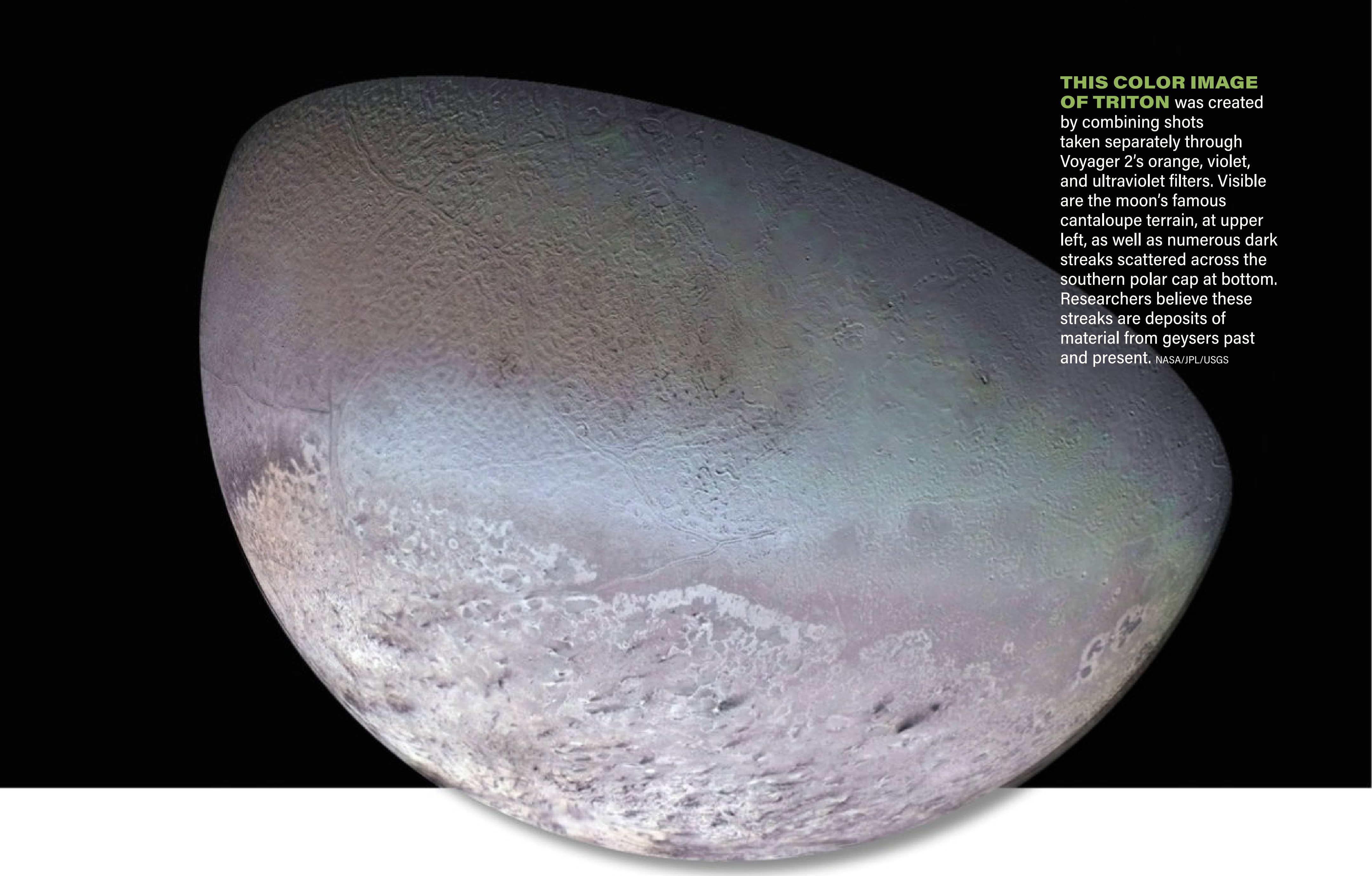
Return to Triton

Earlier this year, the NASA Outer Planets Assessment Group's Roadmaps to Ocean Worlds (ROW) team named Triton the highest priority of the candidate ocean moons. Before researchers can establish Triton as a potentially habitable site in the solar system, they need to determine whether it actually boasts an ocean. "The question about Triton is not so much about its habitability as whether or not it's an ocean world," Hendrix says.

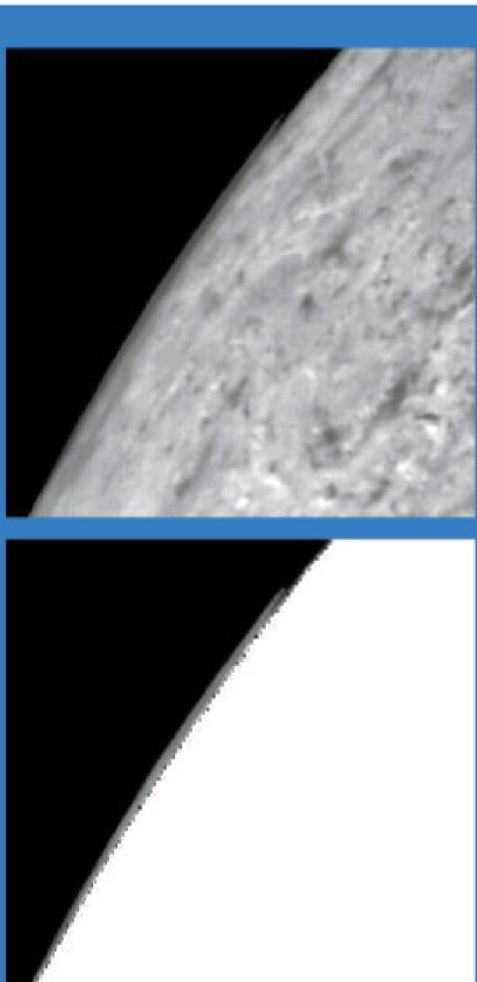
That means sending a mission to the moon. Mandt and Hansen are both part of the Trident mission, whose main goal is to determine whether or not Triton is a water world. Trident would make a single flyby of the moon, lowering its cost to make it eligible for funding as a NASA Discovery-class mission. A magnetometer similar to the one that helped confirm the presence of an ocean on Enceladus should help to answer the important question of whether Triton also has a subsurface ocean. Along the way, Trident would also take images of the surface. The mission is currently in the proposal stage.

Trident's flyby may answer some questions, but an orbiter would answer many more. "I think the whole Neptune system deserves a Cassini-like mission," Hendrix says, referring to NASA's iconic 13-year mission exploring the Saturn system.

That may not be completely out of line. A Uranus mission was one of the highest priorities for the 2011 Visions and Voyages Decadal Survey, which



THIS COLOR IMAGE OF TRITON was created by combining shots taken separately through Voyager 2's orange, violet, and ultraviolet filters. Visible are the moon's famous cantaloupe terrain, at upper left, as well as numerous dark streaks scattered across the southern polar cap at bottom. Researchers believe these streaks are deposits of material from geysers past and present. NASA/JPL/USGS



TRITON'S THIN ATMOSPHERE is composed of nitrogen and methane. During its flyby, Voyager 2 spotted limb clouds stretching about 62 miles (100 km) above the moon's south polar cap. (The images have been stretched to enhance both the clouds and surface features.) NASA/JPL

outlined top scientific goals for the 10-year period between 2013 and 2022. However, the ROW study pointed out that traveling to Neptune would satisfy the requirements of studying an ice giant while also covering Triton.

"We need to go back with a mission that can really map out the compositions of these different terrains," Hansen says, adding that the composition can tell a great deal about the origins.

The bigger picture

Understanding whether Triton has an ocean is key to understanding not only the potential habitability of the small moon, but also establishing the way life may evolve elsewhere in the solar system. Europa and Enceladus, whose subsurface oceans are known to exist, are clearly a high priority. But Hansen is confident that the discoveries made at those sites will affect studies of Triton.

"If we find life at Enceladus, we're going to say, 'Do you think life could be at Europa? How unique is Enceladus?'" Hansen says. "If we don't find it, we'll want to know if it's just Enceladus [that is barren] or is there no life anywhere — let's test Europa. Either way, you're going to go to the other one."

If neither Enceladus nor Europa hosts life, then researchers will want to find other sites where life could have evolved. And even if both worlds are rich in alien life, a study of Triton could increase understanding of the various paths life does — or does not — travel to evolve. "No matter what the outcome is, you want to go to Triton," Hansen says.

For Hendrix, the call to explore Triton is one of diversity. Currently, the Europa Clipper mission is preparing to send an orbiter to Europa to investigate the moon, and there is also talk of a subsequent lander mission. But Hendrix is wary of focusing too much on a single target. "Let's spread out our resources a bit more evenly so we can assess the habitability at one moon while assessing whether there's an ocean world at another," she says. "In that way, we can be understanding the whole spectrum of ocean worlds in our solar system a little better."

Nola Taylor Redd *is a freelance science writer and frequent contributor to* Astronomy.

Life's prospects on PLUTO

Who would have thought this dwarf planet could nurture life? The idea seemed ludicrous before New Horizons explored the world.

BY FRANCIS NIMMO

PLUTO'S VARIED GEOLOGY and surface composition hint that it could support an underground ocean of liquid water. Coupling that with the distant world's supply of organic molecules and energy has some scientists thinking it could be a possible abode for life. ALL IMAGES BY NASA/JHUAPL/SwRI UNLESS NOTED

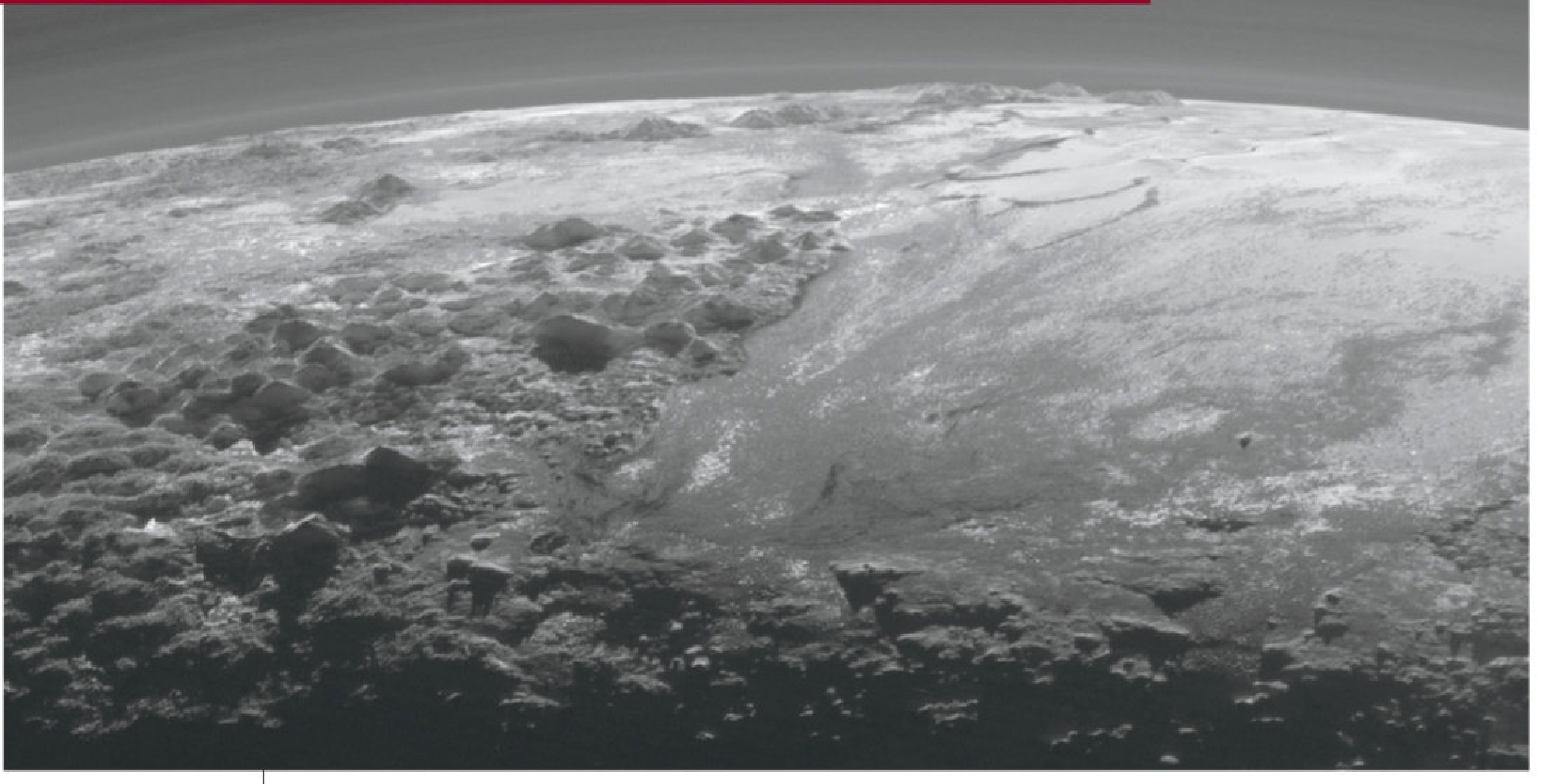
THE DWARF PLANET PLUTO lies in the cold, dark outskirts of our solar system — the Kuiper Belt. At first glance, this would seem like a poor place to search for life. Nonetheless, NASA's New Horizons spacecraft collected evidence that suggests Pluto possesses many of the characteristics required for life. It might even rank alongside more popular candidates for habitability, such as the icy moons Europa and Titan.

Despite decades of Earth-based observations, scientists knew little about Pluto until New Horizons studied it intensively, if only briefly, in 2015. The images it returned showed an unexpectedly diverse and active world, with mountains and rift valleys, glaciers of solid nitrogen, and a thin, hazy atmosphere.

Is it habitable?

Scientists typically assess the habitability of an environment in terms of the energy, organic molecules, and liquid water available. Pluto undoubtedly has the energy. Even before New Horizons, astronomers knew Pluto's density well enough to deduce that it is roughly two-thirds rock and one-third ice by mass. Just like on Earth, radioactive decay within the rocks releases heat over geological time. This is Pluto's dominant energy source, and it provides enough heat to warm the rocks in its interior close to their melting point. Other sources of heat, such as the gravitational energy released as the dwarf planet formed, are smaller but might contribute additional warming. Scientists don't know whether the radioactive decay drives the kind of chemical interactions between water and rock we see at Earth's midocean ridges, but it's clear Pluto has substantial available power.

The dwarf planet also possesses organic molecules. The atmosphere contains about 0.3 percent methane. More importantly, New Horizons found that solar ultraviolet radiation splits these methane molecules apart and produces various simple hydrocarbons, including acetylene, ethylene, and ethane. Methane ice also appears on Pluto's surface, as does a reddish material that is probably hydrocarbon haze particles settling out from the atmosphere. So the surface, at least, contains organic molecules that could provide the feedstock for life. Although it's not clear there's any mechanism to transport these molecules down to a possible ocean, studies of comets show that the interiors of outer solar system objects also can be rich in similar components.



ABOVE: **SHORTLY AFTER NEW HORIZONS** made its closest approach to Pluto, it looked back and captured this stunning view. The low, smooth nitrogen plains of Sputnik Planitia lie to the right; ice mountains casting long shadows appear to the left and below; and haze layers in the atmosphere hang above the limb.

OPPOSITE, TOP: **THE 90-MILE-WIDE** (150 km) Wright Mons (at lower left) shows a central depression and scalloped flanks that suggest it could be a cryovolcano.

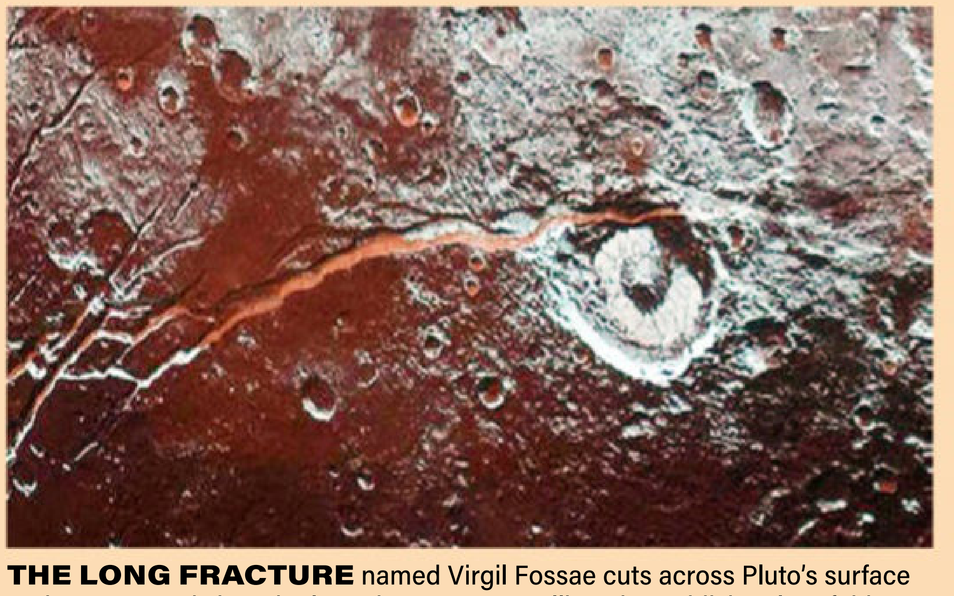
OPPOSITE, BOTTOM: **A NITROGEN ICE GLACIER** flows from the lumpy highlands region at right onto the smooth nitrogen plains of Sputnik Planitia.

That leaves liquid water as the last hurdle to clear. As mentioned earlier, radioactive decay within Pluto releases a substantial amount of heat, enough to warm and melt all the ice several times over. Before New Horizons, it was clear that a subsurface, liquid ocean could exist beneath a thick ice shell. However, there were no assurances that such an ocean did exist. After all, the insulating ice shell might experience slow convection just like Earth's silicate mantle, or a pot of oatmeal on the stove: A convecting shell would remove heat from the interior fast enough that an ocean would never form. That's why theory alone was not enough to deduce whether Pluto has an ocean. For that, we needed spacecraft observations.

An ocean on Pluto?

Three main lines of evidence point to a possible subsurface ocean on Pluto. The first comes from observations of the dwarf planet's surface geology. One particularly striking aspect is the many enormous cracks or fissures that score the surface. These faults — some of which chop through older impact craters — imply Pluto has undergone a small degree of global expansion. One way to produce this planetwide swelling is to refreeze a subsurface ocean. As the water cools and converts back to ice, Pluto's volume would increase and push the surface outward. The expanding ice shell also would press down on the water beneath, pressurizing it. If the pressure grows large enough, the water might squirt out to the surface in eruptions that scientists call "cryovolcanism."

Saturn's small moon Enceladus exhibits active cryovolcanic eruptions, but the evidence at Pluto is much less clear-cut. Two large structures with central depressions and strange, scalloped flanks could be cryovolcanoes, though not all of the New Horizons team is convinced of this. And some of the large fractures exhibit halos of unusual color and composition that could be a sign of material erupted from the interior, though again, not everyone accepts this interpretation. While the geological evidence is ambiguous, both the fracturing and the putative cryovolcanoes are at the very least consistent with what scientists would expect from a slowly refreezing ocean.



THE LONG FRACTURE named Virgil Fossae cuts across Pluto's surface and even extends into the large impact crater Elliot. The reddish color of this and other fractures represents clean water ice, suggesting that they formed in the relatively recent past.

The second line of evidence concerns a feature that Pluto does not possess. Some bodies, like Earth's Moon and Saturn's satellite Iapetus, appear noticeably fatter around the equator than expected. These equatorial bulges formed earlier in their history when the moons spun much faster; later on, these ancient bulges somehow froze in place. In effect, the Moon and Iapetus have retained a memory of an earlier, faster spin state.

Pluto seemed a likely candidate for such a fossil bulge because it must have spun down considerably over time due to the gravitational influence of its large moon, Charon. Yet New Horizons failed to detect any such bulge. Although scientists have come up with several possible explanations, one sure way to remove a bulge is by developing a subsurface ocean — the ice shell above is simply too weak to sustain the bulge, and it collapses.

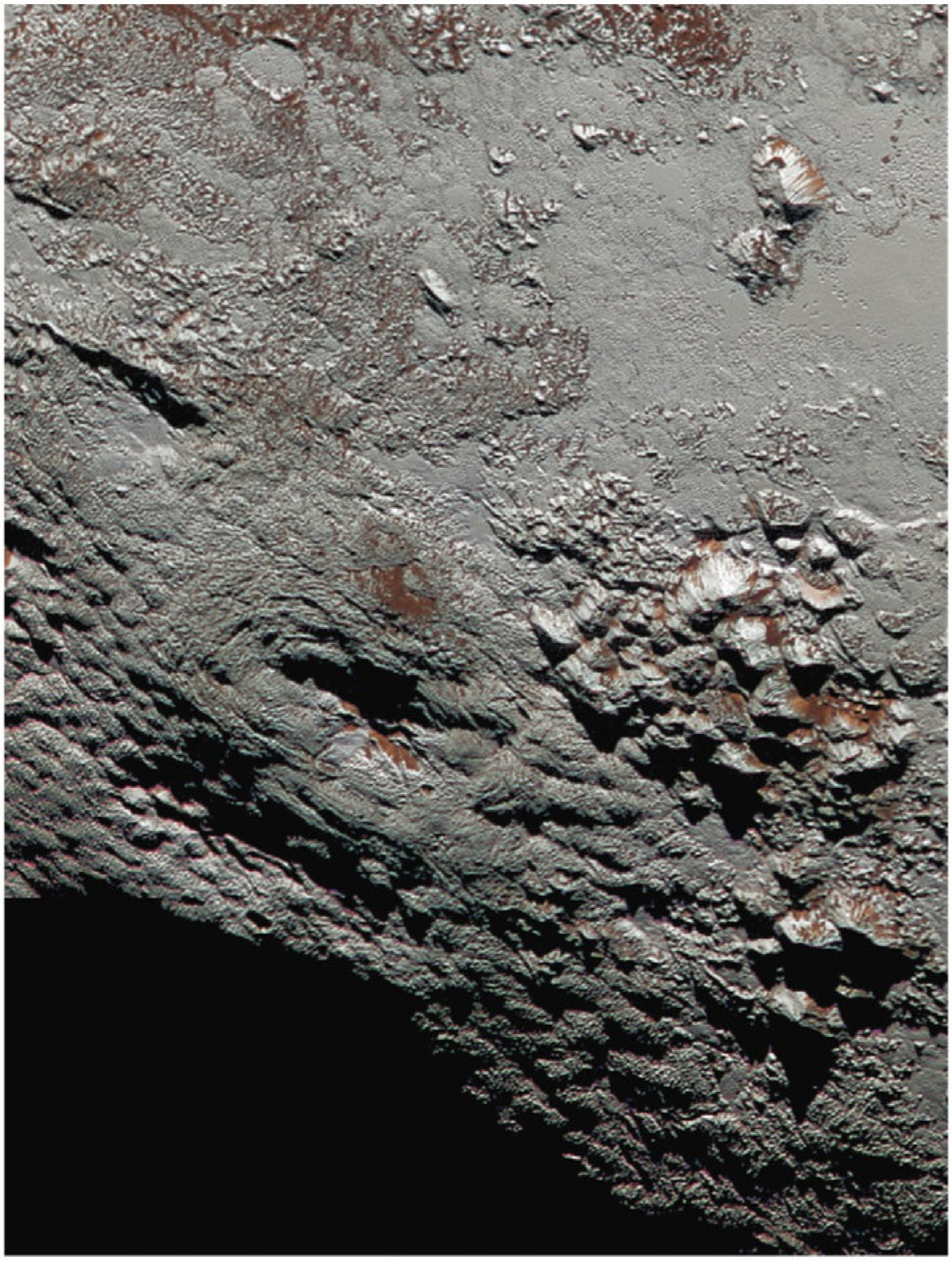
The heart of the matter?

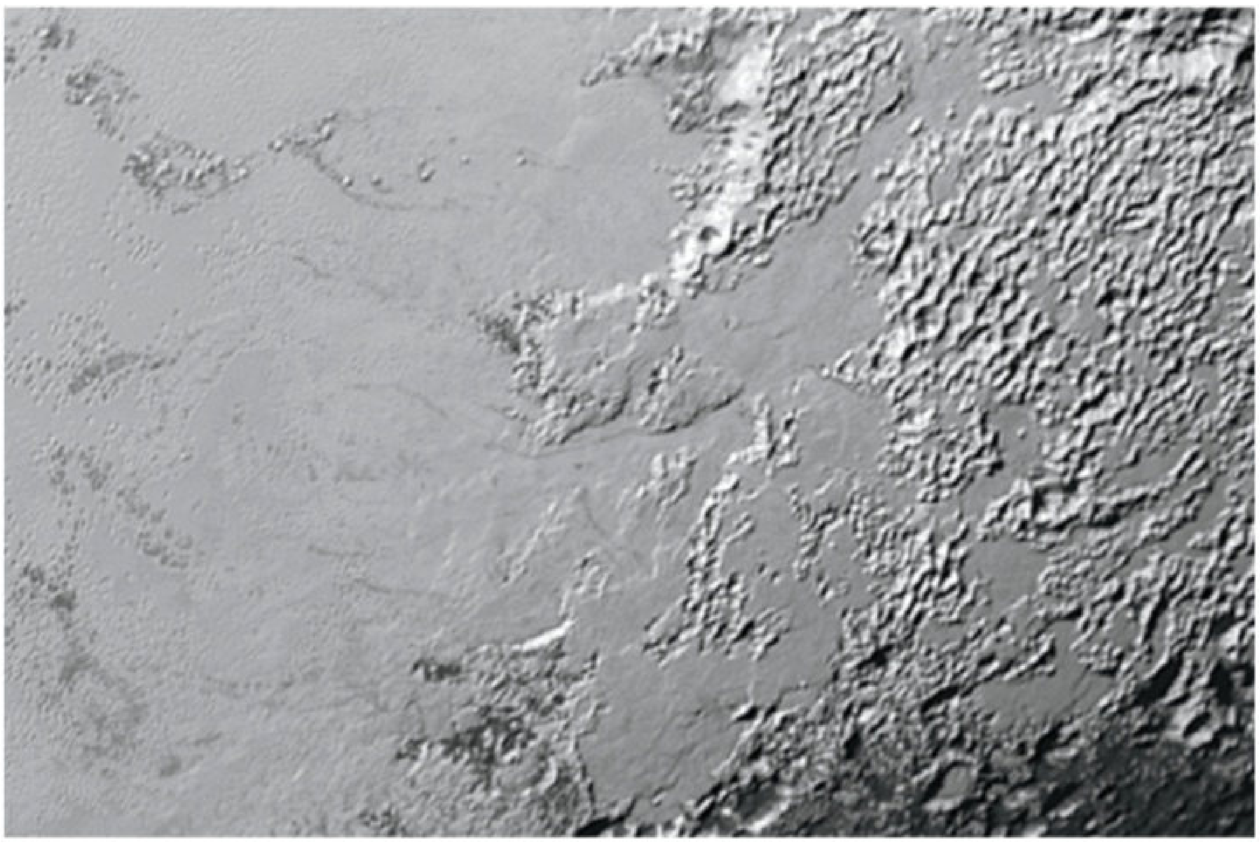
The last line of evidence is the most complicated, but also the most intriguing. It starts with the enormous, bright basin known as Sputnik Planitia. This region appears bright because nitrogen ice fills it, supplied by nitrogen glaciers that flow down from the surrounding highlands.

Another key fact about Sputnik Planitia is its location. It lies almost directly opposite the point on Pluto that continuously faces Charon. (Pluto always presents the same face to Charon, and vice versa.) If you could somehow place an extra mass, like a large mountain, on Pluto's surface, it would cause the planet to roll over until the mountain reached Sputnik Planitia's location. Scientists call this process true polar wander, or TPW.

One consequence of TPW is that Pluto's surface gets distorted in response to the movement of the excess mass. This, combined with the surface expansion, produces fractures — and the observed fracture orientations match those predicted by computer models rather well.

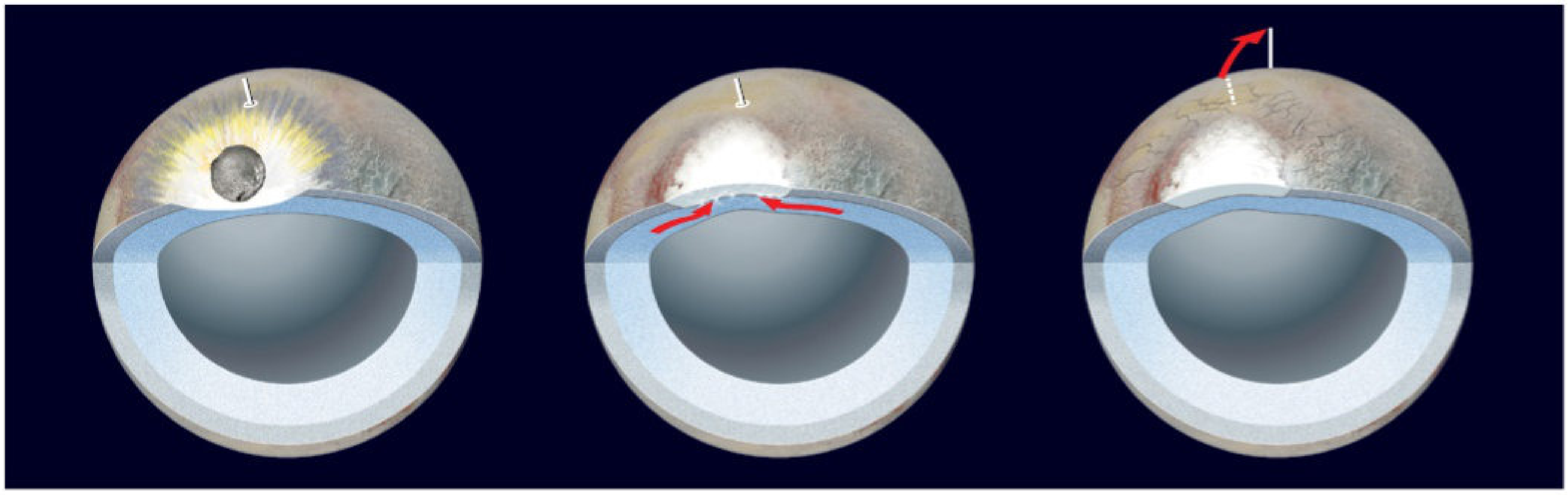
So, Sputnik Planitia's location makes perfect sense if it represents an area of excess mass. But how could the basin achieve this extra mass? After all, it is a hole in the ground. It helps that solid nitrogen is slightly denser than water ice, so filling the basin with nitrogen ice assists a bit. Except in the case of





PLUTO GETS TIPSY

THE FORMATION AND EVOLUTION of Sputnik Planitia may have caused Pluto to tip over. Early in the dwarf planet's history, a Kuiper Belt object slammed into Pluto and gouged out a large impact basin (left). Nitrogen ice later filled the basin, as the ice shell beneath it thinned and rebounded (middle). If water flowed in underneath, it would have created a mass excess that caused Pluto to roll over (right).

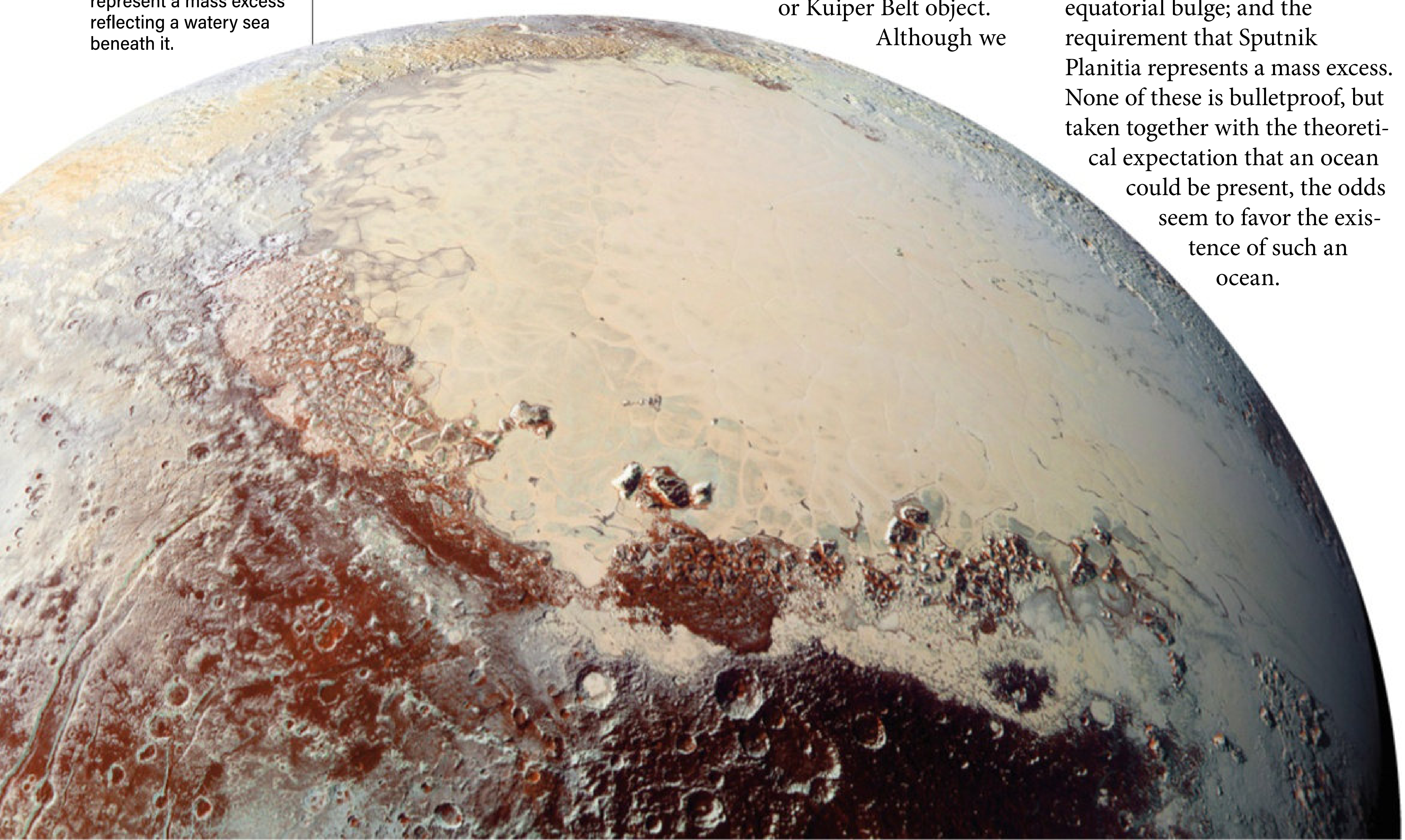


ASTRONOMY: RICK JOHNSON, AFTER FRANCIS NIMMO

implausibly thick nitrogen layers, however, that contribution alone is not enough. One explanation points to a thinning of the ice shell beneath. A thinner shell means denser water has replaced lighter ice, causing an excess of mass. This combination of nitrogen loading from the top and a thinned ice shell beneath can easily produce a mass excess and cause TPW.

Although this picture might seem rather contrived, we know something similar happened on our Moon. Gravity measurements show that many of its lava-filled impact basins represent mass excesses, even though they are still holes in the ground. Again, the crust beneath has thinned and denser mantle material has replaced lighter crust. Computer models show crustal thinning is exactly what you would expect in response to a high-velocity impact with a hefty asteroid or Kuiper Belt object. Although we don't know for sure that Sputnik Planitia formed this way, large elliptical impact basins are common on solar system bodies. And if an impact did create this feature, crustal thinning would have been an inevitable consequence.

So, New Horizons has provided three lines of evidence that a subsurface ocean might be present on Pluto: the surface fractures and possible cryovolcanoes; the absence of a fossil equatorial bulge; and the requirement that Sputnik Planitia represents a mass excess. None of these is bulletproof, but taken together with the theoretical expectation that an ocean could be present, the odds seem to favor the existence of such an ocean.

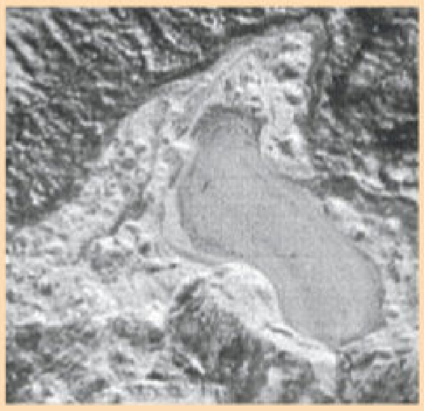


THE SMOOTH NITROGEN-ICE PLAINS of Sputnik Planitia offer a key clue to the possible presence of a subsurface ocean on Pluto. Because it lies in a spot diametrically opposite to the location of the dwarf planet's large moon, Charon, scientists think it may represent a mass excess reflecting a watery sea beneath it.

How can we confirm an ocean?

Over the past two decades, scientists have used several techniques to look for subsurface oceans on icy bodies. Unfortunately, neither of the two best methods will work on Pluto. The first requires a large background magnetic field, which induces currents in a body's salty, electrically conductive ocean. Researchers then look for a secondary magnetic field generated by these currents. The technique has worked well on the moons of Jupiter, but there's no large background magnetic field at Pluto to produce such a signal. The other method relies on measuring the size of a body's tides, because large tides indicate a weak, and possibly liquid, interior. But Pluto and Charon always present the same faces to each other, so they effectively produce no tidal signal.

A spacecraft orbiting Pluto certainly would be able to test whether Sputnik Planitia represents a mass excess, though by itself, this would not prove the existence of a subsurface ocean. Still, a more subtle analysis should tell us for sure. After all, the mass excess (the ocean) lies at depth and the mass deficit (the basin) is at the surface, so their opposing contributions to gravity don't quite cancel out. By measuring how the gravity changes the orbital path of a spacecraft, scientists should be able to test whether an ocean is present and deduce the thickness of the ice shell.



LIQUIDS APPARENTLY EXISTED on Pluto in the distant past, though Alcyonia Lacus was filled with liquid nitrogen, not water, before freezing over. This lake lies in the mountains just north of Sputnik Planitia.

So, just how habitable is Pluto?

Pluto has a warm interior, organic molecules (at least on its surface), and most likely a subsurface ocean. So the dwarf planet probably meets the basic requirements for habitability. This is not to say that Pluto is a haven for life, because the degree of interaction between the ocean and the layers above and below it may be small. Although a fractured rocky core might efficiently transfer heat and perhaps organics to an ocean above, we don't know this to be true. And if the only source of organics is material drifting out of the atmosphere, the shell would need to be in motion to supply them to the interior — and the available evidence indicates the shell is cold and rigid.

So Pluto is not as tempting a target as Europa or Enceladus, which have oceans topped by thin, mobile ice shells. But it might be a more suitable habitat for life than the large moons Titan or Ganymede, where a thick, high-pressure ice layer blocks direct contact between the ocean and the rocks below.

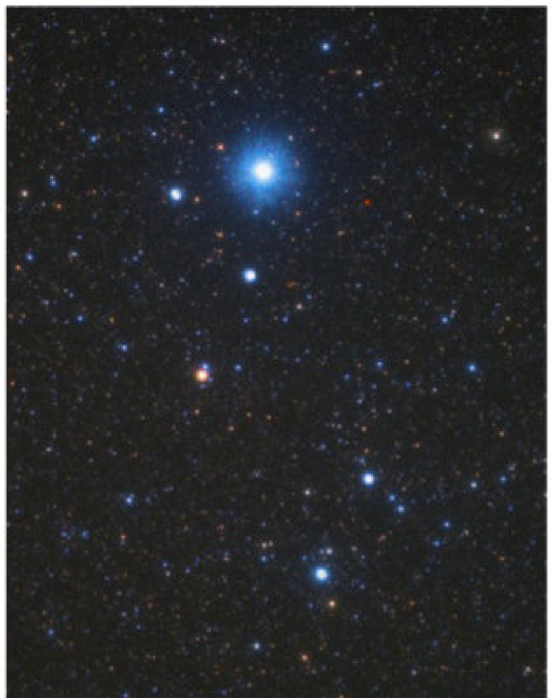
Pluto generates enough heat to comfortably sustain a subsurface ocean over billions of years. The evidence scientists have accumulated so far suggests such an ocean is present — although it most likely remains locked beneath a thick, rigid shell — and would be detectable by a future orbiter. Also keep in mind that Pluto is not unique: Other bodies in the Kuiper Belt have similar sizes and most likely also possess oceans. So, the outermost reaches of our solar system are not universally hostile. Despite the cold and the dark, Pluto and its brethren may represent welcoming oases.

CHARON, Pluto's largest moon, is locked in a gravitational embrace with the dwarf planet, and both always keep the same face toward each other. Pluto's Sputnik Planitia lies exactly opposite Charon, hinting at a subsurface ocean on the dwarf planet.

Francis Nimmo *is a professor in the department of Earth & Planetary Sciences at the University of California, Santa Cruz. In addition to the New Horizons mission, he currently is a team member on the InSight seismometer and several Europa Clipper instruments.*

The stars of Lyra

A parallelogram of fun awaits you in this tiny constellation.



The constellation Lyra offers bright and unusual stars for binocular explorers.
TONY HALLAS

Brilliant Vega in Lyra rules over the early evening sky this month, towering near the zenith as twilight fades, and beckoning us to explore it and the surrounding region. And that's just what we are going to do.

The longest diagonal axis of Lyra's parallelogram frame stretches 6° point-to-point, just small enough to squeeze into the field of most 10x50 binoculars. That makes it easy to compare the four corner stars: Zeta (ζ), Beta (β), Gamma (γ), and Delta (δ) Lyrae. It turns out that each is quite unique.

Let's examine them in clockwise order starting from **Zeta**, which is at the northwest corner and closest to Vega. Zeta is a multiple-star system, with as many as seven suns involved. A quick glance shows the brightest two, a magnitude 4.3 primary star paired with a magnitude 5.6 companion to the southeast. Both are separated by 44", so they are easy to pick out with the smallest binoculars. The Zetas are believed to lie 152 light-years away. If so, then a gap of 2,000 astronomical units (2,000 times the average Earth-Sun distance) separates one from the other.

The brighter star, Zeta A, is classified as spectral type A5m, the *m* standing for metallic. That reflects the star's unusual spectrum, which shows strong absorption lines of certain metals, such as zinc and strontium, and weak lines in others.

Beta Lyrae, also known as Sheliak, is also a binary system, but with a much greater magnitude contrast than Zeta's. Here, we find a 3.6-magnitude primary star and a 6.7-magnitude companion sun. The two are separated by 45", making them another ideal binocular target. At least four more stars belong to the Beta family, although they elude our binoculars.

Beta is a busy stop on our tour. Not only is it a nice stellar pair to enjoy through binoculars, but the brighter sun, known as Beta A, is also an eclipsing binary. Every 12.9 days, Beta A slowly fluctuates in brightness from magnitude 3.3 to 4.3, and back again. The Beta A system is unusual in that both stars mutually cover each other as they orbit a common center of gravity. Each lies so close to the other that the complex interplay of gravity dramatically distorts them into egg-shaped ellipsoids as swirling clouds engulf both.

You can monitor Beta's eclipses by comparing its brightness against the other stars in the Lyra trapezoid. When Beta is near maximum, its appearance matches that of Gamma Lyrae to its immediate east. When near minimum, it closely matches Zeta A.

Gamma, at the southeast corner, is a solo act. Also known by the proper name Sulafat, Gamma is a type B9 blue giant emitting over 2,400 times more energy than the Sun.

While no companion stars are physically associated with Gamma, it serves as the centerpiece for an asterism that, to me, looks like a compact, if not damaged, fan-shaped leaf rake. A trio of 5th- and 7th-magnitude stars to its northwest — SAO 67667, 67630, and 67612, east to west respectively — mark the tips of three of the rake's blades. The rake's handle extends half a degree from Gamma to orangish Lambda (λ) Lyrae.

The Lyre's northeast corner is also a busy intersection. Two stars, 4.3-magnitude **Delta^2** and 5.6-magnitude **Delta^1** are cleaved by 10.3'. That's three times wider than Epsilon (ε) Lyrae, the famous Double-Double. And like the Double-Double, the Deltas can be resolved by eye alone given dark skies.

Through binoculars, the Deltas do much more than just split. American astronomer Charles Stephenson was first to suggest that the Deltas, along with some of the fainter surrounding suns, form a weak grouping. That was back in 1959. There was some debate in the ensuing years as to whether or not the stars actually form a true cluster, but that was all put to rest in 1968. Studies conducted by a team led by American astronomer Olin Eggen proved that the cluster was real and contained some 33 members. The cluster is now appropriately nicknamed the Delta Lyrae Cluster, but is more formally known as **Stephenson 1**, for his original research.

> **Brilliant Vega in Lyra rules the early evening sky this month.**

I heard from reader Rob Datsko that there is an intriguing double triangle asterism within Stephenson 1. As he envisions it, orangish Delta^2 forms the east-pointing apex of an obtuse triangle that includes Delta^1 to the northwest and 7th-magnitude SAO 67550 to the south. Look inside that triangle and you'll see a smaller, equilateral triangle of 8th-magnitude stars. Have you ever spotted a noteworthy pattern of stars through your binoculars? Do as Rob did and tell me about it. Contact me through my website, philharrington.net.

Until next month, remember that two eyes are better than one.

BY PHIL HARRINGTON
Phil is a longtime contributor to Astronomy *and the author of many books.*

BROWSE THE "STRANGE UNIVERSE" ARCHIVE AT **www.Astronomy.com/Harrington**

The coalsacks of Cygnus

Turn your gaze to some of the darker regions of our universe.

ABOVE: Barnard 361 is relatively easy to spot because of the dense Milky Way background in its region. DIGITIZED SKY SURVEY

STEPHEN JAMES O'MEARA

TOP RIGHT: This illustration from *The Trouvelot Astronomical Drawings* (Charles Scribner's Sons, 1881) shows how the author of that work saw the naked-eye appearance of the Northern Coalsack and Le Gentil 3.

Crisp September nights often bring high-contrast skies, which allows us to look up and see darkness well.

That may sound paradoxical, but we need bold swaths of starlight to see the "deep wells" of darkness that mar the Milky Way like celestial graffiti. Mariners of the 16th century called them "coalsacks"; today, we categorize them as dark nebulae. Let's explore some prominent examples in Cygnus.

The Northern Coalsack is an elliptical splash of darkness between Deneb (Alpha [α] Cygni), Sadr (Gamma [γ] Cyg), and Epsilon (ε) Cyg. Despite its popularity, the Northern Coalsack is not particularly obvious to unaided eyes for two reasons. First, it is large (7° by 5°), and second, it is not fully surrounded by bright patches of Milky Way. I'll return to this later.

To target a smaller object, slip over the North America Nebula (NGC 7000) and look for Barnard 352, which sits slightly less than 3° east-northeast of Deneb. On a globe, this 20' by 10' dark cloud would lie at about the position of the Northwest Passages above Hudson Bay. Try to spy it first through binoculars. If that's too difficult, use a telescope at low power.

Arguably the best Cygnus coalsack is Le Gentil 3, sometimes called the Northern Inkspot. You'll find it 8° north-northeast of Deneb. French astronomer Guillaume Le Gentil recorded this 5°-wide naked-eye cloud in 1749, noting that it "seems opaque and very dark." And while Le Gentil 3 is as large as the Northern Coalsack, the Milky Way surrounding it is more uniform in intensity, boosting its contrast and enhancing the darkness.

When the 19th-century French astronomer Étienne Léopold Trouvelot drew the naked-eye Milky Way, he wrote, "It enters Cygnus, where it becomes very complicated and bright, and where several large cloudy masses are seen terminating its left branch, which passes to the right, near the bright star Deneb, the leader of this constellation." In his drawing, this terminating branch is separated by a dark gap at the position of Le Gentil 3. Most telling is that he does not draw (or failed to notice) the dark Northern Coalsack.

Arguably the best Cygnus coalsack is Le Gentil 3, sometimes called the Northern Inkspot.

Now use your scope and low power to look roughly midway between the North America Nebula and open cluster M39 for B361, which I call the Little Cygnus Inkspot. It lies about ¼° west of the 9th-magnitude open cluster IC 1369. Through a 4-inch scope under a dark sky, the 20' well of darkness stands out prominently against the surrounding Milky Way. The view is enhanced by the star cluster's presence, which is only half the dark nebula's size.

We'll end this survey with B168, one of the northern sky's most visually stunning dark nebulae through binoculars and telescopes. It's also a great naked-eye challenge. The Cocoon Nebula (IC 5146) lies in a pool of darkness at the southeast end of this nearly 2°-long stream of darkness. Look just south of Pi^2 (π^2) Cygni, where the Milky Way appears tangled in a cobweb of naked-eye dark nebulae. It is out of this web that a surgeon's cut of darkness trickles like blood into the pool surrounding the Cocoon. It's difficult to see this dark stream without optical aid because it is so narrow. But try sweeping your gaze up and down and left to right for a few minutes and see if you catch glimpses of it. If not, binoculars will show it clearly slicing across the Milky Way.

As always, share what you see and don't see at sjomeara31@gmail.com.

BROWSE THE "SECRET SKY" ARCHIVE AT **www.Astronomy.com/OMeara**

BY STEPHEN JAMES O'MEARA

Stephen is a globe-trotting observer who is always looking for the next great celestial event.

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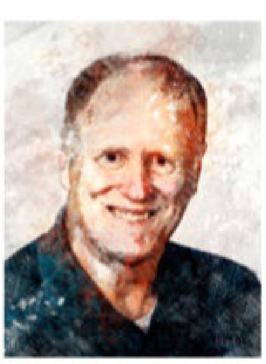
Telescopic targets in Scorpius

Let's complete our tour by zooming in on the Scorpion's gems.

Although the Scorpion holds many targets you can explore with little to no magnification, a telescope reveals the constellation is packed with double stars and globular clusters worthy of a closer look. *ASTRONOMY*: ROEN KELLY



BY GLENN CHAPLE

Glenn has been an avid observer since a friend showed him Saturn through a small backyard scope in 1963.

Last month, we admired Scorpius from afar with the unaided eye and binoculars. We now turn to our telescopes for an even closer look. In deference to those who live in mid-northern latitudes, we'll concentrate on an area of Scorpius that lies above about –30° declination. The chart above, taken from *Astronomy*'s *Atlas of the Stars*, shows the location of our targets.

We'll begin with M4, the globular cluster a little west (right) of Antares. During a small-telescope survey of Messier catalog objects I conducted some years ago, I viewed M4 through a 4-inch rich-field reflector at 74x, noting that it appeared oval in shape and not very "globular." With a 4.5-inch f/8 reflector at 152x, I perceived some resolution — not exactly unexpected, as M4 is one of the nearest of all globulars. Can you spot a distinctive band of stars bisecting the cluster, which was first seen by William Herschel in 1783?

Next, turn your scope to a spot ½° northwest of Antares. Here, we'll find the 9th-magnitude globular cluster NGC 6144. It can be seen with low magnification, but a wide field will bring Antares into view. Use medium to high power to keep the bright star out of the way.

Antares also leads the way to yet another globular cluster — entry No. 80 in Messier's catalog. To find it, perform a low-power search of the area midway between Antares and Graffias (Beta [β] Scorpii). In notes made during my small-scope Messier survey, I wrote that M80 was "Unresolved. Tends to show high concentration towards center."

This part of Scorpius abounds in double stars, so much so that I featured it in the double-star column I wrote for *Deep Sky Monthly* in July 1979. Headlining the group is Graffias, a pair of magnitude 2.6 and 4.5 stars separated by 13.7". With spectral classes of B0.5 and B2, they should appear snow-white. To me, however, the fainter member seems blue-green. See if you agree.

Up next is Nu (ν) Scorpii, a "double-double" I featured in this column a few years ago ("Civil War star," June 2014). Through a common 2.4-inch refractor at a magnification between 30x and 60x, you'll see two stars of magnitudes 4.4 and 6.6 that are a spacious 41.3" apart. Switch to 150x with a 4-inch scope under ideal seeing conditions (or a 6-inch or larger if there's a hint of atmospheric turbulence), and each of these stars is again doubled. The brighter has a 5.3-magnitude partner situated 1.3" to its north, while the fainter is attended by a 7.2-magnitude star currently 2.4" to its northeast.

A much easier double-double is Sh 225 and Sh 226 ("Sh" for the British astronomers James South and John Herschel, who cataloged these pairs in 1824). They appear as a tight pair of stars 1° immediately west (right) of Psi (ψ) Ophiuchi. Sh 225 consists of magnitude 7.4 and 8.1 stars separated by 46.6", while Sh 226 is a closer (12.5") magnitude 7.6 and 8.3 duo.

Next, we turn our scopes to Sigma (σ) Scorpii (magnitudes 2.9 and 8.4, separation 20.3"). Despite how far apart they are, the magnitude difference could make the secondary elusive in small scopes, so use averted vision. Because the companion is west of the main star, it should lead the way as they drift across your field of view.

If you're up for a demanding visual challenge, see if you can spot the 5th-magnitude companion to Antares.

If you're up for a demanding visual challenge, see if you can spot the 5th-magnitude companion to Antares, just 3.2" from the main star and more than 60 times fainter. To see it, you will need: a 6-inch or larger scope; as high a magnification as possible (300x isn't too much); and, of course, optimum seeing conditions. As was the case with Sigma Scorpii, the lesser star is west of the primary and will precede it as the pair drifts across your field of view.

This concludes our Observing Basics look at Scorpius. If you want to dive deeper into the Scorpion, check out Phil Harrington's article "The life and death of stars in Scorpius" in the May 2019 issue of *Astronomy*.

Questions, comments, or suggestions? Email me gchaple@hotmail.com. Next month: We celebrate International Observe the Moon Night. Clear skies!

BROWSE THE "OBSERVING BASICS" ARCHIVE AT **www.Astronomy.com/Chaple**

A GALAXY PAIR CRASH AND BURN

Irregular galaxy NGC 4485 in Canes Venatici has only a single neighbor, but it has proved to be less than welcoming. The Cocoon Galaxy (NGC 4490), which lies off the lower right edge of this Hubble image, sideswiped its partner millions of years ago. The collision left NGC 4485's spiral nature in tatters, though hints of it survive on the galaxy's left side. On the opposite flank, however, gravitational interactions have created a stream of material extending 25,000 light-years to NGC 4490. The crash triggered a firestorm of star birth visible as bright blue star clusters and the reddish emission nebulae that are building new ones. Both galaxies lie about 25 million light-years from Earth. NASA/ESA

November 2019
Mercury transits the Sun

Four planets adorn the western evening sky early this month. The constellation Scorpius the Scorpion joins the scene, looking like it wants to devour a pair of them as it dives toward the horizon.

The brighter of the two lower planets is **Venus**, which shines at magnitude –3.8 and looks like a beacon in the twilight. The planet's eastward motion this month sets up a series of nice conjunctions. On November 4, it passes midway between Beta (β) and Delta (δ) Scorpii. It then slides 4° north of Antares on the 9th and 1.4° south of Jupiter on the 24th. Venus remains disappointing when viewed through a telescope, however, showing an 11"-diameter, nearly full disk.

Mercury serves as Venus' companion in early November. On the 1st, the innermost planet shines at magnitude 0.5 from a perch 3° to the lower left of its neighbor and a healthy 9° above the horizon 45 minutes after sunset. A telescope reveals Mercury's beautiful crescent shape on a disk that spans 9".

The inner world disappears in twilight within a week as it heads toward inferior conjunction on the 11th. But it briefly reappears that day when it passes directly in front of the Sun for the first time since May 2016. You'll need a telescope to view this transit, but make sure to protect your eyesight by placing a safe solar filter over your instrument's front end. Mercury appears just 10" across and looks tiny on the Sun's 1,939"-diameter disk. Observers in South America can witness the entire transit, while those in Africa get to see the initial stages before sunset. The transit runs from 12h35m UT to 18h04m UT.

Look higher in the western sky after sunset and you can't miss **Jupiter**. The giant world shines at magnitude –1.9 against the background stars near the Ophiuchus-Sagittarius border. It makes a striking pair with brilliant Venus for a few days centered around November 24.

Jupiter always looks great through a telescope. Its disk measures 32.7" across the equator and 30.5" through the poles in mid-November. This polar flattening — a result of the planet's rapid rotation — is easy to notice once you know to look for it. You also should see two parallel dark cloud belts that sandwich a brighter zone coinciding with the equator. Above the cloud tops, Jupiter's Galilean moons dance around the planet, changing positions noticeably from night to night.

Scan 20° to Jupiter's upper right and you'll encounter **Saturn**. The golden-colored planet shines at magnitude 0.6 in eastern Sagittarius, a constellation whose brightest stars appear noticeably fainter than the ringed world.

Like Jupiter, Saturn shows distinct polar flattening. At midmonth, its equatorial diameter of 15.7" is 1.3" greater than its polar diameter. But the real reason to point a telescope at Saturn is to view its gorgeous rings. They currently span 36" and tip 25° to our line of sight. This large tilt makes now an ideal time to see ring structure. Look for the dark Cassini Division that separates the outer A ring from the brighter B ring. Any telescope also reveals the 8th-magnitude moon Titan; a 10-centimeter instrument brings in three more 10th-magnitude satellites.

The waxing crescent Moon adds a sparkle to the western evening sky during November's final week. Luna appears slightly below Jupiter on the 28th and stands midway between Venus and Saturn the following evening.

Mars returns to view before dawn during the second half of November. By the 30th, it rises about 90 minutes before the Sun and climbs 6° above the eastern horizon an hour before sunup. You may need binoculars to see the magnitude 1.7 planet against the twilight.

The starry sky

Several years ago, I had a pleasant trip to Cape Town, South Africa. A highlight was a cable-car ride to the summit of Table Mountain overlooking the city. I was rewarded with spectacular views of the city and surrounding ocean.

While I was looking down, I reflected on the fact that I was standing atop the only geographical feature after which a constellation is named. Mensa the Table Mountain resides deep in the southern sky, between declinations of about –70° to –85°, so it is visible throughout the night at all times of the year. French astronomer Nicolas Louis de Lacaille introduced this constellation in the 18th century.

Table Mountain played a pivotal role in 18th-century earth sciences, leading to the erroneous conclusion that our planet is pear-shaped. Lacaille sought to measure the distance over which a particular difference in latitude occurred, a technique used to determine Earth's curvature. But the gravitational attraction of Table Mountain affected his observations. Decades later, astronomer Thomas Maclear redid Lacaille's measurements and showed they were off, returning Earth to a spherical shape.

The constellation's main claim to fame is that part of the Large Magellanic Cloud (LMC), the Milky Way's largest satellite galaxy, occupies its northern section. Several nice deep-sky objects — especially star clusters — lie in that direction.

The rest of this little constellation is far from exciting, save for a curious object located 6° from the South Celestial Pole. The 11th-magnitude globular cluster NGC 1841 is an LMC outlier and visible as a tiny patch of light through 15-cm and larger telescopes. To find it, start at 6th-magnitude Xi (ξ) Mensae and then star-hop 1.6° to the south-southwest.

STAR DOME

HOW TO USE THIS MAP

This map portrays the sky as seen near 30° south latitude. Located inside the border are the cardinal directions and their intermediate points. To find stars, hold the map overhead and orient it so one of the labels matches the direction you're facing. The stars above the map's horizon now match what's in the sky.

The all-sky map shows how the sky looks at:

11 P.M. November 1
10 P.M. November 15
9 P.M. November 30

Planets are shown at midmonth

MAP SYMBOLS

- Open cluster
- Globular cluster
- Diffuse nebula
- Planetary nebula
- Galaxy

STAR MAGNITUDES

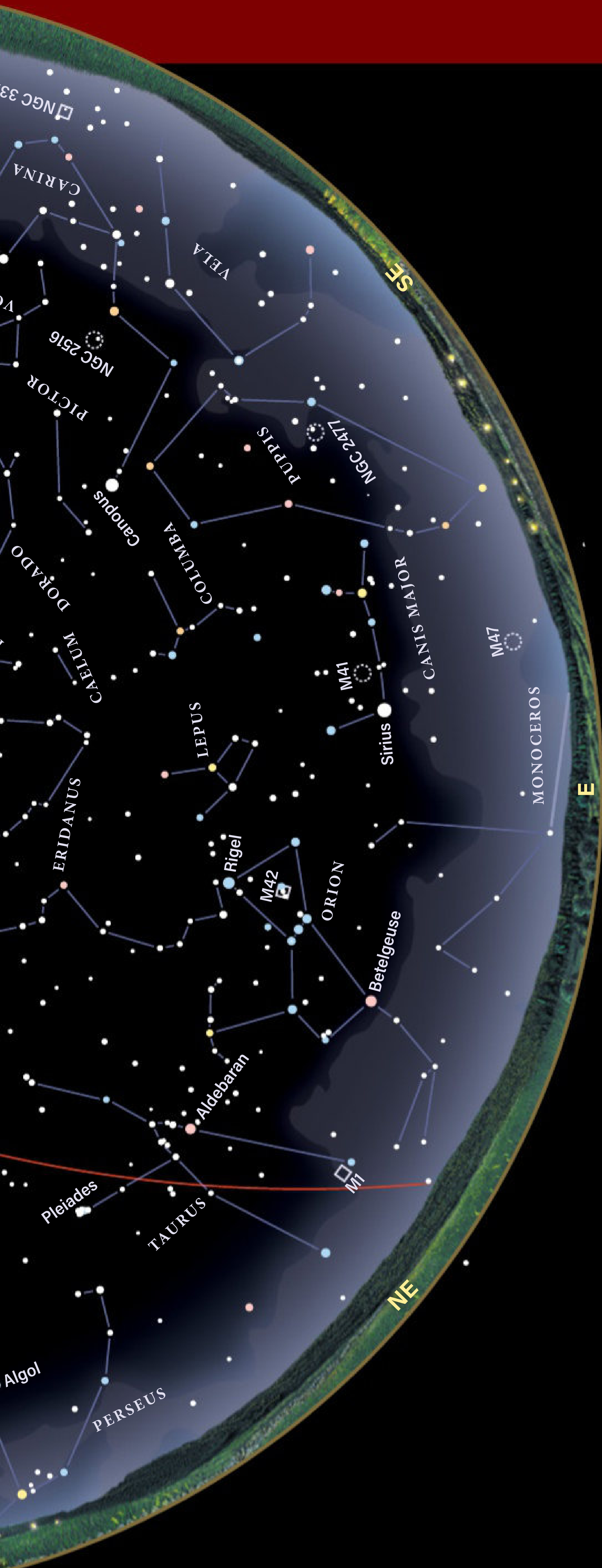
- Sirius
- 0.0
- 1.0
- 2.0
- 3.0
- 4.0
- 5.0

STAR COLORS

A star's color depends on its surface temperature.

- The hottest stars shine blue
- Slightly cooler stars appear white
- Intermediate stars (like the Sun) glow yellow
- Lower-temperature stars appear orange
- The coolest stars glow red
- Fainter stars can't excite our eyes' color receptors, so they appear white unless you use optical aid to gather more light

BEGINNERS: WATCH A VIDEO ABOUT HOW TO READ A STAR CHART AT **www.Astronomy.com/starchart.**



NOVEMBER 2019

SUN.	MON.	TUES.	WED.	THURS.	FRI.	SAT.
					1	2
3	4	5	6	7	8	9
10	11	12	13	14	15	16
17	18	19	20	21	22	23
24	25	26	27	28	29	30

ILLUSTRATIONS BY *ASTRONOMY*: ROEN KELLY

Note: Moon phases in the calendar vary in size due to the distance from Earth and are shown at 0h Universal Time.

CALENDAR OF EVENTS

2 The Moon passes 0.6° south of Saturn, 7h UT

The Moon passes 0.4° south of Pluto, 18h UT

4 First Quarter Moon occurs at 10h23m UT

7 The Moon passes 4° south of Neptune, 5h UT

The Moon is at apogee (405,058 kilometers from Earth), 8h36m UT

8 Mars passes 3° north of Spica, 15h UT

9 Venus passes 4° north of Antares, 11h UT

11 The Moon passes 4° south of Uranus, 4h UT

Mercury is in inferior conjunction, 15h UT; transits the Sun

12 Asteroid Vesta is at opposition, 9h UT

Full Moon occurs at 13h34m UT

18 Leonid meteor shower peaks

19 Last Quarter Moon occurs at 21h11m UT

20 Mercury is stationary, 15h UT

23 The Moon is at perigee (366,716 kilometers from Earth), 7h41m UT

24 The Moon passes 4° north of Mars, 9h UT

Venus passes 1.4° south of Jupiter, 14h UT

25 The Moon passes 1.9° north of Mercury, 3h UT

26 New Moon occurs at 15h06m UT

27 Neptune is stationary, 20h UT

28 Mercury is at greatest western elongation (20°), 11h UT

The Moon passes 0.7° north of Jupiter, 11h UT

The Moon passes 1.9° north of Venus, 19h UT

29 The Moon passes 0.9° south of Saturn, 21h UT

30 The Moon passes 0.5° south of Pluto, 4h UT