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SCIENCE NEWS BY AGU

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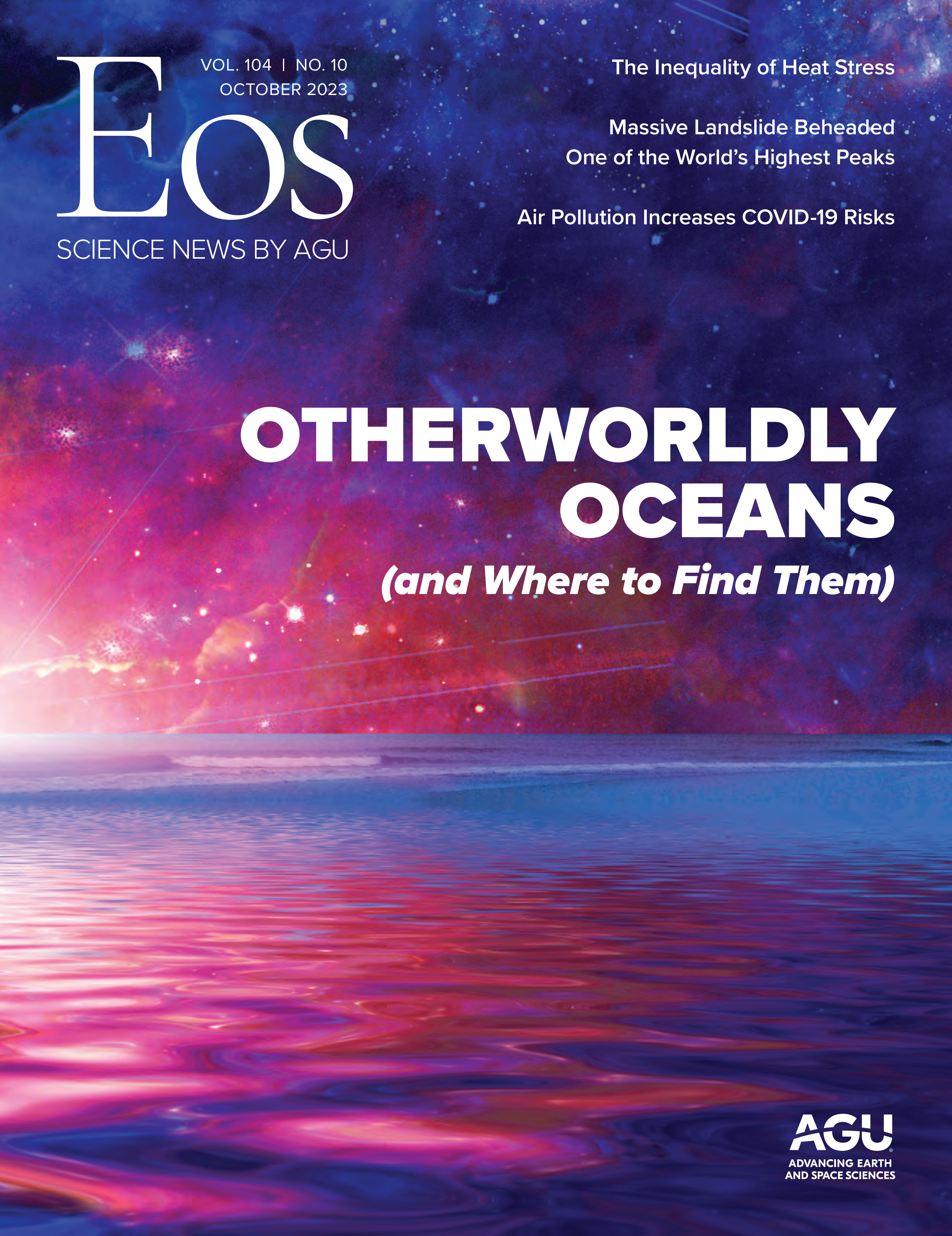
OTHERWORLDLY OCEANS

(and Where to Find Them)



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FROM THE EDITOR

Oceans of Opportunity

This month, we're diving deep into outer space.

Our solar system's ocean worlds—planets and moons covered in ice-crusted oceans—are weird, wonderful, and ripe for exploration. And that's exactly what scientists are encouraging space agencies to do, says Kimberly Cartier in "Uranus: A Time to Boldly Go." Uranus tilts more than 90°, is enormous itself but ringed by micrometer-sized particles, has many moons that remain largely invisible…and don't get us started on the planet's magnetosphere. "Every aspect of the Uranian system challenges our most basic understanding of how planets work," says planetary scientist Mark Hofstadter. Read more about the ice-blue ice giant on page 24.

Planetary scientists interested in ocean worlds like Enceladus and Europa are first getting their feet wet on terra firma. In "Marine Science Goes to Space," Damond Benningfield provides a sea-sized view of how ocean worlds are redefining what constitutes a habitable zone and how missions in development, like JUICE and Europa Clipper, are relying on terrestrial deep-sea scientific advances to look for oceanic activity that's out of this world (p. 30). Meanwhile, older missions are still contributing to the discourse, as archival Cassini data helped scientists identify phosphorus—the rarest element necessary for life as we know it—on Enceladus (p. 8).

In addition to the ocean, planetary scientists are keeping an eye on Earth's volcanoes to help them understand dazzling extraterrestrial eruptions. Some of these eruptions, however, don't really have an earthly analogue. The ice volcanoes of the outer solar system likely erupt in volatiles such as ammonia (as opposed to silicates such as feldspar), offering hints about habitability on their host world. Topographic evidence of these icy eruptions is as ephemeral as the eruptions themselves, as "you can't make relief with water," says volcanologist Sarah Fagents. Fellow volcanologist Erik Klemetti explores "Cryovolcanism's Song of Ice and Fire" on page 24.

Back on Earth, researchers have meticulously recorded changes in the environment in what some scientists argue should be internationally recognized World Heritage Data Sets. Emma J. Rosi, Emily S. Bernhardt, Irena Creed, Gene E. Likens, and William H. McDowell make the case for protecting data sets as varied as the Keeling curve and the flowering dates of Kyoto's cherry trees. Read "Taking the Pulse of Global Change with World Heritage Data Sets" on page 14.

Caryl-Sue Micalizio, Editor in Chief

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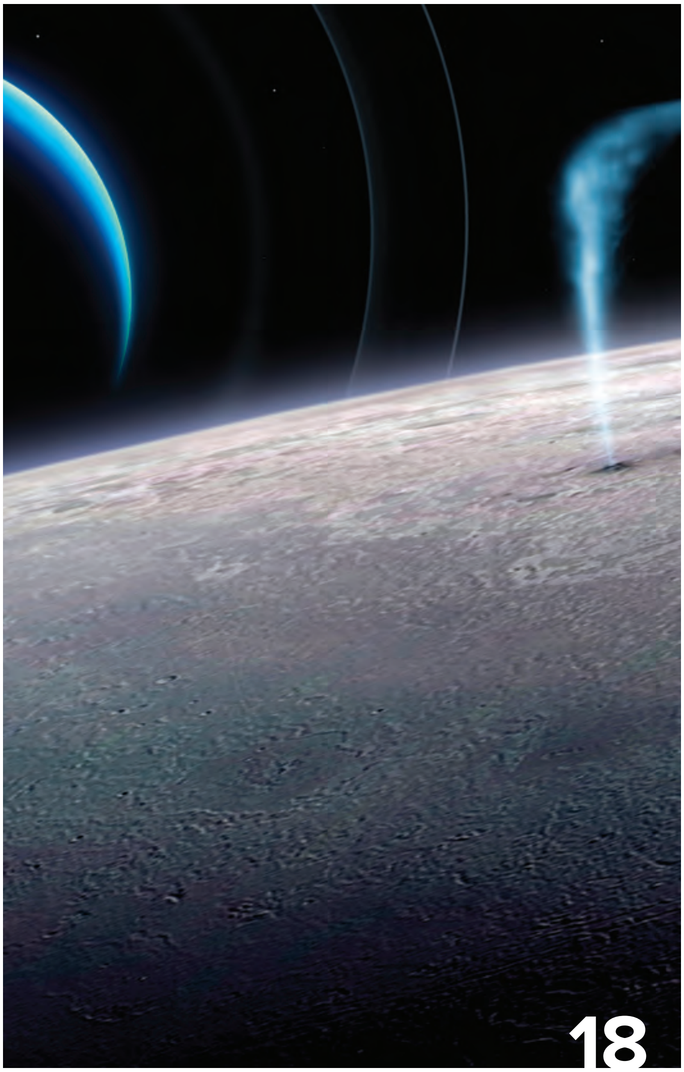
Janice Lachance, Interim Executive Director/CEO



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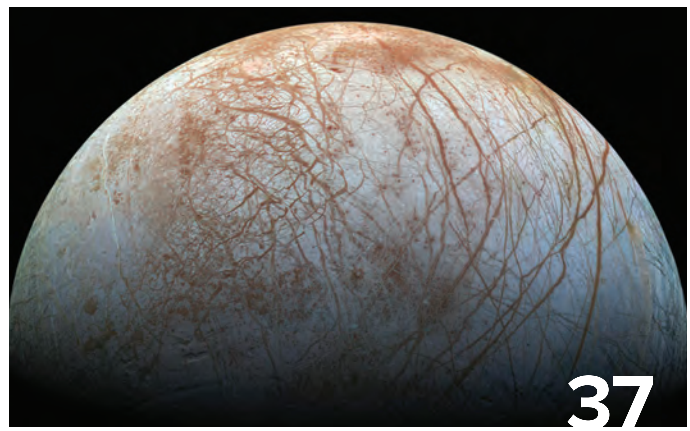

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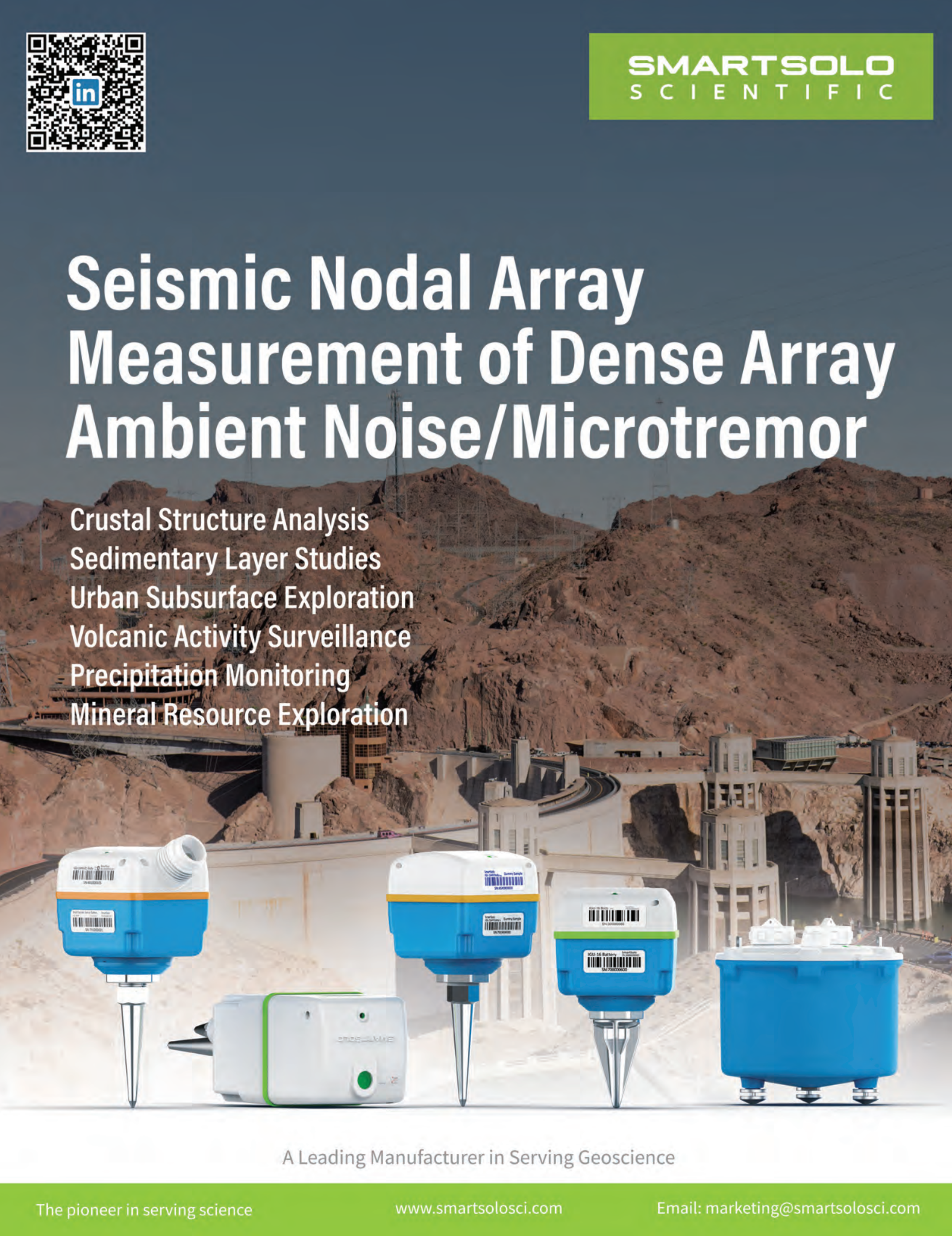
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A Massive Landslide Beheaded One of the World's Highest Peaks

Why don't mountains grow forever? Colliding tectonic plates continuously push mountains up, so what pulls them back down?

Colossal landslides are one of the erosive processes that take down the highest peaks, geologist Jérôme Lavé of the Centre National de la Recherche Scientifique and his colleagues show in a paper recently published in *Nature* (bit.ly/Annapurna-landslide).

The researchers provided evidence that hundreds of years ago, around 23 cubic kilometers of sediment fell from the Himalayan peak Annapurna IV—a thousand times greater than the largest recent landslides in the area.

"A landslide of this size is unheard of," said glacial geologist Ann Rowan of the University of Bergen in Norway. But the study lays out convincing evidence that such events shape the highest regions of Earth once every few hundred thousand years, she and other experts said.

"It's a really high-quality paper," Rowan said.

This face of Annapurna IV, in Nepal, collapsed in the late 1100s. Credit: Jérôme Lavé

"A landslide of this size is unheard of."

Teflon Peaks Escape a Glacial Buzz Saw

Few mountain ranges on Earth compare to the Annapurna massif in Nepal, where peaks soar thousands of meters above the nearby city of Pokhara.

A force scientists call a "glacial buzz saw" curtails the growth of some parts of this rugged landscape. As glaciers flow slowly downhill, they pull the underlying land with them. Debris caught in the glaciers also abrades the mountains below, keeping peaks from rising forever.

Annapurna IV is a "Teflon peak," however; ice and snow slide off its steep, smooth sides, just as pancakes slide off a nonstick pan, letting it grow to a height above the altitude where glaciers form. Permafrost makes the mountaintop even more difficult to destabilize.

Despite the peak's stability, sediment from a landslide did fill the valley below Annapurna IV, researchers realized back in the 1980s. Until now, they were unsure when the landslide occurred and whether the sediment came down all at once or in chunks.

Lavé and his colleagues went to the Himalayas to reconstruct the ancient processes that shaped the region.

The group used a helicopter to reach a remote valley between Annapurna IV and a nearby peak called Annapurna III. There they sampled sediment from the landslide; then Lavé and two pilots continued on to collect more samples from above, where the air was almost too thin for the helicopter to maintain altitude. Lavé's colleagues stayed below to lessen the weight of the aircraft.

Back at the lab, the researchers reconstructed Annapurna IV's historical peak by analyzing the sediment samples in three ways. First, they tested how long the sediment they'd collected had been exposed to cosmic rays—particles produced during supernovas that constantly bombard Earth. Cosmic rays interact with a common mineral called calcium carbonate to produce an isotope called chlorine-36, which scientists can count using a mass spectrometer to get an idea of how long the mineral has been exposed to the atmosphere. They supplemented these measurements with carbon dating and analysis of quartz to see when it was last deformed by an event such as a landslide.

A Medieval Mystery

Around 1190, the top of Annapurna IV came crashing down all at once, the researchers found. If Pokhara—Nepal's second most populated metropolitan area—had existed at the time, it would have been decimated. Instead, the landslide created the flat surface that allowed people to build a city in the region.

The study's results raised new questions; for example, what triggered this massive landslide? Lavé and his colleagues suggested that the Medieval Climate Anomaly, during which Earth's climate warmed by more than 1°C, may have thawed and weakened the base of Annapurna IV. Without a strong foundation, the peak toppled. "That is a potential trigger," Rowan said.

Alternately, an earthquake may have caused the collapse. There's no record of an earthquake in 1190, however, leading Lavé and his colleagues to conclude that this scenario is unlikely. But geological dating methods have uncertainty, and the earthquake record may be incomplete, so some scientists aren't ready to rule out the possibility.

The exact sequence of events is "simply very difficult to determine with the methods that we have on hand," said geomorphologist and sedimentologist Anne Bernhardt from Freie Universität Berlin, who was not involved in the study.

Researchers also have debated how the sediment that fell from Annapurna IV moved down the mountain's slope after the initial collapse. Lavé and his colleagues suggested that the sediment flowed downhill slowly, at a rate of about 1 meter per year. But geomorphologist Wolfgang Schwanghart of the University of Potsdam and his team, who were not involved in the new study, have found sediment deposits that are meters thick downstream of the initial collapse, as well as deposits that were pushed kilometers upstream. "That doesn't happen gradually," he said. "That must be catastrophic."

Today, loose sediment from the landslide still sits on the mountain slope above Pokhara, Bernhardt said. Some of that material could pose a modern-day geohazard. Heavy rain or an earthquake could cause it to flood into a densely populated area, where it could damage critical infrastructure or cut off transportation routes. "The aftermath of these events goes on and on," she said.

The exact sequence of events is "simply very difficult to determine with the methods that we have on hand."

By **Saima May Sidik** (@saimamaysidik), Science Writer

Air Pollution Increases COVID-19 Risks

Air quality affects COVID-19 outcomes, according to two studies out of Belgium (this image was taken in Brussels) and Denmark. Credit: Belfius/Wikimedia, CC BY-SA 3.0 (bit.ly/ccbysa3-0)

Exposure to air pollution increases the risk of contracting COVID-19 and results in more-severe cases of the disease, according to two new studies comparing medical outcomes and pollution levels in Belgium and Denmark, published in the *European Respiratory Journal*.

Scientists found that COVID-19 patients who lived with poor air quality spent more days in the hospital, were more likely to need intensive care, and faced a greater chance of dying from the disease. The finding signals ways governments can reduce deaths from not only COVID-19 but also other respiratory illnesses and future pandemics.

A Population View

In the Danish study, researchers collected data from the Danish National COVID-19 Surveillance System on the 3.7 million people older than 30 who were living in the country during the first 14 months of the pandemic (bit.ly/Denmark-COVID). These data were combined with the pollution levels at people's home addresses for the previous 20 years.

In addition to pollution data, the researchers had access to comprehensive data for testing, hospitalization, and death, thanks to a centralized collection system. "We could follow the entire population of the country," said environmental epidemiologist Zorana Jovanovic Andersen of the University of Copenhagen in Denmark.

Andersen and her colleagues found that increased long-term exposure to nitrogen dioxide and fine particulate matter, even at levels within the European Union's currentlegal standards, increased the risk of contracting COVID-19 by more than 10% and that of being hospitalized by more than 9%. People exposed to higher levels of air pollution had a 23% greater chance of dying from the disease, the researchers found.

Those from less affluent backgrounds or with certain chronic illnesses, such as heart disease and asthma, were most vulnerable to the combined effects of air pollution and COVID-19.

"We are sure that we see an association," Andersen said. "We knew even before COVID that air pollution does something to our immune systems and makes us more vulnerable to infections like pneumonia."

A Finer Look

In the study out of Belgium, researchers focused on 328 patients who were hospitalized for COVID-19 between May 2020 and March 2021 (bit.ly/Belgium-COVID). By comparing the pollution levels at the patients' home addresses with their medical outcomes, the researchers found that those with higher exposure to air pollution in the week before being hospitalized stayed in the hospital an average of 4 more days. High exposure to nitrogen dioxide more than doubled the risk of admission to an intensive care unit (ICU).

Having been exposed to air pollution was equivalent to being a decade older, according to the authors of the study in Belgium. Reduced exposure decreased patients' hospitalization time by 40%–80%—as much as did some of the best available treatments at the time.

"To put it very simply, a 40-year-old with high air pollution [exposure] and a 50-year-old with low air pollution [exposure] are at about the same risk," said environmental epidemiologist Tim Nawrot of Hasselt University in Belgium.

In both studies, the researchers determined the pollution levels to which people were exposed by using chemical transport models, which are computer simulations that combine meteorological data, satellite observations, pollution levels measured at sampling stations on the ground, topography, and other factors.

The researchers in Belgium also took blood samples from the patients to measure their levels of black carbon—a soot remnant of the incomplete combustion of fossil fuels and biomass. Like nitrogen dioxide, black carbon is often linked to vehicle engine exhaust and wood burning.

Patients with higher soot levels in their blood were 36% more likely to need intensive care.

The findings were expected, Nawrot said. Even before the pandemic, researchers had seen that patients exposed to higher levels of pollution in the weeks before admission required longer ventilation time in the ICU, independent of the cause of hospitalization.

"We knew even before COVID that air pollution does something to our immune systems and makes us more vulnerable to infections like pneumonia."

"It was surprising to see the magnitude of the effect even though it is a small exposure," said doctoral student Stijn Vos from Hasselt University, one of the lead authors of the Belgian study.

Strong Evidence

"We have now quite clear, consistent evidence of the relationship between air pollution and COVID severity," said Cathryn Tonne, an environmental epidemiologist at the Barcelona Institute for Global Health in Spain who wasn't involved with either study. Tonne's research showed similar results in Catalonia, a region in northeastern Spain with a population about the size of Denmark's.

Although earlier studies showed a link between COVID-19 and air pollution, they were what epidemiologists call ecological studies, which use averaged data for whole populations. They can provide an early assessment but are subject to many problems and factors that cannot be controlled.

The new studies consider the situation of each patient, looking at factors such as occupation, educational level, income, and number of people in the same household to avoid bias introduced by these factors.

Universal health care policies afforded the researchers detailed data. "You can't do this in the U.S.; you can't do this in many other places where you don't have universal health care or it's a much more fragmented system," Tonne said.

Clean Air Is Good for All

Air pollution is the fourth-greatest health risk factor, after smoking, high blood pressure, and diet. Worldwide, it causes more than 6 million deaths every year. Airborne particulates and toxins are responsible for many diseases, but as a risk factor, exposure to them affects everyone, not only those with other risk factors.

For that reason, small reductions in air pollution bring significant public health benefits, Andersen said. Policies regarding air quality could be seen as public health measures. "That's why we don't need to stress people over it, but we need to stress our governments," Andersen said.

The new studies show that lowering air pollution is an important part of pandemic preparedness, Tonne said. "If we have high levels of air pollution, you're going to have a much worse time when the next pandemic comes," she added.

By **Javier Barbuzano** (@javibarbuzano), Science Writer

Essential Ingredient for Life Found on Enceladus

Sunlight shines through plumes of ice crystals and dust grains jetting from Saturn's moon Enceladus, as seen by the Cassini mission. Credit: NASA/JPL/Space Science Institute

Saturn's moon Enceladus couldn't look less Earth-like. Instead of an atmosphere and oceans warmed by the Sun, it has a thick shell of ice that covers a global sea, likely kept liquid by tidal squeezing from its host planet.

And yet Enceladus is one of the likeliest candidates for life beyond Earth in the solar system, an intriguing status that has become even more possible, thanks to a new discovery.

Using archival data from the Cassini mission, researchers uncovered evidence of phosphorus in the form of sodium phosphates in Enceladus's subsurface ocean, the first time the chemical has been measured in a liquid environment beyond Earth. Sodium phosphates are a family of molecules that combine sodium (Na^+) and phosphate ions (PO_4^{3-}) with various other elements.

Phosphorus is the rarest of elements necessary to life as we know it. It's often found locked up in rocks, unavailable for organisms to use. The presence of phosphorus in water on Enceladus at more than 100 times greater abundance than on Earth is suggestive of how available it might be throughout the outer solar system.

"The previous concern that phosphorus might be a bottleneck for the emergence of life on Enceladus is gone," said Frank Postberg, a planetary scientist at the Free University of Berlin who coled the new study published in *Nature* (bit.ly/Enceladus-phosphates).

Phosphorus is one of six elements present in the proteins and genetic molecules—DNA and RNA—of all known life. Of the six, carbon, hydrogen, nitrogen, and oxygen are common in the solar system and beyond, with sulfur being rarer and phosphorus rarer still. Much of the challenge for determining the origins of life is tracing how these elements (often written as CHNOPS and pronounced "schnapps") came together and the conditions necessary to build the first recognizable biochemicals.

"We already knew that Enceladus has a number of things we tend to think of as requirements for life," said Sarah Hörst, a planetary scientist at Johns Hopkins University who was not involved in the study. Her work uses Cassini data as well as laboratory experiments. "Now we see that there are phosphorus-containing compounds, which gets us closer to the possibility of the chemistry of life as we know it."

The Probe That Keeps On Giving

The Cassini mission was launched in 1997 and ended in 2017 when the spacecraft's controllers deliberately crashed it into Saturn. That was done, in part, to prevent the probe from possibly contaminating Saturnian moons with elements from Earth.

"The previous concern that phosphorus might be a bottleneck for the emergence of life on Enceladus is gone."

When Cassini first flew past Enceladus in 2005, researchers spotted plumes of ice jetting from surface cracks near the moon's south pole. Over the next decade, controllers directed the spacecraft through the plumes several times to grab material for analysis.

Data collected by the craft's Cosmic Dust Analyzer revealed salty, alkaline water and organic molecules in the plumes, opening the possibility of finding life.

Of course, organic molecules by themselves don't mean life: Astrochemists have found them in comets and interstellar clouds, neither of which are hospitable. However, Cassini revealed that Enceladus has hydrothermal activity and an ocean underneath its ice, which provides shelter from radiation and an energy source—things the atmosphere and the Sun provide on Earth to allow life to flourish.

"Enceladus has been very helpfully throwing its material into space where it is much easier to measure with spacecraft," Hörst said. "The Cosmic Dust Analyzer obviously wasn't designed to measure Enceladus because we didn't know about the plumes, but it's become a really powerful tool for measuring the composition of Enceladus's ocean. Enceladus is awesome."

Biochemical Riddles in the Dark

The data set obtained from Cassini was so huge it couldn't be fully processed while the probe was operational.

"Enceladus is awesome."

It took 3.5 years to find sodium phosphates, Postberg said. "We didn't look for phosphates or anything specific; we just wanted to look for something new."

Even then, he and his colleagues had to answer two important questions: Was this analysis reliable, and how could Enceladus have so much more phosphorus in its oceans than Earth does?

Over the next year and a half, part of the team performed geochemical experiments and modeling to answer those questions. They showed that assuming the rocky seabed of Enceladus has a chemical makeup similar to that of most meteorites and many comets, an alkaline ocean like Enceladus's would dissolve the amounts of phosphates measured in the plumes.

Postberg cautioned that none of the data so far have contained clear signatures for the sixth essential element for all known life: sulfur.

As both Postberg and Hörst pointed out, Enceladus bears similarities to many other icy moons in the outer solar system, including Saturn's moon Titan and Jupiter's moon Europa. If the geological and chemical conditions for life are widely present on these worlds, that raises the distinct possibility that life-bearing worlds very different from Earth are common in the cosmos.

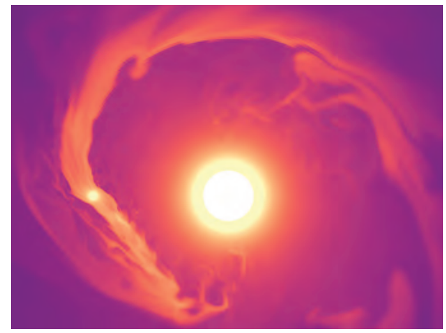
By **Matthew R. Francis** (@DrMRFrancis), Science Writer

A Planet Is Dramatically Losing Its Atmosphere

Earth's atmosphere is just a thin veneer of gas. Despite its seemingly ephemeral nature, however, our atmosphere, for the most part, isn't going anywhere. That's not the case for all planets.

Scientists observing a distant exoplanet recently found vast quantities of helium rapidly streaming away from the planet's upper atmosphere. Filaments of gas several million kilometers long stretch away from the distant world, a finding that highlights the dynamic nature of planetary systems.

About 900 light-years away, a Jupiter-sized gas planet orbits HAT-P-32, a run-of-the-mill star slightly hotter than the Sun. But this star's planetary system looks nothing like our own: There's just one planet, HAT-P-32b, and it orbits far closer to its host star than even Mercury orbits the Sun. (HAT-P-32b completes an orbit—that is, a planetary year—in just over 50 hours, or more than 40 times faster than Mercury.)



This simulated image shows gigantic streams of helium escaping the atmosphere of planet HAT-P-32b as it orbits its host star. Credit: M. MacLeod (Harvard-Smithsonian Center for Astrophysics) and A. Oklopčić (Anton Pannekoek Institute for Astronomy, University of Amsterdam)

Scientists observing a distant exoplanet recently found vast quantities of helium rapidly streaming away from the planet's upper atmosphere.

Follow the Gas

Because HAT-P-32b orbits so close to its host star, it's constantly bombarded with high levels of radiation. All that energy dumping onto the planet has a striking outcome: Hydrogen and helium gases are streaming away from HAT-P-32b's upper atmosphere. To better understand where all that gas is going, Zhoujian Zhang, an astronomer at the University of California, Santa Cruz, and his colleagues trained the University of Texas at Austin's Hobby-Eberly Telescope on the HAT-P-32 system.

The researchers opted to observe the planet over its full orbit, timing their observations precisely so that their data captured views of HAT-P-32b when it was not only directly in front of its host star but also off to both sides and behind it.

Previous observations of the HAT-P-32 system have typically focused only on recording transits, when the planet is directly in front of the star, as seen from Earth. "It's rare for people to cover the full orbital period," Zhang said.

Transit observations reveal information about only a small portion of HAT-P-32b's orbit. To look for evidence of material at different points in the planet's orbit, it's obviously necessary to look over the entire 360°, Zhang said. "If we only focus on the planet's transit, then we would miss the chance to determine whether the planet's escaping atmosphere is extended."

A Two-Tailed Planet

The researchers' persistence paid off: The spectrographic data they amassed confirmed that not only was helium streaming away from HAT-P-32b but also the gas extended even farther in space than previously believed. (The instrument the researchers used was sensitive to only helium, not hydrogen.) The new observations were most consistent with simulations that modeled two tails of helium gas extending from HAT-P-32b, one ahead of the planet in its orbit and one behind.

Other planets with trailing tails of gas have been spotted, but HAT-P-32b is the first extrasolar planet known to have both leading and trailing tails. "It's pretty special," said

Zhang, who, along with his colleagues, reported the new results in *Science Advances* (bit.ly/exoplanet-tails).

Together, the projected length of those two tails is more than 6 million kilometers, or more than 50 times the radius of the planet, the team calculated. That's astonishingly large, said Stefan Czesla, an astronomer at the Karl Schwarzschild Observatory in Tautenburg, Germany, who was not involved in the research but has extensively studied the HAT-P-32 system. "It's a huge structure," he said.

One Trillion Kilograms per Second

Zhang and his team also used their computer simulations to estimate the rate at which helium is escaping from HAT-P-32b's upper atmosphere. They calculated that more than 1 trillion kilograms of helium are streaming away from the planet every second. That's orders of magnitude more than the paltry 50 or so grams of helium lost each second by Earth's atmosphere.

Despite the prodigious rate of escape, it would still take well over a billion years for HAT-P-32b to lose its atmosphere entirely, the researchers calculated. And even that's not likely to happen, Czesla pointed out, because the star in the system will probably die before then. The gas's rate of escape means that the atmosphere will remain "longer than the star will live," he said.

"It's rare for people to cover the full orbital period."

HAT-P-32b is a dramatic example of a planet losing its atmosphere. By studying more worlds like this one, astronomers might be able to solve a long-standing mystery, Zhang said. Scientists have long been baffled by a relative dearth of Neptune-mass planets with close orbits around their stars. One idea is that these planets are literally disappearing, molecule by molecule, as their atmospheres are stripped away by high-energy radiation. "Mass loss is one of the scenarios that can explain the observations," Zhang said.

By **Katherine Kornei** (@KatherineKornei), Contributing Writer

Rocky Exoplanet May Have a Magnetic Field

Astronomers have detected radio bursts from a small red star that might be caused by magnetic interactions between the star and one of its planets. If future observations reveal more of this activity, the Earth-sized planet would be the first rocky exoplanet discovered to have a magnetic field.

"It's potentially important for planets to have a magnetic field because it can play a role in whether those planets are habitable," said J. Sebastian Pineda, an astrophysicist at the University of Colorado Boulder. Pineda is the lead author of the *Nature Astronomy* paper that reported the discovery (bit.ly/star-radio-bursts).

So far, astronomers have detected magnetic fields around a few giant-sized gaseous exoplanets. The discovery of such a field surrounding a rocky exoplanet would offer insight into the interior structure, atmospheric evolution, and potential for life of Earth-sized planets.

Stellar Space Weather

A magnetic field can be both a burden and a boon to a planet, said coauthor Jackie Villadsen, a radio astronomer at Bucknell University in Lewisburg, Pa. It's like bringing a shield to a water balloon fight: The shield makes you a bigger target, and even though you are protected from a direct hit, you might still get splashed around the shield's edges.

Similarly, a magnetosphere can increase the chance that particles from a stellar flare interact with the planet. But it also fends off some of those particles traveling along a star's magnetic field lines by bending those lines around the planet.

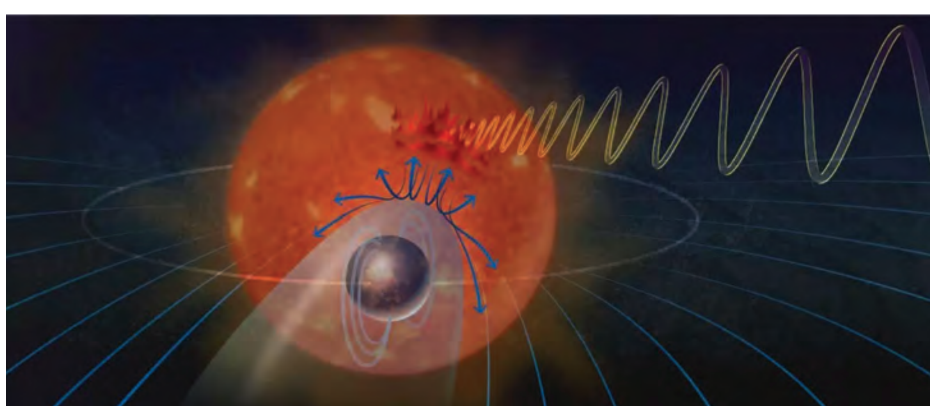
When the latter happens, the particles release energy that can travel back to the star and cause ripples in the stellar magnetic field lines, like plucking a guitar string, Villadsen explained. Those ripples can create a detectable burst of radio energy.

Using the Very Large Array radio telescope in New Mexico, Pineda and Villadsen searched for radio bursts from the nearby red dwarf star YZ Ceti. The star is just 12 light-years away and has three known exoplanets.

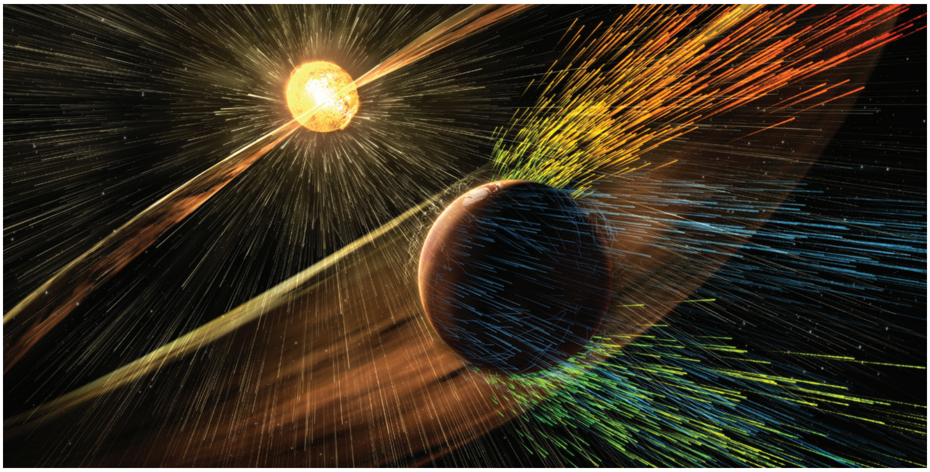
The first several radio bursts they saw were not so strange, the researchers said. Small red stars can be quite active. And though the star is older than the most active stars of similar size, it's plausible that it still produces strong flares.

But a subsequent burst caught the team's attention because it occurred just 2 days after a prior one. That interval matches the orbital period of the star's innermost planet, YZ Ceti b, which is 70% of Earth's mass and probably rocky.

"The radio waves themselves are coming from near the star's surface," like an aurora in the star's atmosphere, Pineda said. The timing suggests that an interaction between stellar wind and YZ Ceti b's magnetic field might have caused the bursts. This stellar space weather could be the first evidence of a magnetic field generated by a rocky exoplanet.



During star-planet magnetic interactions, stellar plasma (blue lines) is deflected by the exoplanet's magnetic field (blue arrows). That interaction bends the star's magnetic field and generates energy that can turn back toward the star. If that energy reaches the star, it can create auroras and release radio waves (yellow waves). Credit: National Science Foundation/Alice Kitterman



Magnetic fields can protect a planet's atmosphere from being stripped away by a star's wind. Mars, illustrated above, lacks such a protective field and has lost much of its atmosphere to solar wind. Credit: NASA/GSFC, Public Domain

The study "is a nice piece of work," said Philippe Zarka, an astrophysicist at Observatoire de Paris who was not involved with the new research. The two clear bursts are consistent with astronomers' understanding of how stars and planets interact magnetically, he noted.

But to confirm, the team would need to monitor the star over a long period of time, Villadsen said. If it releases a radio burst every time YZ Ceti b returns to the same spot, the bursts are probably caused by the planet's magnetic field. That would be the "absolute smoking gun," Zarka said.

Know the Star, Know the Planet

The researchers could not definitively say that YZ Ceti b has a magnetic field, in part because so little is known about flares coming from older red dwarf stars such as YZ Ceti. Their flares may produce these kinds of radio bursts all on their own.

Past studies have discovered magnetic star-planet interactions for Sun-like stars whose magnetic properties are better understood. "This experiment has yet to be done for small rocky planets around low-mass stars like YZ Ceti," explained Evgenya Shkolnik, "but this study is an important, early step." Shkolnik is an astrophysicist at Arizona State University and was not involved with this research.

"The good news is that planetary magnetic fields are ubiquitous in our own solar system," Shkolnik added, "so they should also be so in exoplanetary systems."

Studying flares and radio bursts from many stars like YZ Ceti will clarify how these kinds of stars typically behave and help researchers home in on planet-generated radio bursts.

"Ultimately, radio telescopes that monitor a wider portion of the sky will be really valuable," Villadsen said. As would a space-based radio telescope, which could measure the magnetic field–generated radio signal from the planet rather than from the star, said Cornell University scientist Jake Turner, who studies exoplanet magnetic fields and atmospheres and was not involved in the new study. (Earth's atmosphere blocks those lower-energy radio signals from reaching ground-based radio instruments.)

An adage guides exoplanet researchers: To understand the planet, you have to first understand the star.

"'Know the star, know the planet' is really, really true here," Pineda said. "But it's going to require expanding 'know the star' to all sorts of things that so far haven't been the focus for studying exoplanets."

By **Kimberly M. S. Cartier** (@AstroKimCartier), Staff Writer

The Inequality of Heat Stress

When record-breaking temperatures and heat domes envelop swaths of the United States each summer, people across the country experience these extreme heat events differently. Those living in historically redlined neighborhoods, where segregation and racisim informed discriminatory land use and housing policies, are at higher risk for hotter temperatures and the health effects caused by heat stress.

In a new study published in *One Earth*, researchers showed that heat stress disproportionately affects poor and non-white residents in 481 American cities (bit.ly/heat-stress-disparity). "We found that the actual disparity was pretty consistent across cities: In over 90% of the cities we considered, we found both income and race-based inequalities in heat exposure," said TC Chakraborty, an Earth scientist at Pacific Northwest National Laboratory and lead author of the study. This type of information can help city leaders to use better measures of heat disparities as well as to protect the populations most at risk from heat exposure.

The Danger of Unrelenting Heat

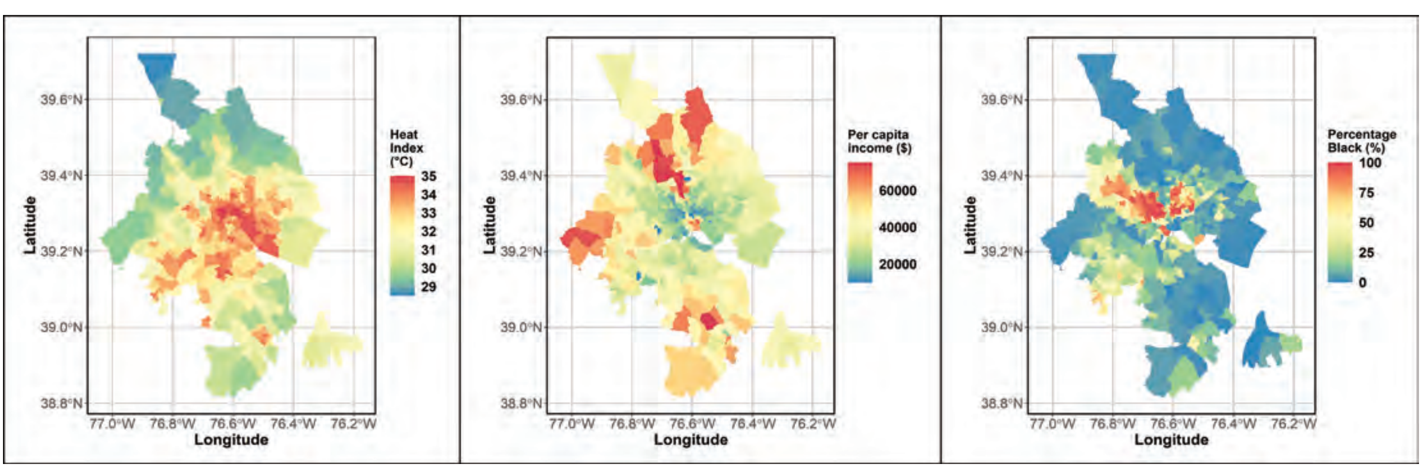
Urban heat islands, hot pockets of a city where asphalt and dense construction cause temperatures to rise higher than in surrounding areas, are home to millions of people who are not able to properly escape unrelenting summer heat.

"People who live in an urban area tend to walk to do their daily tasks. It's one of the great things about living in a city, that things are close by and you can use public transportation, but that also means you have to spend more time outdoors," said Neelima Tummala, a physician and codirector of the Climate Health Institute at George Washington University, who was not involved in the study.

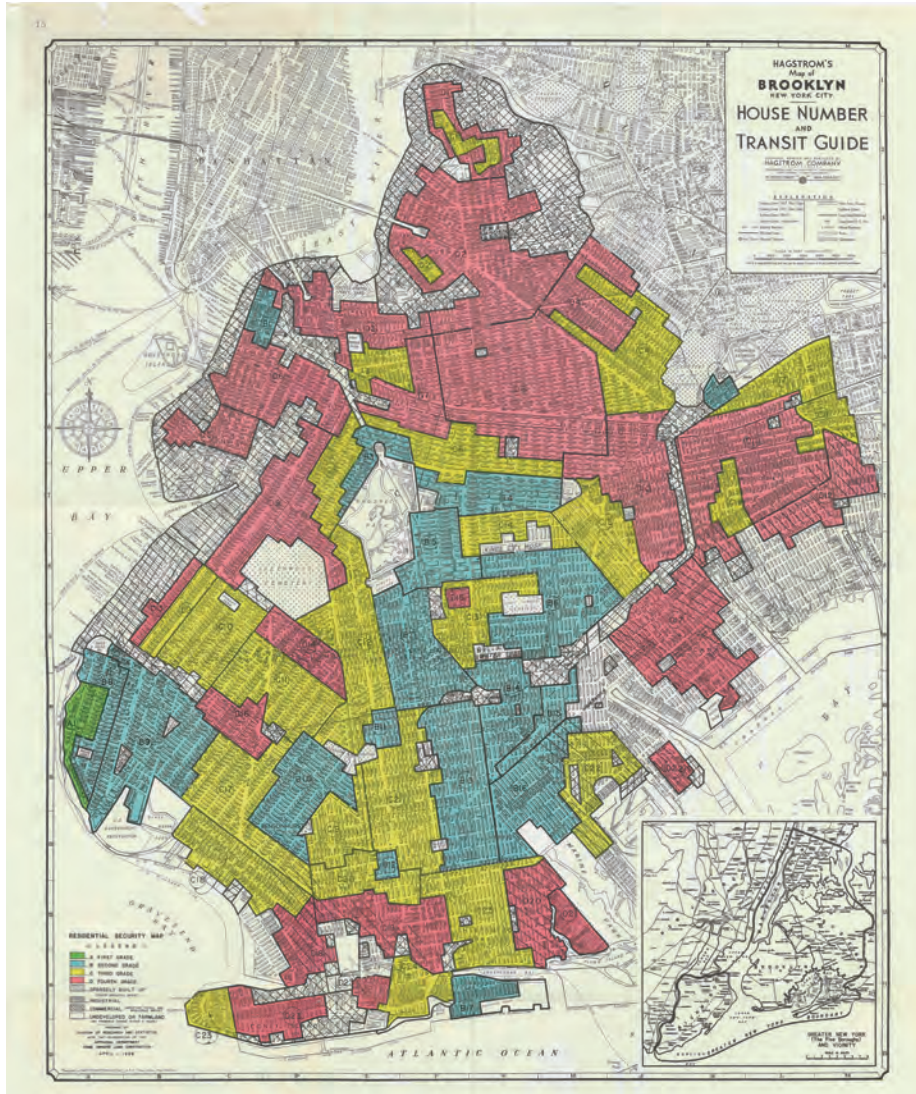
In neighborhoods without parks or mature trees, where asphalt and buildings absorb the summer heat, residents may find it difficult to avoid extreme temperatures both indoors and outside. That type of continuous exposure can be very dangerous. The body

Chronic exposure to excessive heat has an impact on cardiovascular, respiratory, and mental health.

becomes unable to cool itself properly through sweating. Chronic exposure to excessive heat has an impact on cardiovas-



These maps show Baltimore census tracts colored by income, heat index, and percentage of residents who are Black. A comparison indicates that where a higher proportion of residents are Black, heat stress is greater. Credit: TC Chakraborty/PNNL cular, respiratory, and mental health, Tummala said. "Long-term exposure to higher nighttime temperatures may affect your sleep quality and your mental and heart health," she said. "You're constantly at an elevated temperature that your body has to address."



A 1938 map of Brooklyn, N.Y., from the Home Owners' Loan Corporation, depicts neighborhoods color-coded by loan worthiness. Areas in red—redlined neighborhoods—indicate where banks and other lenders generally considered residents not worthy of inclusion in homeownership and lending programs. Redlined neighborhoods had a disproportionate number of Black residents. Credit: Home Owners' Loan Corporation, Public Domain

Mapping Heat Disparity

Previous studies on urban heat have used satellite data to estimate land surface temperatures. Chakraborty and his colleagues instead evaluated heat stress using the U.S. National Weather Service's heat index and the Meteorological Service of Canada's humidity index (humidex), which combine air temperature and humidity to better describe what heat feels like. Using models that combined these variables was a more accurate way to catalog heat stress across American cities between 2014 and 2018.

Mapping heat indices onto census data revealed that lower-income neighborhoods and residents of color experienced hotter temperatures and higher humidity, together amplifying heat stress. Census tracts with higher income saw less heat stress. Heat stress was also generally higher in tracts with a larger percentage of Black residents.

The researchers compared these findings to historical data in 177 cities to further note this income and race-based disparity over time.

In the 1930s, the U.S. government graded neighborhoods for investment suitability. Many of the neighborhoods that were home to poor and minority populations, especially Black residents, were deemed riskier investments and therefore received less funding for development and homeownership programs. Today these redlined neighborhoods have far worse environmental conditions than other parts of their respective cities. They have less tree cover and higher surface temperatures than originally nonredlined neighborhoods.

The disparities were pervasive, Chakraborty said. Redlined neighborhoods, which lending programs generally graded D, had a higher heat index than A-graded neighborhoods. "This was a very interesting result—that this degree of inequality and segregation is related so strongly with the degree of heat disparity," he said.

Protecting the Most Vulnerable

"Studies like this, that seek to further understand existing disparities in heat exposure, are important for identifying which communities are most at risk from climate change–related environmental changes such as worsening heat extremes," Tummala said. Public health measures and mitigation strategies are needed to protect city residents most at risk from heat—especially as soaring temperatures become increasingly common.

"Areas with fewer street trees, less access to green space—that's where you start to see the legacy of disinvestment and institutional racism that has come into play," said Lara Whitely Binder, climate preparedness program manager for King County, Washington, who was not involved in the study.

Because the climate is changing, cities must prepare for hotter summers and more frequent deadly heat waves. "We need to not only better understand where is it hot, but what are the socioeconomic factors for the people who live in those areas," Whitely Binder said. "We can start to unpack what's in the heat island and use that to start informing the policy decisions we're going to make."

By **Rebecca Owen** (@beccapox), Science Writer

Taking the Pulse of Global Change with World Heritage Data Sets

Cherry trees in bloom line a path along the Kamogawa (Kamo River) in Kyoto, Japan. Credit: Ryosuke Yagi, Flickr, CC BY 2.0 (bit.ly/ccby2-0)

In 2021, the famous cherry trees of Kyoto, Japan, reached their full flowering on 26 March, the earliest they had done so in more than 1,200 years. We know this because across the centuries, observers recorded this important phenological and cultural event in imperial court diaries and newspaper advertisements [*Aono and Kazui*, 2008; *Christidis et al.*, 2022]. The result of this recordkeeping is an important and irreplaceable chronicle of climate change, documenting later-than-average flowering dates during the cold periods of 1330–1350, 1520–1550, 1670–1700, and 1825–1830 and progressively earlier flowering dates since about 1900 as the influence of global warming has grown (Figure 1).

Human actions of ritual or curiosity have often led to data sets that provide important and unexpected insights into life and our interactions with the environment. Examples abound (Figure 2).

In March 1958, Charles Keeling took the first of many measurements of atmospheric carbon dioxide (CO_2) levels at Mauna Loa in Hawaii—in what would become the Keeling curve—measuring a concentration of 313 parts per million. Over the next year, Keeling's daily measurements revealed the natural seasonal pattern of the biosphere's "breathing": Atmospheric CO_2 declines rapidly during the Northern Hemisphere's spring to summer transition as growing plants take in the gas and then gradually increases through winter [*Keeling*, 1960].

After just a few years of dedicated sampling, it became apparent that CO_2 concentrations were not only oscillating seasonally; they were also increasing over time. In 2023, daily average atmospheric CO_2 concentrations measured at Mauna Loa have hovered around 420 parts per million. The Keeling curve has provided compelling evidence—now replicated across global networks of CO_2 monitoring stations—of how fossil fuel combustion has altered the chemistry of Earth's atmosphere.

Shortly after Keeling began his observations at Mauna Loa, Gene Likens, Herb Bormann, and Noye Johnson began measuring the chemistry of precipitation and stream water samples collected each week in the Hubbard Brook watershed in New Hampshire's White Mountains. Their intent was to study nutrient inputs to and outputs from watershed ecosystems [*Bormann and Likens*, 1967], but they were quite surprised by the acidity of the rain samples they collected.

This observation ended up catalyzing decades of study and widespread monitoring of precipitation that proved acid rain was derived from the release of sulfur and nitrogen oxides from fossil fuel–fired power plants and that these acid inputs were harming forests and freshwaters [*Likens and Bormann*, 1974; *Whelpdale et al.*, 1997]. The science was so convincing that it ultimately led to legislation, namely, the U.S. Clean Air Act and the U.S. Clean Air Act Amendments, aimed at reducing emissions of these and other pollutants. Continued weekly sampling of precipitation chemistry at Hubbard Brook from 1963 to the present has documented the efficacy of this legislation in reducing the acidity of rain and snow as well as in mitigating legacy impacts of acid rain on the health of forests, soils, and streams [*Likens et al.*, 1996; *Likens*, 2010].

These cases show the tremendous power that long-term data sets can have, but their histories also vividly illustrate the fragility of such data sets.

These three cases show the tremendous power that long-term data sets can have, but their histories also vividly illustrate the fragility of such data sets. Kyoto's cherry blossom record before the 1800s is reconstructed from ancient texts, and a flowering date is missing for many years. Both Keeling and Likens and their respective teams faced budget cuts and funding gaps that at times threatened the continuation of their long-term records. And just recently, the eruption of Mauna Loa in late 2022 forced scientists to halt measurements for the Keeling curve atop the volcano and relocate to nearby Mauna Kea. (Atmospheric data collection resumed at Mauna Loa in mid-March of this year.)

Sustaining long-term environmental records, and sharing them with the world, always requires intention, attention, and dedicated financial support. There are likely many short-duration data sets that, had they been continued, could have had influence comparable to the examples from Kyoto, Mauna Loa, and Hubbard Brook. Most data sets that do survive over many years, decades, or longer are maintained not only by funding but also through some combination of good luck and sheer willpower. Still, most exist on a financial knife edge, always one rejected proposal or unfortunate happenstance away from being discontinued.

Long-term records that document the many dimensions of our changing natural world are incredibly valuable to society [*Lindenmayer et al.*, 2012; *Hughes et al.*, 2017; *Schradin and Hayes*, 2017]. They represent vital data for informing environmental policy and public communication, and unlike the model reconstructions and forecasts that are critical to most formal environmental change analyses, these data sets are remarkably easy for nonexperts to understand.

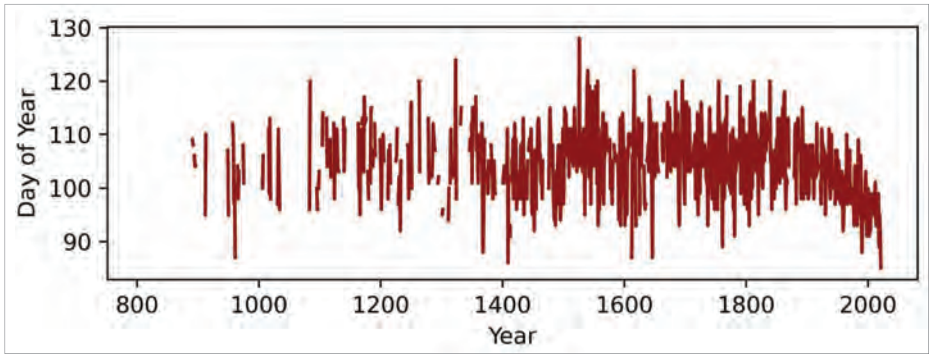


Fig. 1. The record of observed full flowering dates for cherry trees in Kyoto, Japan, kept since the 9th century, shows periods when the dates have been later than average, such as from about 1520 to 1550, as well as the steady trend toward earlier dates since about 1900. Credit: Christidis et al. *[2022], CC BY 4.0 (bit.ly/ccby4-0)*

Sustaining long-term environmental records, and sharing them with the world, always requires intention, attention, and dedicated financial support.

We contend that some data sets are so valuable, so integral to our understanding of the world around us and our place in it, that leaving their continuation to the vagaries of fate or funding cycles is illogical and irresponsible. These data sets are part of humanity's heritage and should be treated accordingly.

We thus propose the need for an international organization to designate universally valuable long-term records as "World Heritage Data Sets."

What Makes a World Heritage Data Set?

Much of the inherent value of long-term data sets is accrued over time, yet the challenge of maintaining funding increases alongside a record's age. Scientific research agencies around the world tend to focus their attention on transformational research and ideas for new research that can address questions or produce results quickly. Furthermore, the majority of research grants last less than 5 years. The continuing availability of financial support is thus a major hurdle for most long-term data sets [*Schradin and Hayes*, 2017], as is the security of the collected data for future generations.

One might imagine that governments would recognize the need to support these crucial data resources—and sometimes they do—but in reality, government agencies have stopped collecting long-term data in many cases because of changing budgetary priorities, changes in leadership, or shifts in political priorities. For example, the U.S. EPA has suspended numerous air quality monitoring sites in its Clean Air Status and Trends Network, the U.S. Geological Survey (USGS) has terminated hydrologic monitoring at sites with decades-long records, and the USGS National Water-Quality Assessment program has stopped collecting new data.

The idea to designate certain environmental records as World Heritage Data Sets was inspired by the protocols used by the United Nations Educational, Scientific and Cultural Organization to designate as World Heritage sites locations whose cultural and natural heritage represents "priceless and irreplaceable assets...of humanity as a whole." This designation increases a site's global visibility, provides international standards for its preservation and protection, and entails access to U.N. funding for protection and repairs in the event of threats or damage from exceptional circumstances such as war or natural disaster.

We envision similar criteria and benefits developed by an international organization, such as the United Nations Environment Programme, for designating remarkably valuable long-term environmental records as World Heritage Data Sets. The designation would acknowledge these data sets for the crucial place-based insights they provide into the ways the natural world is changing and into humanity's effects on our planet. It would also sustain the continuity of data collection and promote the data sets' protection and widespread dissemination.

We suggest five key criteria for any environmental data set to be designated as a World Heritage Data Set. These data sets should be as follows:

1. High impact. A compelling case has been established in peer-reviewed literature that the data are currently, or are expected to become, outstandingly important for understanding basic or applied questions of high societal interest or importance.

2. Consistent. Attention to consistency in methods of collection, analysis, and recordkeeping has ensured a data set of the highest integrity and quality.

3. Sustained. The data record has persisted well beyond the length of the average grant cycle.

4. Available. The data set is freely available to all and includes sufficient metadata to allow its widespread reuse and interpretation.

5. Accessible. The data and resulting findings are shared beyond the scientific literature in formats that allow the public to easily understand, interpret, and interact with the data set.

By these criteria, the three records we highlight above could qualify, as could many others (Figure 2). For example, roughly 60 years of chimpanzee observations at Gombe Stream National Park in Tanzania, begun by Jane

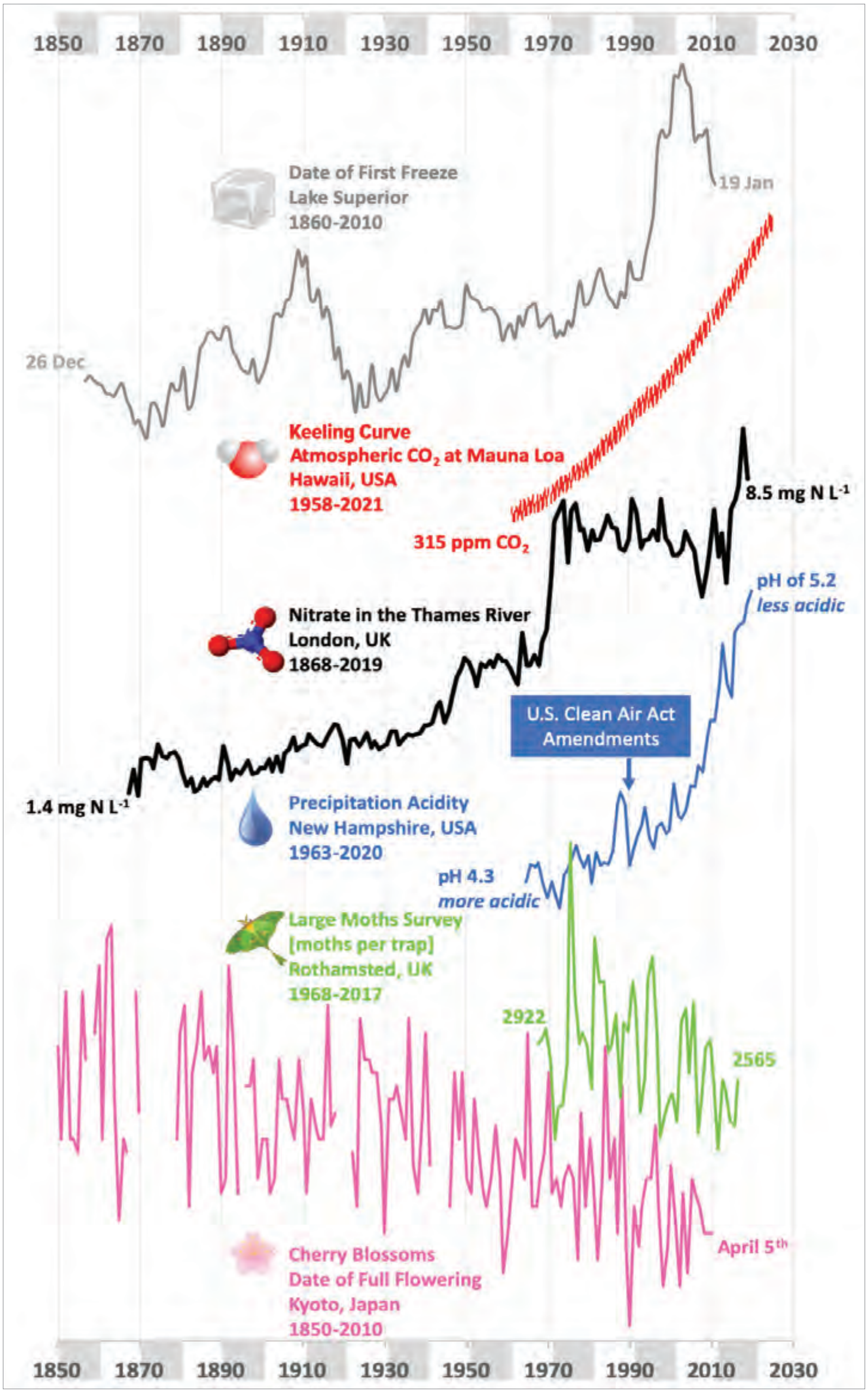


*Fig. 2. Some environmental data sets have proven especially useful in shaping scientific understanding of global change. A few such data sets, potential candidates for a proposed World Heritage Data Set designation, include (from top to bottom) the record of ice cover (i.e., date of first freeze) from Lake Superior's Bayfield Bay starting in 1860 [*Sharma et al.*, 2021]; the Keeling curve, compiled since 1958; nitrate concentrations in the River Thames since 1868 [*Howden et al.*, 2010]; the acidity of precipitation at Hubbard Brook in New Hampshire since 1963; the large moths survey collected in Rothamsted, U.K., since 1968; and the timing of the full flowering of cherry trees in Kyoto, Japan since 1850 [*Christidis et al.*, 2022].*

Three decades of research on the spotted hyena continue to provide insights into multigenerational dynamics of these social animals.

Goodall, have led to countless opportunities to learn about how a species closely related to humans interacts, learns, and behaves as the planet warms. Three decades of research on the spotted hyena in Kenya continue to provide insights into multigenerational dynamics of these social animals. Records of river discharge and flooding in the Amazon and Pantanal regions of Brazil dating back more than 120 years have enabled scientists to examine trends and drivers of the hydrology, ecology, and greenhouse gas emissions in these globally significant ecosystems.

Developing the Designation

Ideally, World Heritage Data Set designations would raise the profile and enhance the utility of established, long-term data sets by increasing their visibility and credibility among wider audiences. In addition, the designations would provide models of how efficient, impactful data collection efforts have been carried out that could motivate new collection efforts globally, particularly in regions where environmental monitoring is greatly needed but financial support for data collection is hard to procure.

Of course, before a World Heritage Data Set designation is codified, various logistical factors and questions must be addressed. Important questions that arise from our initial list of criteria, for example, include whether new data would need to be collected and added indefinitely to a data set to sustain a World Heritage designation. In addition, could a designated data set be created by combining a short-term modern data set with historic proxies or archival materials that extend the record into the past? Could records that ended at some time in the past be of sufficient value to be named World Heritage Data Sets?

We recommend that an international body of experts from a diverse range of disciplines—including but not limited to environmental scientists and historians—be created to further develop the criteria by which World Heritage status is applied to environmental data sets and to grapple with these and other important questions regarding requirements of the recognition.

Such a robust, widely accepted mechanism would help secure funds and ensure the longevity and accessibility of critical environmental data sets—covering everything from rainwater chemistry to cherry trees—and would encourage further explorations that are needed to reveal the extent and significance of ongoing global change.

Acknowledgments

This article extends and develops ideas first presented in a letter published in *Science*. The idea of identifying World Heritage Data Sets first arose during a dinner that E.S.B., I.C., and W.H.M. attended during a Royal Society meeting at Chicheley Hall in Buckinghamshire, U.K., in January 2020. The concept was further developed by E.J.R., E.S.B., and G.E.L. in discussions about the challenges of sustaining the Hubbard Brook Watershed Ecosystem Record, a data set of weekly stream and precipitation chemistry from the White Mountains in New Hampshire that was sustained by G.E.L. from 1963 to 2013 and that is now being stewarded by E.J.R., E.S.B., and Chris Solomon, also of the Cary Institute. Solomon helped streamline and frame this article, and in a more generous world in which *Eos* had less strict limits, this paper would have included all six authors.

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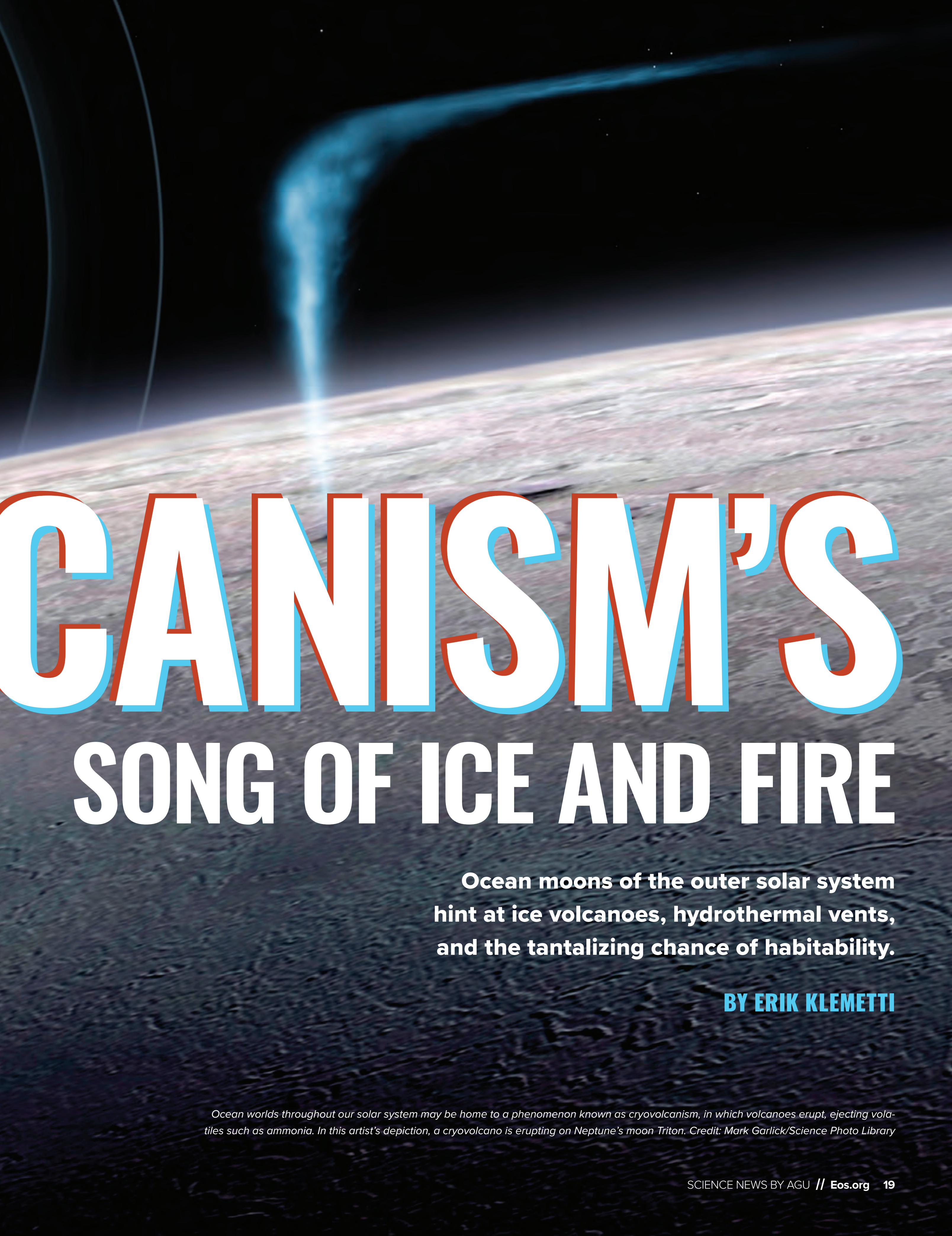
CRYOVOLC



CANISM'S SONG OF ICE AND FIRE

Ocean moons of the outer solar system hint at ice volcanoes, hydrothermal vents, and the tantalizing chance of habitability.

BY ERIK KLEMETTI

Ocean worlds throughout our solar system may be home to a phenomenon known as cryovolcanism, in which volcanoes erupt, ejecting volatiles such as ammonia. In this artist's depiction, a cryovolcano is erupting on Neptune's moon Triton. Credit: Mark Garlick/Science Photo Library

“Can you even imagine [that] ‘more water than on Earth’ is now possibly a common thing elsewhere in the solar system?” asked Steve Vance, a planetary scientist at NASA’s Jet Propulsion Laboratory and a project scientist for the agency’s Europa Clipper mission.

Earth might be the showiest blue marble, but Jupiter’s moons Europa and Ganymede, Saturn’s moons Enceladus and Titan, and more objects in the outer solar system have turned out to be remarkably active ocean worlds. Their surfaces show evidence of vibrant resurfacing on timescales shorter than we imagined. Their interiors are filled with exotic forms of ice and vast seas of water. They may have hydrothermal vents feeding into oceans. All of these characteristics add up to potential habitability.

The driver for much of this dynamism is volcanism. Deep in these moons’ interiors could lie the silicate volcanism so common on Earth, whereas a more exotic form of volcanism may churn their icy surfaces. The mix of heat, water, ice, and rock makes these worlds fascinating to planetary and Earth scientists alike.

Could these icy, volcanic moons host life? What does it take to create habitable zones in the outer solar system? Clues from these ocean worlds might upend how we search for habitable worlds and help inform how life might arise across the galaxy.

The Need to Keep Warm

All ocean worlds, including Earth, need one thing: heat.

On our planet, heat originates from two sources. The heat that keeps our oceans liquid mainly comes mainly from the Sun. Earth’s interior, on the other hand, is kept warm by radioactive decay of elements and residual heat from our planet’s formation. All that internal heat must go somewhere—“It is really hard for such a large object to get all of its radioactive heat out,” explained Vance—and volcanism is an efficient mechanism to make it happen.

In the outer solar system, something else is needed to generate the heat that allows for liquid water and volcanism. At such distances, the Sun doesn’t provide enough energy to keep water liquid, and whereas the moons of gas giants are sizable—some larger than Mercury—they are still too small to host the amount of radioactive decay or residual heat needed to fuel the sorts of volcanism familiar on Earth.

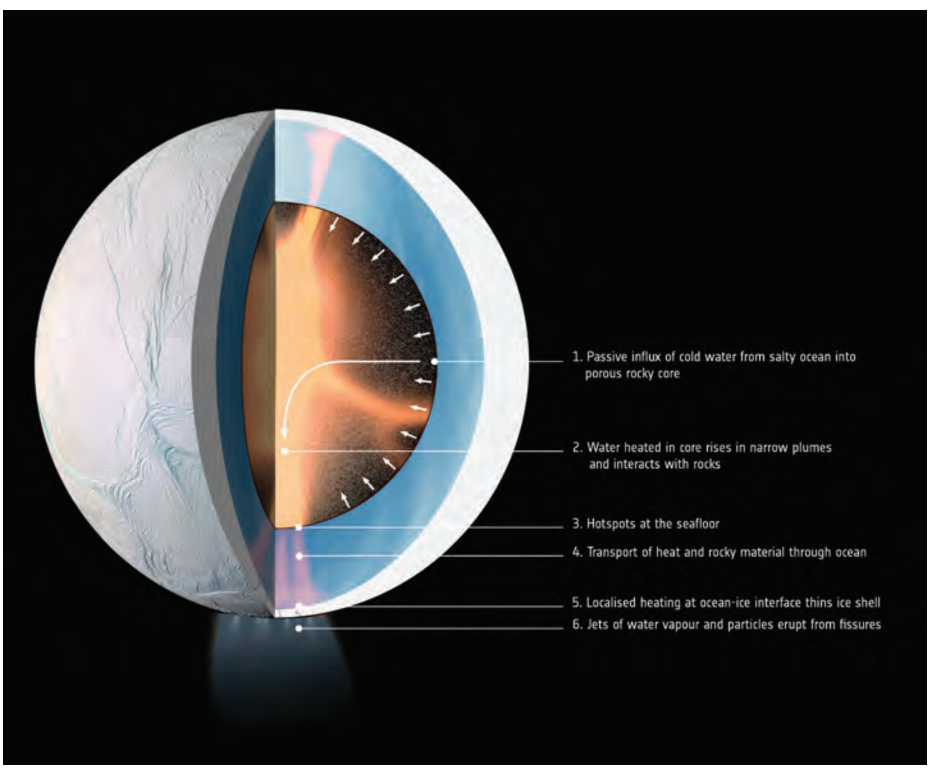
Much of the heat found inside these ocean worlds comes from tidal forces. As it zips around a gas giant in concert with other moons, the ocean moon itself is stretched and distorted on a regular basis. Some of this energy is converted to heat.

We see this most dramatically on the innermost of Jupiter’s four Galilean moons, Io. Its orbit around Jupiter and its interactions with Callisto, Europa, and Ganymede mean that Io is tormented to the point that it is the most volcanically active body in the solar system.

Tidal effects on Jupiter’s other moons are less dramatic but still strong enough to sometimes allow for liquid water oceans beneath thick, icy shells. In the case of Europa, the tidal heating might even be sufficient for magma to form in its rocky mantle.

We don’t have direct evidence for silicate volcanism on any of these moons other than Io, but models indicate that their interiors could contain sufficient heat to cause rock to melt.

“What remains to be seen is how much… thermal and dynamic linkage there is between silicate volcanism in the interior and what happens above it,” explained Sarah Fagents, a planetary volcanologist at the University of Hawaiʻi at Mānoa.



One theory of how Enceladus’s plumes may form relies on the tidally heated interior of the moon. Credit: Surface: NASA/JPL-Caltech/Space Science Institute; interior: LPG-CNRS/U. Nantes/U. Angers. Graphic composition: ESA

Cryovolcanism

These moons may actually be the source of not one but two types of volcanism: silicate volcanism and its distant cousin, cryovolcanism.

Cryovolcanism describes the process in which a volcano erupts volatiles such as ammonia (as opposed to silicates such as feldspar) into an environment below the volatiles’ freezing point. In the outer solar system, the surfaces of most objects are so cold that water is always frozen. This is part of why images of potential cryovolcanism from NASA’s Voyager, Galileo, and Cassini missions were so startling to scientists.

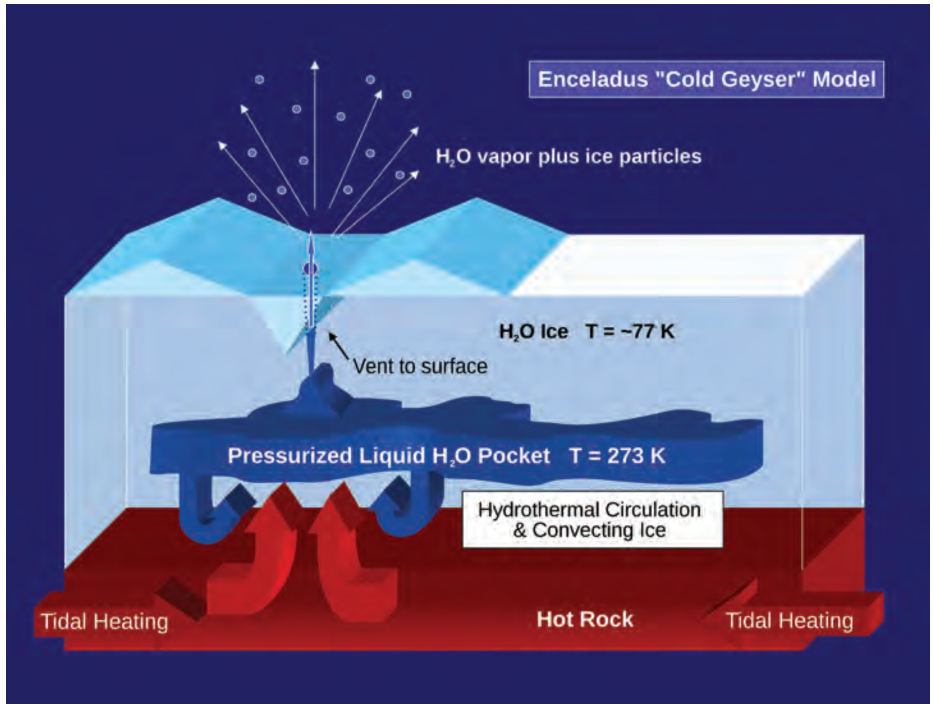
The plumes of Enceladus are almost certainly examples of cryovolcanism, which may have contributed to such features as the ridges of Europa and the mountains of Titan.

Fagents was studying earthly “basaltic lavas and explosive things,” she remembered, when “my boss pulled me into looking at surface features on Europa. It was astonishing. You look at the surface of Europa and it’s covered in such a diversity of features.… [T]here are these little dome-like and flow-like features that really look to me like fluids were on the surface."

To Fagents and other volcanologists, the dome-like and flow-like features of Europa brought to mind the familiar lava domes and flows in places like the Cascades or Yellowstone in North America. Yet the surface of Europa is made entirely of ice, and according to the geophysical data we currently have, no rocks exist for hundreds of kilometers below its icy carapace.

"There are features on the surfaces of these bodies that we don't have a good terrestrial analogue for," Fagents explained. "We try to make…silicate volcanic analogues, but I don't think those are necessarily the best."

This alternative to silicate volcanism opens the door between disciplines. "There is a lot we can learn from the fields of glaciology and hydrology that might be more pertinent than volcanology," Fagents said. "You need to bring in a diversity of expertise and viewpoints" to better understand the phenomenon.



Another theory of how cryovolcanism may work on Enceladus considers water's transition to a solid. When water freezes to form ice, its volume (and the pressure exerted on it) increases and fluid-filled fractures, like the plumes, relieve the pressure. Credit: Cflm001/Wikimedia, CC BY-SA 3.0 (bit.ly/ccbysa3-0)

Fracturing Theories

Lynnae Quick, a planetary geophysicist at NASA Goddard Space Flight Center and a mission scientist on Europa Clipper, was one of those people whose expertise helped bridge scientific observation with scientific process. "While I was in graduate school studying physics, [planetary scientist] Louise Prockter offered me an internship at APL [Johns Hopkins University Applied Physics Laboratory], so I spent a summer studying Europa," recalled Quick. "I really fell in love with it. I found a link between planetary science and my physics background in thinking about geophysical fluid dynamics on Europa."

Quick was intrigued by the mechanisms of cryovolcanism because, at least compared with terrestrial volcanism, the phenomenon can appear counterintuitive. Silicate magma tends to be less dense and more buoyant than the rock around it, causing it to rise and erupt. Liquid water, on the other hand, is denser than its solid counterpart. (Anyone who has observed the ice in a drink has seen this contradiction in action: Ice floats.) So the idea that liquid water in the icy shell of Europa could rise and erupt above ice was challenging to imagine.

"Volcanism is a purely endogenic process driven by melting and buoyant rise…but cryovolcanism is a little trickier than that," said Fagents. There must be fractures in the icy shell and then a mechanism to get liquid to flow through those fractures. "The density difference isn't great, but it certainly would want to keep ocean water where it is, especially if it is briny and denser than regular water."

> "I found a link between planetary science and my physics background in thinking about geophysical fluid dynamics on Europa."

Two main theories have emerged for how liquid water (cryomagma) can erupt, and in both, tidal forces again come into play. The first theory involves the tidal stretching and squeezing that ocean worlds experience as they orbit their home planet. These tidal processes may cause pockets of water to pressurize during certain parts of the moon's orbit, and potentially trigger eruptions.

The second theory, proposed by Fagents in 2003 and developed further by Elodie Lesage of the Jet Propulsion Laboratory, considers water's transition to a solid and the accompanying increase in volume, which can be a powerful force. On Earth, for instance, it can destroy mountains with frost wedging. On an ocean world like Europa, where pockets of liquid water might reside in the icy shell, increasing ice volume would raise the pressure in such pockets.

"You have pockets of melt in the crust, and they have excess pressure acting on them," explained Quick. "We're assuming that these pockets are not necessarily going to deform within brittle ice to accommodate the excess pressure. The only way to relieve the pressure is to have fluid-filled fractures that are created by the pressurization of these pockets to rise to the surface."

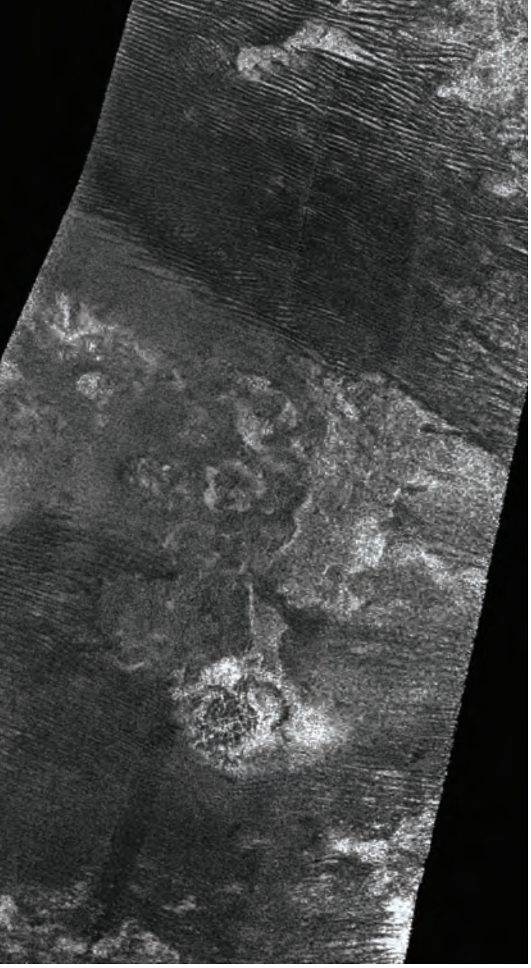
"It's surprising how many feature types we see that could potentially be cryovolcanic," said Fagents. "We haven't really got a smoking gun except for Enceladus."

More Questions Than Answers

Right now, Fagents said, scientists are left with more questions than solutions.

"We know that pieces of the puzzle work in isolation," she said, but "we don't know how the puzzle pieces go together and whether they really *do* go together in terms of understanding volcanism from depth to the surface."

Some of those puzzle pieces include how fractures in the ice are kept open to allow for



The giant volcanic mountain Doom Mons on Saturn's moon Titan, suggestive of relatively recent cryovolcanism, dominates the lower portion of this image from Cassini. Credit: NASA, Public Domain

eruptions to occur. "One of the sticking points is the fact that it's so hard to get throughgoing fractures in the ice shell, especially for the thicknesses of ice shells we're looking at," explained Fagents. "Clearly Enceladus manages it, but with thicker ice shells, you have static pressure wanting to close any fractures that open up."

Another problem is the mechanism by which planetary features with liquid water or icy slurries are made. "Liquid water has a very low viscosity," she added. "You can't make relief with water."

Yet another puzzling characteristic of the moons is the age of their icy surface features. Data have revealed that the surfaces of these ocean worlds are much younger than scientists anticipated when Voyager 1 and 2 first headed to the outer solar system.

"On Europa, we know that the liquid in the subsurface has salts and minerals and all these wonderful things," explained Quick as she described how to interpret the surfaces of icy moons. "If we see a feature that is low albedo—that's a relatively dark surface—we know it's pretty fresh, it's pretty young."

Quick pointed out that on Titan, Cassini-Huygens imaged what may be an ammonia-rich fluid coming out of the Doom Mons volcano. This flow was likely solid at the time, she said, but still hinted at recent cryovolcanism.

Things could be even weirder. Vance thought there could be "brine volcanism" driven by denser, salt-rich fluids on worlds with thick icy shells above a liquid ocean. "It's inverted volcanism," he explained, and not entirely unfamiliar on Earth. Such phenomena are "short lived in Antarctica, but that's because [the] volumes of material [the brines] can flow through are small. It is intriguing to imagine, in a 30-kilometer ice shell on Europa, some means for accumulating lots of brines—strong chemical gradients, especially if, in the case of Europa, you have oxygen-rich ice flowing into relatively reducing ocean."

Ice, Volcanoes, and Life

All this theorizing hinted at the most captivating question of all: Could there be life? Answering that question requires us to understand how the rock, water, and ice components of these ocean worlds connect.

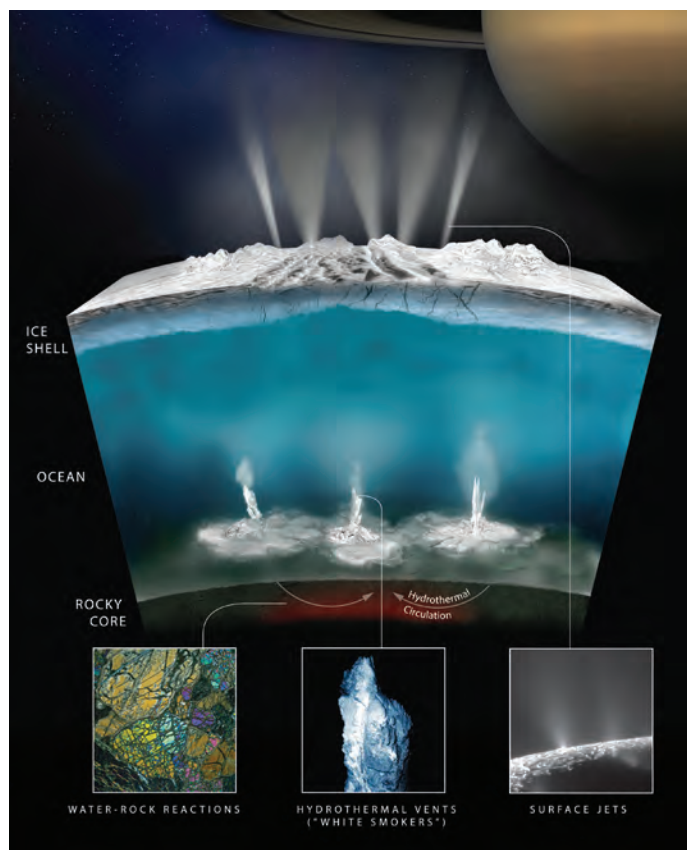
"If you think about moons like Europa and Enceladus, where there are oceans that sit right on top of rocky mantles, that means they have a seafloor," said Quick. "If that rocky material is warm in any way, we expect there to be hydrothermal vents and the type of chemistry that we see at the Earth's seafloor."

That is the next frontier.

"We know that for life, we need a source of energy. We need liquid water. We need organics," said Quick. "For places like Europa and Enceladus, we've detected organics, we know we have liquid water, and we have tidal heating."

> "Cryovolcanism really kind of stirs the pot to make it so that the energy and organics are cycled through the shallow subsurface."

So the pieces may be in place for life, or at least for habitability, in the outer solar system. The question of whether life could emerge on ocean worlds like Enceladus, Europa, or Titan comes down to where those different components meet.



This graphic illustrates how scientists on NASA's Cassini mission think water might interact with rock at the bottom of the ocean of Saturn's icy moon Enceladus. Credit: NASA/JPL-Caltech/Southwest Research Institute, Public Domain

NASA's Europa Clipper, scheduled to launch in October 2024, is one of several missions headed to the ocean worlds of the outer solar system. Credit: NASA/JPL-Caltech, Public Domain

In the outer solar system, "the open ocean and mid-depths don't have a lot going on because that's not where the primary strong gradients of energy are located," said Vance. More promising locations may be found where chemical and energy gradients occur, driving chemical reactions. On ocean worlds, these interfaces include areas between rocky interiors and oceans, or even the boundary between oceans and icy shells.

Jennifer Glass, an associate professor in the School of Earth and Atmospheric Sciences at Georgia Institute of Technology, approached the question of habitability and life outside Earth from a different angle.

"The main way you can build up biomass," she explained, "is respiration, that is, having a source of electrons (a reductant) and then a sink for those electrons (an oxidant) and then moving the electrons along a membrane and pumping protons."

This respiration process may have occurred on early Earth at hydrothermal vents, with volcanism and magmatism making it possible. Tidal heating may play that role on ocean worlds like Enceladus, Europa, and Titan. Without it or another "source of internal heat of some form, this is all off the table," said Glass. "You need heat and a source of reduced compounds.... Environments like vents would also be advantageous because you get strong gradients."

Glass thinks that after Earth, ocean worlds likely harbor the most habitable conditions in our solar system. But then it gets complicated. "We are really thinking of a system that is just an island in the deep," Glass said of hydrothermal vents, "but it's still very much reliant on oxidants from the surface."

An influential study by Eric Gaidos of the University of Hawai'i at Mānoa and his colleagues described how challenging it would be for life to gain a foothold on an icy ocean world (https://bit.ly/life-ice-covered-oceans). "Even if Europa's interior is geologically active, energy-generated reactions such as methanogenesis and sulfur reduction used by terrestrial organisms would not be available to hypothetical life-forms," Gaidos and his coauthors wrote. "[C]arbon and sulfur will be outgassed as reduced rather than oxidized species."

Hypothetical life-forms might instead depend on manna from above. "Look at water, energy, organics," said Quick. "Cryovolcanism really kind of stirs the pot to make it so that the energy and organics are cycled through the shallow subsurface."

"What makes cryovolcanism important [for potential life on ocean worlds], in a way that's distinct from silicate volcanism, is [that] it's what keeps normally cold moons warm and could provide places for life within their ice shells," Quick said. "We have cryomagmas moving through the ice shell, so then you have warm, slushy, salty pockets of water."

Fagents agreed. "Moving fluids through an ice shell would be really important as well, because [the process brings] nutrients into contact with habitable environments," she said.

Those pockets of water might even be a habitat unto themselves. "There are bacteria in gas clathrates" on Earth, explained Glass. "You could think of them as almost an ice niche. If you have any melted pockets of water [on an ocean world], that could be habitable for them."

Diving into the Outer Solar System and Beyond

"These worlds have really changed our thinking about what makes a habitable world and where that has to be around the star," said Quick.

Habitable worlds can circle large planets and generate heat needed for volcanism—and liquid water.

Data from the James Webb Space Telescope are enriching astronomers' knowledge of exoplanets every day, and a veritable flotilla of missions will head to the outer solar system over the next decade. NASA's Europa Clipper will orbit Europa, Dragonfly will visit the surface of Titan, and the European Space Agency's JUICE (Jupiter Icy Moons Explorer) will make observations in unprecedented detail of Callisto, Europa, and Ganymede.

Scientists look forward to comparing new data with those collected by earlier missions. "If Europa Clipper sees surface features that were characterized as potential cryolava flows or plume deposits when first imaged by the Galileo spacecraft, and those features have since become larger or are still very low albedo, then this might suggest that cryovolcanism has been a regular occurrence and that eruptions have been occurring, at least sporadically, since the feature was first imaged," explained Quick.

Exploring the ice and volcanoes of the outer solar system will also help scientists learn about our own planet and its origins. "When we think about destinations like Saturn's moon Titan," Quick said, "it's kind of like we're able to look...back in time on Earth. And it's wonderful that we have the capabilities to do that."

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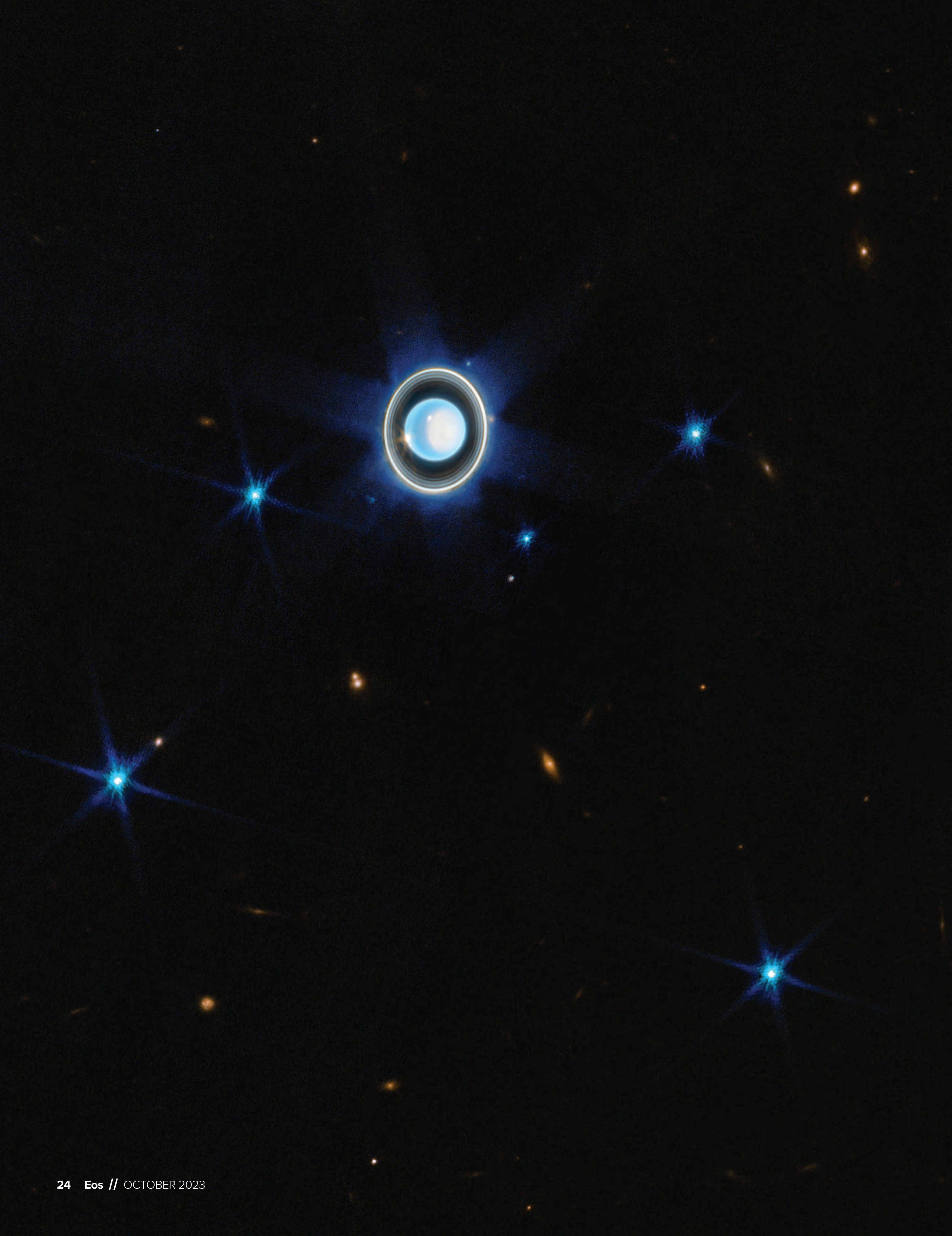
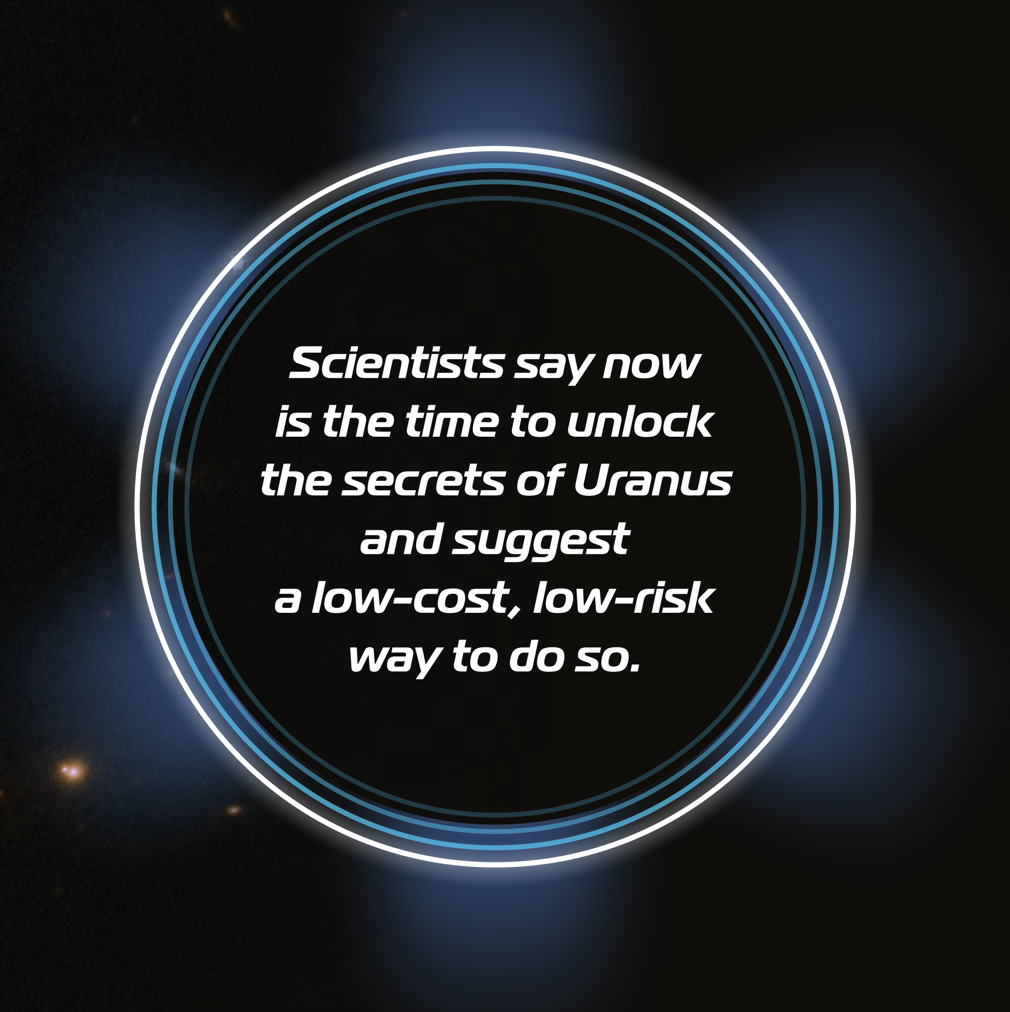


Uranus: Time to Boldly Go

By Kimberly M.S. Cartier



Scientists say now is the time to unlock the secrets of Uranus and suggest a low-cost, low-risk way to do so.

The James Webb Space Telescope's Near-Infrared Camera captured this image of Uranus, its rings, and 6 of its 27 moons in April 2023. Credit: NASA, ESA, CSA, STScI, Joseph DePasquale (STScI)

Uranus is one of the most mysterious planets in the solar system. It might not seem like much on its surface: Many photos show it to be a featureless blue-green orb with nary a cloud in sight. But its unique tilt, unusual ring system, misaligned magnetosphere, and curious variety of moons suggest that it has an interesting history that could unlock the evolutionary past of our solar system and tell us quite a bit about the planets beyond.

A brief visit to the planet decades ago by the Voyager 2 spacecraft and more recent remote observations have left scientists with more questions than answers about it.

A window of time is fast approaching during which astronomers could launch a spacecraft to Uranus. In fact, such a mission is at the top of their wish list. With abundant scientific potential and few technological hurdles, scientists argue that now is the time to return to Uranus—and this time, to stay a while.

"Every aspect of the Uranian system challenges our most basic understanding of how planets work," said Mark Hofstadter, a planetary scientist at NASA's Jet Propulsion Laboratory in Pasadena, Calif. "Voyager and Earth-based observations since then have seen things in the planet itself, in its rings, its small moons, its major satellites, and its magnetosphere that violate our expectations of how things should be," he said.

"It is therefore critically important that this once-in-a-lifetime opportunity to visit Uranus be able to explore all aspects of the system and to carry a diverse instrument suite to respond to the surprises that await us," Hofstadter said.

"Every aspect of the Uranian system challenges our most basic understanding of how planets work."

Voyager

In January 1986, the Uranian system received its first and, so far, only visitor from Earth. NASA's Voyager 2 spacecraft spent 32 days flying past the planet, capturing a small bit of gravitational energy to change its trajectory on its way out of the solar system.

While in the planet's vicinity, Voyager 2 gathered the first close-up images of Uranus's upper atmosphere, the cratered and uneven surfaces of several of its moons, and its ultrathin ring system. The craft also took measurements of Uranus's magnetic field, sampled the radiation environment near the planet, and discovered Uranian lightning.

But plenty of questions remain. Why is the planet tilted more than 90° on its side? What chemistry swirls in its interior? How does its magnetosphere interact with the solar wind throughout the Uranian year? What weather pops up as the seasons change? Could the planet's moons have recent or active cryovolcanism or subsurface oceans?

Voyager 2 flew by Uranus around the southern hemisphere's summer solstice, when the planet's northern hemisphere was completely in the dark. Uranus's moons, which orbit roughly along its tilted equator, were also only partly illuminated. "That had implications for what we could see of the satellites, the magnetosphere, and atmospheric weather patterns," Hofstadter said.

"At the time of Voyager, Uranus was famously bland looking," Hofstadter said. "It was referred to as the blue billiard ball, and so few atmospheric features were seen that the atmospheric science group of Voyager discussed giving up some of their precious observing time to other teams."

Uranus completes an orbit (and therefore a seasonal cycle) every 84 Earth years, and by 2007, it had moved into its equinox. Since Voyager, observations from the ground and from space "have found the atmosphere to be much more active and energetic at seasons other than summer," Hofstadter said. Arriving at Uranus during a different season, he said, means initiating a mission now.

The Next Generation

With several large strategic NASA missions now underway or well into development (including the James Webb Space Telescope (JWST), Perseverance rover, Parker Solar Probe, Nancy Grace Roman Space Telescope , Europa Clipper, and a Mars Sample Return mission), astronomers' next-highest priority is a mission to Uranus that includes an orbiter and an atmospheric probe. Missions this size are also known as flagship-class missions, NASA's largest and most expensive type of project that can answer multiple high-priority science questions.

"Uranus and Neptune remain the two unexplored planets in our solar system, each with its own exciting system of moons, rings, complex magnetosphere, and dynamic atmosphere," said Amy Simon, a planetary scientist at NASA Goddard Space Flight Center in Greenbelt, Md. Of the two, Uranus is closer and therefore more easily reached.

A Uranus flagship mission has appeared in past planetary science decadal surveys, which scientists proffer as a road map for NASA's budgetary priorities. The request has steadily crept up the priority list until it reached the top slot in 2022. A mission to the Uranian system has "vast potential for broad, cross-disciplinary science," Simon said.

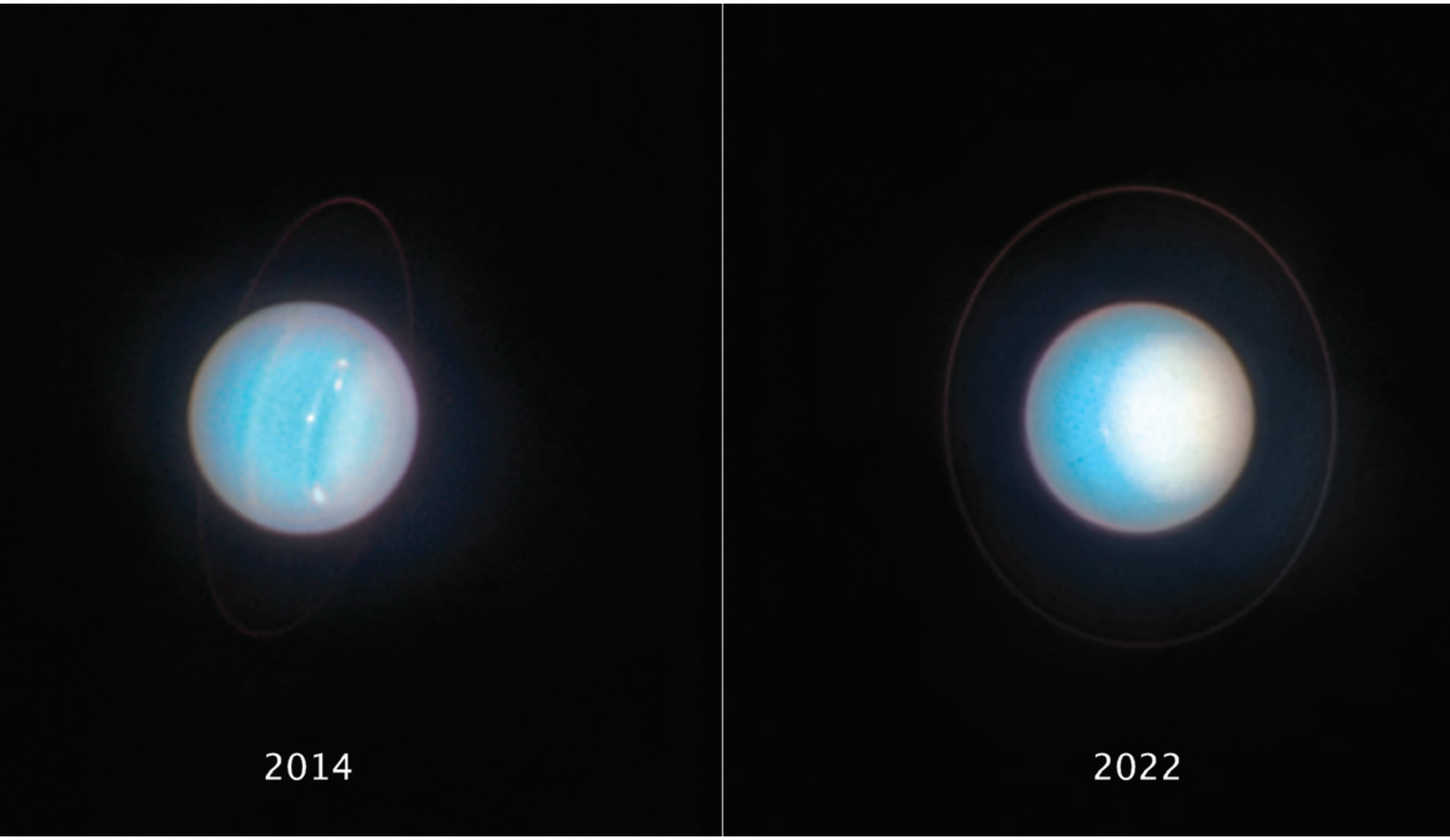
A group of planetary scientists and engineers designed a mission concept called the Uranus Orbiter and Probe (UOP) and has proposed the mission to NASA for review. The mission would deploy an atmospheric probe shortly after arrival, tour several moons, and then settle into orbit for 4.5 Earth years. The most recent planetary science and astrobiology decadal survey evaluated this mission as low risk, relatively low cost, and high reward.

It takes a lot of time and energy to travel to Uranus, said Athena Coustenis, a planetary scientist and director of research at Centre National de la Recherche Scientifique in France. An efficient flight path would take a spacecraft past Jupiter to gain some energy through a gravitational slingshot. A launch window in the early 2030s would provide the necessary planetary alignment, but there would be launch opportunities for several years following, too.

UOP's spacecraft design would rely on technologies proven to work on past missions while also offering NASA opportunities for international collaboration on instrumentation. Currently available technology is still a big step up from what was on board Voyager 2 during its flyby, Coustenis said.

"Although new technology is exciting, the community made clear in the decadal survey that waiting to explore this planet is holding up major questions in planetary science," said Kathy Mandt, a planetary scientist at NASA Goddard Space Flight Center. "Time is of the essence, so this mission needs to rely on existing technology."

The reliance on existing technology means that "the primary challenges involve cost and schedule," said Richard Anderson, a systems



With its 92° axial tilt, Uranus's seasons are vastly different from those on any other solar system planet and vary dramatically throughout its year. In 2014, 7 years after Uranus's equinox, the Hubble Space Telescope imaged the planet with several equatorial storms with clouds made of methane ice crystals. In 2022, 6 years before its northern solstice, its north pole glowed bright, and the planet displayed fewer storms. Credit: NASA, ESA, STScI, Amy Simon (NASA-GSFC), Michael H. Wong (UC Berkeley), Joseph DePasquale (STScI), Public Domain

engineer at the Johns Hopkins University Applied Physics Laboratory in Laurel, Md., and the study lead on the UOP concept. "We are actively looking into ways to reduce cost and conserve critical resources such as the plutonium needed to fuel [the spacecraft's] radioisotope thermoelectric power generators," he said.

The mission concept is smaller in size and cost than past flagships such as Galileo (which explored the Jovian system) and Cassini (which explored Saturn) but would have a similar scientific scope. "It would carry an atmospheric probe, as well as science instruments that can sense all aspects of the Uranian system," said Simon, who was a science colead for the UOP concept.

Even with no new technology, "large missions still require a long time to design, build, and test," Simon said.

Despite being similar in scale to past flagship missions, Mandt said, "what is really important about UOP is that if we focus the design to use current technology and carefully manage the scope, we have the opportunity to set a new precedent for cost-effective large-scale missions."

"A mission to the Uranus system can be completed more cost-effectively than one to Europa, for example," Anderson said.

Strange New Worlds

Many planetary scientists are particularly excited about the possibility of exploring Uranus's largest moons, Oberon, Titania, Ariel, Umbriel, and Miranda. These moons are thought to be made of rock and water ice in roughly equal amounts. (Uranus has 27 known moons, some only 15 kilometers across and blacker than asphalt.)

Given the lighting conditions at the time, Voyager 2 could map only around 40% of the surfaces of these moons. Even that much, however, was enough to demonstrate that they have wildly different surface geologies and degrees of cratering.

An arrival near equinox—which will next occur in 2049—would mean that the unseen hemispheres of the moons would be illuminated, allowing scientists to finish mapping their surfaces. "Close flybys that allow imaging or spectroscopy will tell us about surface geology and composition, as well as possibly the age of the features we observe," Simon said.

All five large satellites may have subsurface liquid water oceans at the boundary between their rocky interiors and icy surfaces. "Looking for oceans will be a very high priority and should be achievable at least for the inner moons," said Francis Nimmo, who studies planetary evolution at the University of California, Santa Cruz and was a science colead for the UOP concept.

A magnetometer on board a spacecraft could pick up on a magnetic field from a subsurface ocean. Galileo mission scientists used this method to confirm oceans on Jupiter's Europa, Callisto, and Ganymede.

Scientists are particularly interested in the oceanic possibilities of Ariel, whose smooth topography might be evidence of resurfacing from cryovolcanism. Thermal measurements and images taken at a high angle to a moon could illuminate any currently active cryovolcanoes or geysers, said Simon.

As with other watery worlds, there is the potential for life. Though many eyes turn to Enceladus and Europa as top astrobiology targets, there's no reason Uranus's ocean moons couldn't support life, too.

"What I'm most excited about is learning more about the habitable conditions around the ice giants and whether we can extend the possibility for life emergence in these remote regions," Coustenis said. Within Uranus's moons, scientists can look for plumes of complex organic molecules, subsurface heat, and organics at the surface, she added.

"If these worlds are indeed ocean worlds harboring deep, dark, hidden oceans of water below their icy crusts," said Leigh Fletcher, "then that might have implications for which environments in our solar system we could consider habitable and, by extension, the potential abodes for life in the universe." Fletcher is an atmospheric scientist at the University of Leicester in the United Kingdom.

Discovery

Beyond Uranus's enigmatic moons, planetary scientists are keenly interested in studying the planet itself. At the top of their scientific goals is measuring the internal structure and composition of the planet, which have been hard to model with existing data. A probe dropped into the planet's atmosphere would be key to that endeavor.

"We see ice giant planets everywhere we look in our galaxy, and it is amazing to me that we don't know what they are made of!" Hofstadter said. He's been chipping away at the question of Uranus's composition for more than 3 decades. The planet's upper cloud layers, as seen by Voyager 2, have 100 times less ammonia and far more hydrogen sulfide than expected from models.

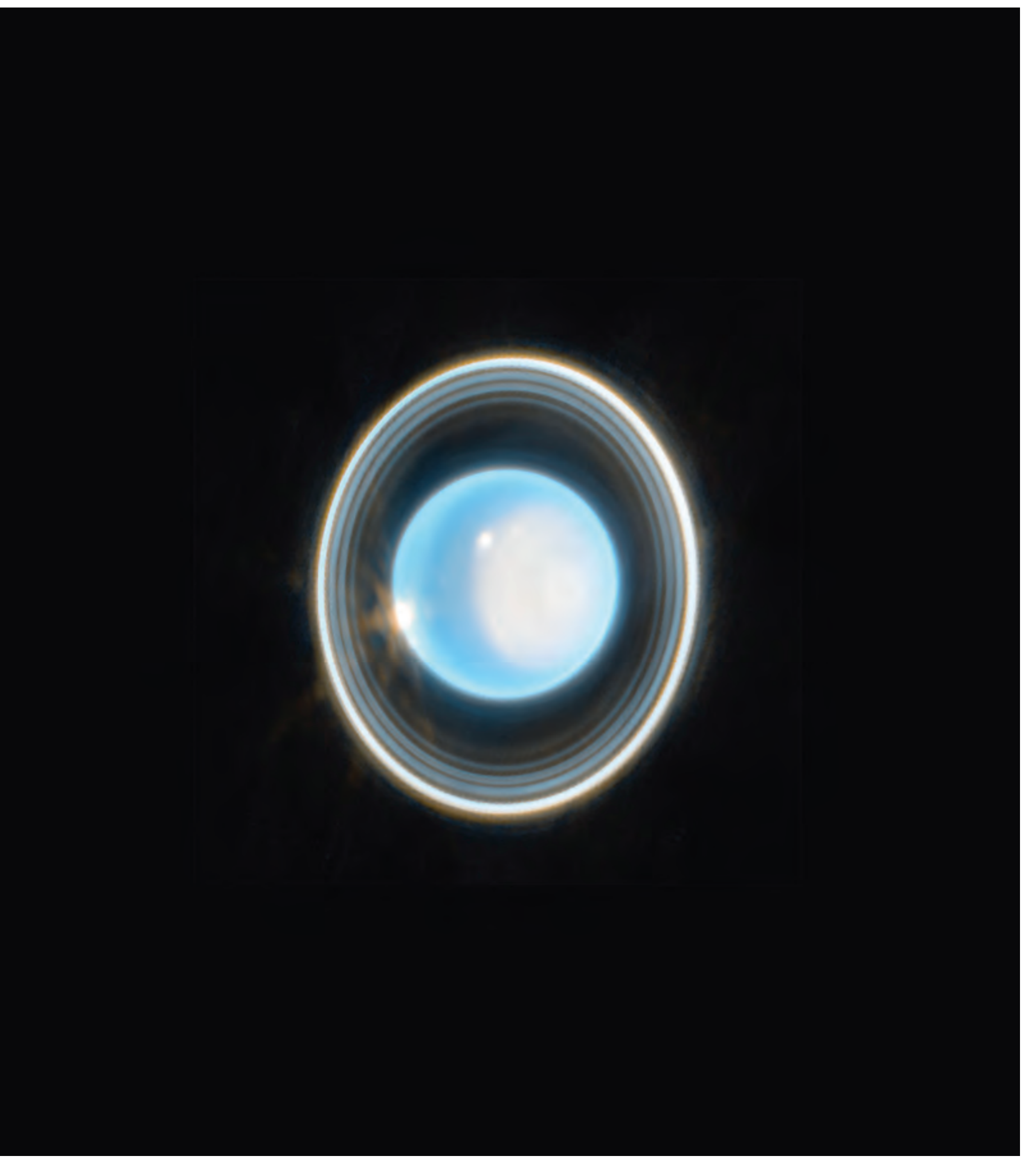
Unknown atmospheric photochemistry or mixing of cloud layers might be to blame, and a probe descending into the planet's atmosphere would return data on the chemistry, temperature, pressure, and dynamics hidden beneath the clouds.

"Uranus is a world of extremes for an atmospheric scientist like me," Fletcher said. "There's really nowhere else like it, with its bizarre seasons and eerily calm atmosphere. I can't wait to see this up close, to see how its climate, circulation, and meteorology differ from the better studied Jupiter and Saturn."

Uranus's tilted spin axis means that its seasons are quite different from those on Earth: At the height of summer, one hemisphere is always illuminated, and the other is entirely dark—just as at Earth's North and South Poles, but lasting for decades. Only around the equinoxes do both hemispheres experience rapid day-night cycles and the temperature changes that come with them.

Voyager 2 passed through the system during the southern hemisphere's summer, but a mission that launches in the mid-2030s would arrive at Uranus in the early 2040s, just before the planet's equinox. The changing season might produce new weather phenomena and reveal how the planet's tilted and misaligned magnetosphere interacts with solar wind.

Detailed study of Uranus's rings could also reveal hidden details about the planet itself. "We might be able to use the rings of Uranus as a seismometer to probe the planet's internal structure, as has been done—extremely successfully—at Saturn," Nimmo said. The smoothness of planetary rings depends on the uniformity of a planet's gravity field, and shifting or swirling material inside a planet creates gravitational dis-



The James Webb Space Telescope captured this image of Uranus, the "blue billiard ball," along with its narrow ring system and several of its moons, on 6 February 2023. Credit: NASA, ESA, CSA, STScI. (U. Arizona), Public Domain turbances. Any internal changes would appear as waves, ripples, or spirals in the rings and would be visible to an orbiting spacecraft.

Really, there are a lot of Uranian oddities to explore. “I also want to give a shout-out to the tiny moon Mab,” Hofstadter said. Less than 5 kilometers across, this moon is the likely source of Uranus’s mu ring, which is made of micrometer-scale particles.

“The only other ring in the solar system having similar properties is Saturn’s E ring, which is generated by the water plumes erupting on Saturn’s moon Enceladus. Mab is far too small to have active plumes, so how is the mu ring generated and maintained?” An onboard spectrometer could help pin down the exact size and composition of the ring particles, determine whether they’re a match for Mab, and, from there, narrow down how and why Mab sheds material—maybe even catch it in the act.

Deep Space (Planet) Nine

A long-term mission to the outer solar system could yield scientific discoveries that go far beyond Uranus and its moons, astronomers argue. First and foremost, any discoveries made about Uranus have the potential to expand our understanding of its fellow ice giant Neptune, as well as planets outside our solar system. Astronomers have found that many exoplanets are similar in size or mass to Uranus and Neptune.

“This was surprising,” Hofstadter said, “because most of our planetary formation models predicted that Uranus-sized planets should be very rare. To fix our formation models and to get a better understanding of what all these ice-giant-sized exoplanetary systems are like, we need to learn more about Uranus and Neptune.”

> ***“Everything we learn about Uranus is relevant to understanding this class of exoplanet.”***

Mandt added, “Everything we learn about Uranus is relevant to understanding this class of exoplanet, such as the interior structure, how they formed, and what their atmosphere would look like in future telescopes.”

There is also the potential for science while the spacecraft is in its decade-long cruise phase. Although many instruments would likely be unpowered or in a low-power state during transit, the spacecraft would still need to periodically contact Earth to report its status, location, and speed. Those ranging data provide an opportunity to locate any undiscovered massive objects in our solar system, be they asteroids, comets, or a planet.

A Uranus orbiter ideally would include onboard instruments to measure the magnetic, gravitational, and plasma environments around the planet. Data from those instruments could also provide glimpses into the solar wind and cosmic ray flux in the outer solar system that haven’t been seen since the Voyager missions.

It might even be possible to detect gravitational waves while in transit, Hofstadter said. The Earth-based Laser Interferometer Gravitational-Wave Observatory (LIGO) and the future space-based Laser Interferometer Space Antenna (LISA) observatory will detect gravitational waves from many types of black hole mergers, he said, but they likely will be unable to detect them from the merger of supermassive black holes. “If properly equipped, the Uranus mission could make those observations during its 10-year cruise out to Uranus.”

Enterprise

A flagship mission to Uranus—whether the Uranus Orbiter and Probe or one of several proposed to other space agencies—is still hypothetical. Here is the reality: The ideal launch window for a mission to the outer solar system is less than 10 years away and no mission has been green-lighted. Even though the leading mission concept does not require any new technologies, it could still take at least a decade to get it from the drawing board to the launchpad.

In fact, scientists are worried that NASA is already prioritizing other missions ahead of a mission to the outer solar system despite a sense of urgency from the community. The oft-delayed and over budget JWST stalled other NASA astrophysics projects for more than a decade, and astronomers have begun to worry that the NASA–European Space Agency Mars Sample Return mission will do the same to the docket of planetary science missions.

NASA’s initial response to the idea of a flagship mission to Uranus was positive, but it, too, acknowledged budgetary difficulties. In a NASA Planetary Science Division (PSD) town hall following the release of the decadal survey, PSD director Lori Glaze said that the agency plans to initiate studies of an orbiter and probe mission no later than fiscal year 2024. However, Glaze also cautioned that “it’s pretty challenging to start a new flagship in the very near short term due to some budget constraints.”

At a later town hall at AGU’s Fall Meeting 2022, she clarified that “there’s significant stress on the planetary budget. It’s been a bit brittle and fragile.” The COVID-19 pandemic, supply chain issues, inflation, and labor costs have put pressure on the budgets of in-progress projects, which had to be absorbed by the PSD budget, Glaze explained.

“A final challenge, which money can solve, is the availability of radioisotope power systems for the mission,” which agencies can purchase, Hofstadter explained. “Uranus is far enough from the Sun that we almost certainly need to rely on a plutonium-based power supply, and right now NASA doesn’t have enough of it for all the missions it hopes to launch in the next decade.”

The bottom line is this: If a flagship mission to Uranus is going to happen during the upcoming launch window, the whole enterprise must start moving fast.

“Excitement has been building in the planetary science community,” Fletcher said. “There’s no time to wait. Jupiter will continue to move on in its orbit, making the cruise trajectories to Uranus less favorable,” he said. “We must get started soon to meet this opportunity.”

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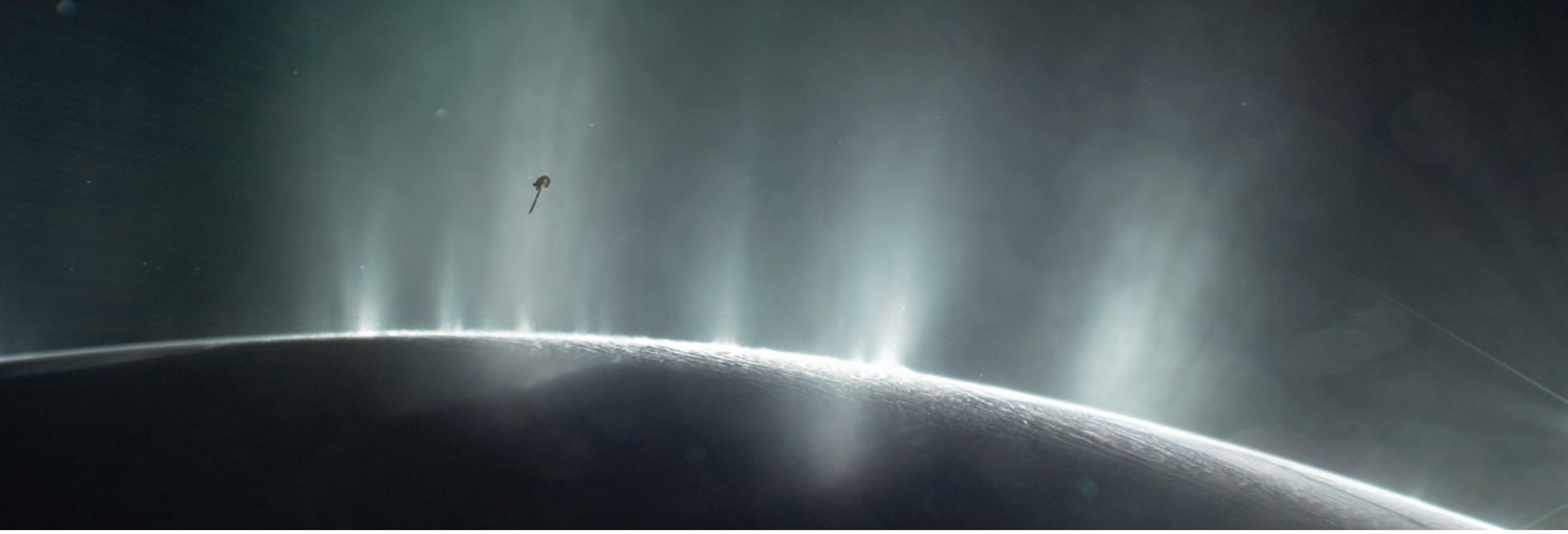
Read the the article at Eos.org

MARINE SCIENCE Goes to Space

Space and ocean researchers take a splash course in multidisciplinary science to chart our solar system's ocean worlds.

By Damond Benningfield

Both planetary scientists and oceanographers have been intrigued by the ocean worlds sprinkled throughout our solar system (and possibly beyond it). Credit: rolffimages/Depositphotos

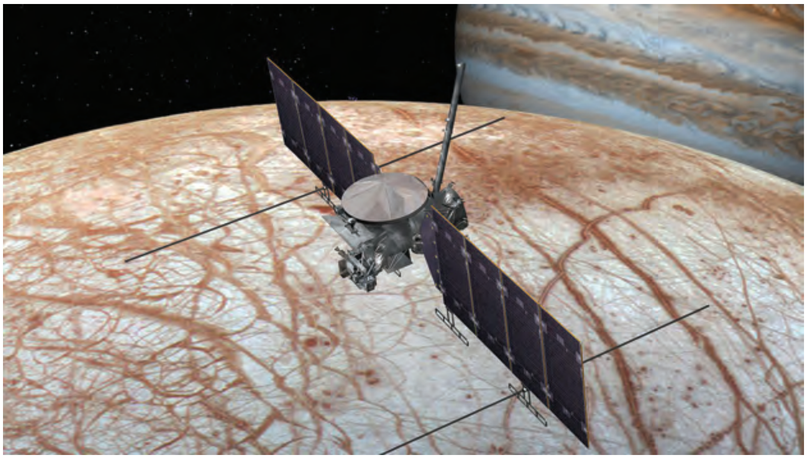


In 2015, NASA's Cassini spacecraft dove through the watery plumes of Saturn's moon Enceladus. Credit: NASA/JPL-Caltech

When the Cassini spacecraft first flew above the south pole of Enceladus, a moon of Saturn, it did something no solar system explorer had done before: It took a shower. The craft zipped through plumes of water vapor and ice grains spewing from cracks in the icy moon's surface. Cassini didn't need to towel itself dry because the spray was thin. Combined with the craft's earlier images, however, they spray provided strong evidence that a global ocean lies beneath the moon's crust. Later analysis found hydrogen, carbon dioxide, methane, and tiny particles of rock in the plumes, suggesting that the ocean could contain all the major ingredients for life.

The Cassini discoveries added Enceladus to a growing list of possible ocean worlds in our solar system—bodies with large amounts of liquid water hidden from view. Some of them could contain more water than all of Earth's oceans combined. And in addition to Enceladus, planetary scientists have counted at least one other member of the list, Jupiter's moon Europa, among the ranks of the "possibly habitable."

"There could be life in our own solar system, and we may already have flown past it," said Christopher German, a senior scientist at Woods Hole Oceanographic Institution and a coleader of Network for Ocean Worlds (NOW), a NASA-funded effort to advance research on these intriguing bodies. "Instead of just a sci-fi thing, suddenly we have grounds for wondering if there's life on these nearby worlds—places we have the technology to reach."



Scheduled to launch in 2024, NASA's Europa Clipper mission will search for signs of potential habitability on Jupiter's icy ocean moon Europa. Credit: NASA/JPL-Caltech

"There are a lot of exciting places out in the universe, but for me, the *most* exciting are nearby," said Tracy Becker, a group leader in planetary sciences at the Southwest Research Institute (SwRI) in San Antonio. "We can learn a lot about life in our own solar system, then extrapolate from that to learn about life elsewhere in the universe."

As one key step in exploration, NASA wants to increase collaboration between planetary and Earth scientists, combining knowledge of the solar system with the experience of exploring Earth's oceans and extreme habitats.

"Planetary and Earth scientists are in different orbitals," said Alison Murray, a research professor at the Desert Research Institute in Reno, Nev., and a NOW coleader. "We're trying to bring scientists together to begin conversations, to identify areas of common interest."

One early effort is Ocean Sciences Across the Solar System, which German described as a "public outreach effort for scientists." It has included workshops and other steps that resulted in a white paper and a set of articles for a special issue of *Oceanography*.

"The coordinated efforts of scientists that work in both Earth's ocean and oceans in other parts of the Solar System will allow knowledge gaps to be filled and opportunities to be identified for testable ideas based upon existing knowledge of the Earth's system," according to the white paper. "The two communities began as one, and this initiative will bring the two communities back together for a unified focus."

"We have a lot to learn from each other," said Amanda Hendrix, a senior scientist at the Planetary Science Institute in Tucson, Ariz., and coleader of a NASA committee that produced a 2019 report on exploring ocean worlds. "People have been studying Earth's oceans for many decades, so they have a head start. That [experience] can be leveraged by planetary scientists to help us understand and put into perspective the oceans in the outer solar system."

Expanding the Goldilocks Zone

And there's plenty for scientists to explore.

German said scientists have identified five "confirmed" ocean worlds beyond Earth: Jupiter's moons Callisto, Europa, and Ganymede and Saturn's moons Enceladus and Titan. That list could be just the tip of the planetary iceberg, however. "There are probably 20 candidates from places that haven't been studied closely since the Voyager missions of the 1980s," German said.

Some of those worlds appear to contain the major ingredients for life: water, an energy source, and the right chemistry.

"Fifty years ago, we confidently thought there was only one habitable world in our solar system," said German. "Now we're not so sure that's a safe assumption."

"These moons have flipped the whole paradigm of the 'Goldilocks zone,'" the distance from a star where conditions are considered most comfortable for life, said Ved Chirayath, a professor of Earth sciences at the University of Miami and a former director of the Laboratory for Advanced Sensing at NASA's Ames Research Center in California. "They're really far from the host star, so they should be rigid, frozen bodies. But Europa might have more water than all of Earth's oceans, which is mind-boggling—we hit the celestial jackpot. It opens up endless possibilities. You don't have to be in the Goldilocks zone to be considered a home for life."

Enceladus and Europa are the highest-priority targets for study. Their oceans are the most accessible of all the watery worlds and are thought to be the most comfortable for life.

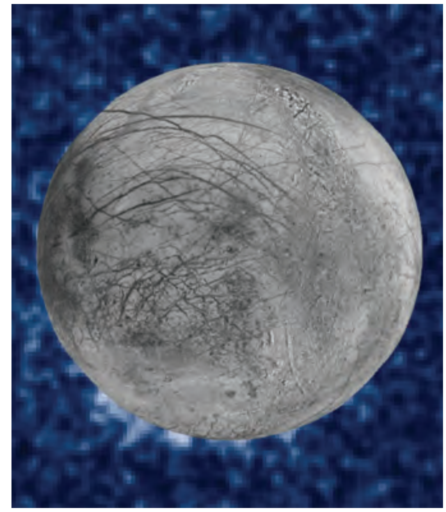
Europa's ocean was discovered first. When Voyager 1 and 2 flew through the Jovian system in the late 1970s, their photographs of Europa revealed icy terrain similar to that found in the Arctic and other frozen regions on Earth. The almost pure ice is extremely smooth, with few impact craters, indicating the surface is young. Large blocks of ice are jumbled at odd angles, suggesting they're floating atop a layer of liquid.

Long, dark grooves that crisscross the icy crust may mark the edges of large Europan ice sheets—the equivalent of tectonic plates on Earth. "Europa seems to have its own form of plate tectonics," said Robert Pappalardo, project scientist for the Europa Clipper mission at the Jet Propulsion Laboratory (JPL) in California. "There seem to be places where the icy lithosphere has disappeared into the interior. There are rift zones and spreading regions that may be analogous to mid-ocean ridge spreading. As a geologist, that gets me really excited."

What sealed the deal on identifying Europa as an ocean world, however, were observations by the magnetometer on the Galileo spacecraft, which looped through the Jovian system from 1995 to 2003. "Subsurface oceans reveal themselves magnetically through a process called electromagnetic induction," said Corey Cochrane, leader of the Europa Clipper magnetometer at JPL. Interactions with Jupiter's magnetic field create electric currents within Europa, spawning secondary magnetic fields.

"I'd give it a 90-ish-percent chance of being a salty ocean," said Pappalardo. "The magnetic data [imply] that there has to be a salty ocean. The readings are hard to explain otherwise."

The heat to keep the ocean from freezing comes from a tug-of-war between Jupiter and some of its large moons, which twists and pulls Europa's interior, generating heat. Models suggest there could be hydrothermal vents on Europa's seafloor, belching hot, mineral-rich water into the ocean. On Earth, such vents typically support vigorous ecosystems sustained by microbes that obtain their energy from molecules in the water.



This composite image of Europa shows Hubble Space Telescope observations of a possible plume of water (bottom left) superposed on a Galileo image of the moon. Credit: NASA/ESA/W. Sparks (STScI)/USGS Astrogeology Science Center

"Everything we know about Europa makes it seem habitable," said Murray, who was a member of a science definition team for a possible Europa lander.

"I'm [cautiously optimistic] that we'll find life," said Hendrix. "Nobody expects to see aliens walking around, but just the fact that life could form in a simple microbial state is really important. It helps us understand the potential beginnings of life on Earth and what is required to sustain life."

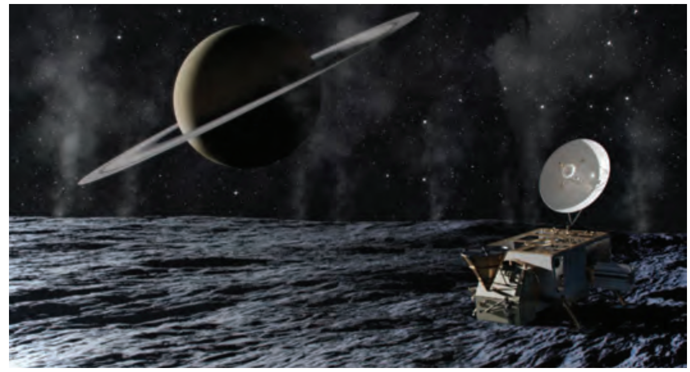
> **"There could be life in our own solar system, and we may already have flown past it."**

Europa Clipper will help confirm the moon's ocean and habitability for life. It is scheduled to launch in October 2024 and settle into orbit around Jupiter in 2030. It will sail past Europa more than 50 times, at distances of as close as 25 kilometers.

At that range, Clipper's magnetometer will provide a far more detailed profile of the ocean. Its radar will measure the thickness of the ice cover and the depth of the ocean. Its imaging systems will map the ice at high resolution, perhaps revealing spots where water is flowing to the surface.

And it will measure how much the crust is flexing in response to tides; models predict a 30-meter daily flexure if there's a subsurface ocean but only about 1 meter if there's nothing but solid ice, Pappalardo said.

Other instruments will search for particles in possible plumes erupting from below the surface. A 2012 observation by the Hubble Space Telescope showed a possible plume of water and ice squirting up to 200 kilometers high. "If we find them, we have the potential to fly through the plumes with the dust collector and mass spectrometer and get down to the heart of what's in that ocean," said Becker.



The proposed Orbilander mission would orbit Enceladus for about a year, then land and sample freshly fallen plume material. Credit: Johns Hopkins University Applied Physics Laboratory

Keeping Contact Between Water and Rock

Hopping through a cold shower like the ones they hope to find on Europa is how scientists discovered the ocean on Enceladus, of course, and future missions with better detectors could provide a far more detailed profile.

"Enceladus is the easy, low-hanging fruit," said Chirayath. "If you get to orbit, you have the ocean brought to you. It could contain bacteria, which you can sample from your comfy orbital home. As for detecting that life, I'm very much of the camp that you'll know it when you see it. It shouldn't be that hard to detect."

The ocean could be 40 kilometers deep, with some spots 20 kilometers deeper, below an ice crust that averages about 20 kilometers thick. As at Europa, the ocean is thought to be in contact with the rocky mantle, which is a key to habitability: The mantle offers the possibility of hydrothermal vents to supply the energy and chemistry for life.

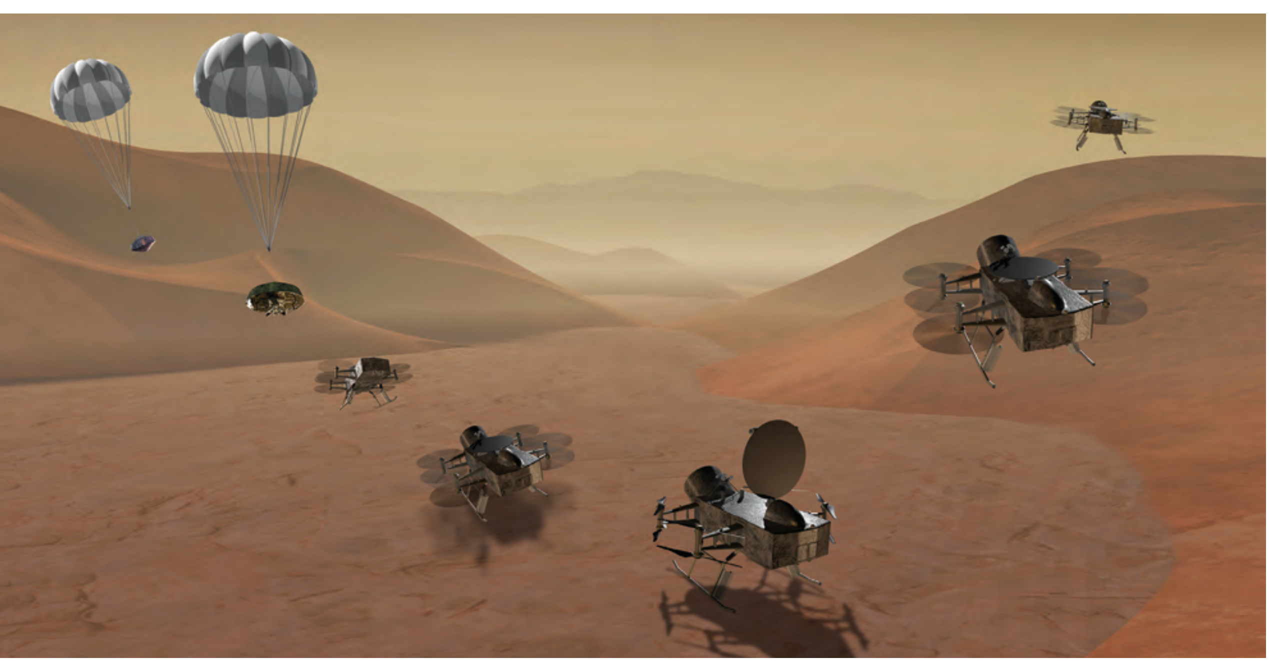
A recent study suggested that the vents could supply phosphorus, a critical ingredient for life on Earth. "Phosphorus has two critical roles," said Christopher Glein, a lead scientist at SwRI and one of the authors of the study. "One is with genetic molecules—it joins the building blocks of DNA and RNA—and one is with energy-bearing molecules—it allows cells to transfer energy through different reactions. As far as we know, phosphorus is essential for life." Glein and colleagues are perusing the Cassini observations to see whether the craft sniffed phosphorus in the plumes.

The 2023–2032 decadal survey for planetary science and astrobiology, an advisory report from the National Academies of Sciences, Engineering, and Medicine that outlined exploration goals for NASA, recommended a flagship mission to Enceladus. Known as Orbilander, it would orbit the moon for about a year, sampling the plumes and mapping possible landing sites. It then would land and sample freshly fallen plume material around "tiger stripes"—the dark cracks from which the plumes emanate.

"The plumes are really, really thin, so we're limited because there's not a lot of stuff in them," Glein said. "But if you can go to the surface and get a big scoopful, now you're in business."

Another high-priority target is Titan, a "double" ocean world, with liquids on, as well as beneath, the surface. Lakes and seas of liquid methane, ethane, and nitrogen dot Titan, the largest moon of Saturn and the only solid body in the solar system other than Earth with liquids on its surface. In addition, scientists suspect Titan has a buried ocean of liquid water mixed with ammonia and other compounds that could be the most massive ocean in the solar system.

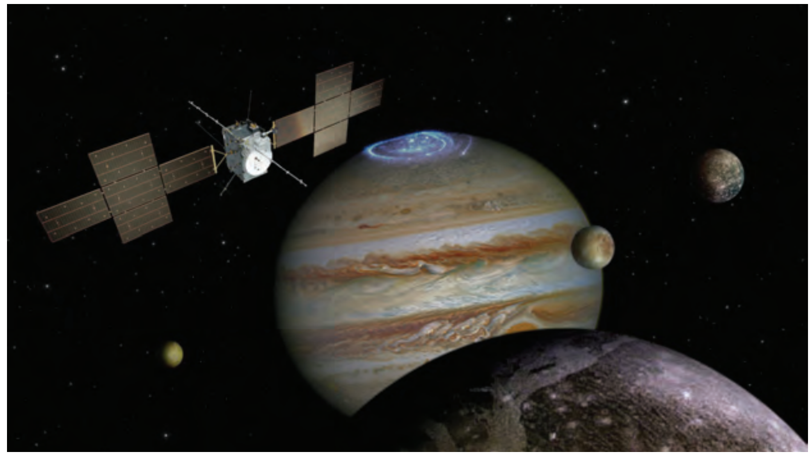
Titan's cold, dense atmosphere consists mainly of nitrogen, with a smattering of methane and smaller amounts of other organic compounds that envelop the moon in an orange



Dragonfly lands on Titan, then cranks up its rotors and heads off to explore its new home in this artist's conception. Credit: NASA "smog." Methane and ethane form clouds, producing rains that carve river channels and fill the lakes and seas.

"Its hydrocarbon seas could be just as hospitable for life as liquid water oceans," said Chirayath, although he noted that Titanian life might not resemble Earth life at all. The deep ocean could provide marginally habitable conditions for Earth-like microbes, and ice volcanoes could carry some of the moon's water to the surface, where future missions might sample it.

NASA already has one Titan explorer on the books. Dragonfly is a quadcopter—a box with rotors at each corner—that's being developed as a New Frontiers mission (the same program as New Horizons, which flew past Pluto). Scheduled for launch in 2027 and arrival in 2034, Dragonfly will photograph the landscape from altitudes of up to 4 kilometers, measure weather conditions, and collect samples for analysis by a mass spectrometer.



The Jupiter Icy Moons Explorer (JUICE) mission launched in April 2023. Credit: ESA

Sandwiches and JUICE at Jupiter

Many of the solar system's other putative ocean worlds will be much harder to penetrate, either because of their distance or because their oceans are less accessible.

The latter is the case for Jupiter's largest moons, Ganymede and Callisto. Evidence has suggested they have extensive oceans, but they're buried quite deep, and there's no obvious way for water to percolate to the surface. "Their ice shells are probably a hundred or more kilometers thick because they don't have as great a degree of tidal heating," said Pappalardo.

In addition, the stronger gravity of both worlds probably helps create "sandwiches" of alternating layers of water and ice, with ice forming the bottom slice of bread. That means the liquid water isn't in contact with rock, so the rocky layers can't inject energy and life-supporting chemical compounds, reducing the moon's habitability.

We should learn much more about both Ganymede and Callisto from the Jupiter Icy Moons Explorer (JUICE), a European mission that launched in April 2023 and is scheduled to arrive at Jupiter in 2031. It will fly past Ganymede, Callisto, and Europa several times before entering orbit around Ganymede in 2034. Among its goals is characterizing the oceans of the two biggest moons.

"We're having conversations with the JUICE scientists on what kinds of synergies there are—how having both [JUICE and Europa Clipper operating] at the same time can contribute to even better science," said Pappalardo.

Some of the moons of the ice giants Uranus and Neptune are good ocean world candidates, but the planets are so remote that each has been visited only once, by Voyager 2, in 1986 and 1989, respectively. The decadal survey recommended visiting both systems again. A Uranus orbiter and probe was its highest-ranked new flagship mission for the next decade, with a mission to Neptune among the priorities for a New Frontiers mission.

One goal of the Uranus mission would be to reconnoiter the system's moons, at least five of which are in the "possible" ocean world category (none of them has been confirmed, though).

"Despite the fact that they are part of a giant planet system, the moons have benefited from little tidal heating throughout their history," said Julie Castillo-Rogez, a planetary scientist at JPL who has a paper about the moons scheduled for publication. "One of the key parameters driving tidal heating is the mass of the planet—the bigger the planet, the bigger the tidal deformation and the resulting tidal dissipation. As Uranus's mass is 7 times smaller than Saturn's mass, tidal dissipation in the moons of Uranus is about 50 times less than dissipation in the moons of Saturn."

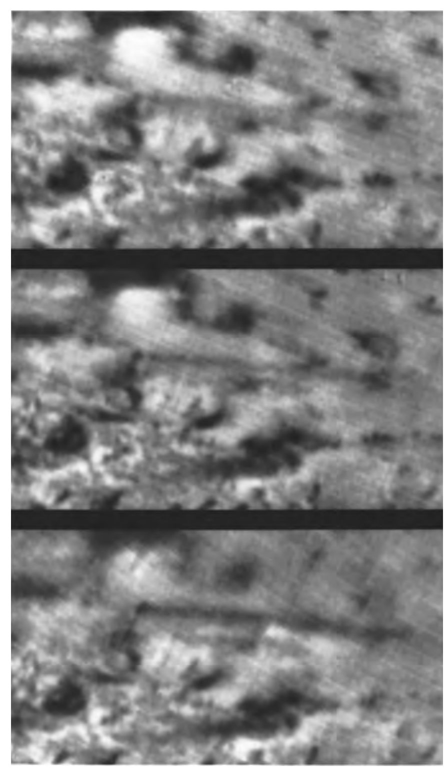
That means that the smaller of the candidates, Miranda, Ariel, and Umbriel, are more likely to be frozen through. But Castillo-Rogez said the two largest moons, Titania and Oberon, should be better able to retain their internal heat. In addition, motions within the mantles of both worlds should pump hot water into the icy layers above. "So there is a high likelihood that these moons would hold deep oceans at present," she said.

Instruments on the Uranus mission would look for evidence of oceans and locations where they might interact with the surface, plot magnetic fields generated by the oceans, and measure the chemistry of the surface and any possible plumes.

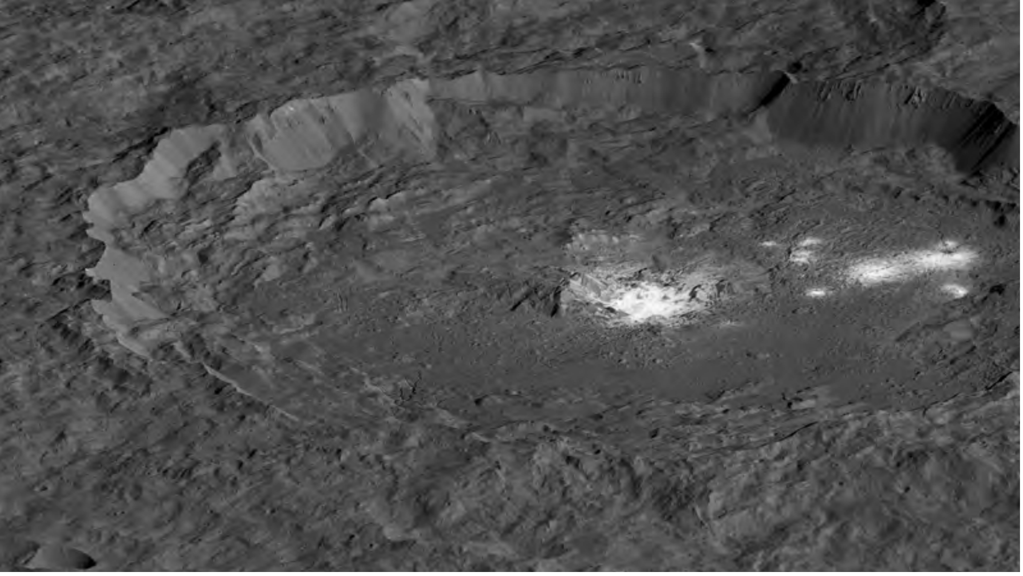
Plumes are among the many intriguing features of Triton, the largest moon of Neptune, which is a high priority for a possible New Frontiers mission.

"Triton is a 'maybe'—it's not a confirmed ocean world," said Hendrix. "But Voyager found tantalizing clues of a subsurface ocean."

Voyager 2's pictures of Triton revealed one of the oddest



These three sequential images, taken 45 minutes apart by NASA's Voyager 2 spacecraft, show an elongated cloud mysteriously disappearing from the surface of Neptune's moon Titan. They could show an erupting ice volcano. Credit: NASA/JPL



Bright deposits of brine, probably burped up from a buried ocean, decorate the floor of Occator crater on the dwarf planet Ceres in this perspective view based on images from NASA's Dawn orbiter. Credit: NASA/JPL-Caltech/UCLA/MPS/DLR/IDA

and most intriguing surfaces in the solar system. It consists of frozen nitrogen, water, and carbon dioxide, and it displays terrains found nowhere else in the solar system. Geysers of frozen nitrogen and other ices, mixed with dark organic compounds, shoot up to 8 kilometers high and deposit surface streaks many kilometers long.

Triton probably has enough internal heat to sustain a habitable subsurface ocean. The organic compounds in the geysers heighten the interest in studying the big moon, which may be a captured dwarf planet.

"I think of ocean worlds as a spectrum. Each one is different, and each one tells us about how oceans form."

Dwarf Planets and Beyond

The dwarf planets Pluto and Ceres also are on the list of possible ocean worlds.

When New Horizons flew past Pluto in 2015, its images revealed a surprisingly active surface. They also revealed cracks and ridges that suggested Pluto began with an ocean of liquid water in contact with the rocky core. The ocean could have been 150 kilometers deep, and although it has partially frozen, it could still exist today. If so, Pluto could have remained habitable for almost the entire history of the solar system.

Verifying that scenario probably requires a follow-up mission. Thanks to Pluto's great distance, however, that mission is not likely to happen for decades. But a much closer dwarf planet, Ceres, is a more inviting target. In fact, the decadal survey recommended a sample return mission as a possible New Frontiers priority.

Ceres is the largest member of the asteroid belt, and scientists obtained a thorough reconnaissance from NASA's Dawn mission, which entered orbit in 2015 and operated until late 2018.

The mission created a sensation as it approached Ceres because its early images showed a brilliant white spot on the otherwise dark disk. As Dawn settled into orbit, it found that the spot and several smaller ones were deposits of salts that probably bubbled to the surface from an ocean.

Ceres is about 25% water. Most of it probably is frozen, although some could still form a subsurface ocean or individual seas.

"Dawn found organics on the surface and active geology—brine-driven activity on the surface," said Hendrix. "That makes it an extremely interesting target. It's not clear what type of ocean it might have, or even if it currently has one. It's definitely not an ocean world like Europa or Enceladus.

"I think of ocean worlds as a spectrum," Hendrix said. "Each one is different, and each one tells us about how oceans form, how they're sustained, how they become habitable, how they remain habitable, and whether they really can sustain life. In my ideal world, we'd have missions to all of them."

It's not surprising that this is a common sentiment among both planetary and marine scientists. Characterizing the oceans of other worlds can tell us much more about how Earth's oceans formed and evolved, reveal details about the formation and evolution of the Sun's entire planetary system, and guide studies of exoplanets and their moons. "Ocean worlds may be the most common habitats in the universe, not for complex life but for simple life," said Pappalardo.

Even finding no life on the solar system's ocean worlds would be an important discovery, scientists said.

"One of the real pivotal reasons to explore these worlds is to get clues to where we came from," said Glein. "If we find life and it's similar to life on Earth, it might make a linkage between hydrothermal systems and the origins of life. But if we find that someplace like Enceladus is a great place to live, with all sorts of nutrients and energy sources and other critical requirements, but there's nothing there but a sterile ocean, then that would be profound.... From an emotional standpoint it would be disappointing, for sure. But scientifically, we'd gain a whole new piece of knowledge. So let's go have a look."

"Ocean worlds in the solar system turn out to be a lot more common than we thought even 20 years ago," said Murray. "What will we know in another 20 years?"

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Damond Benningfield, Science Writer

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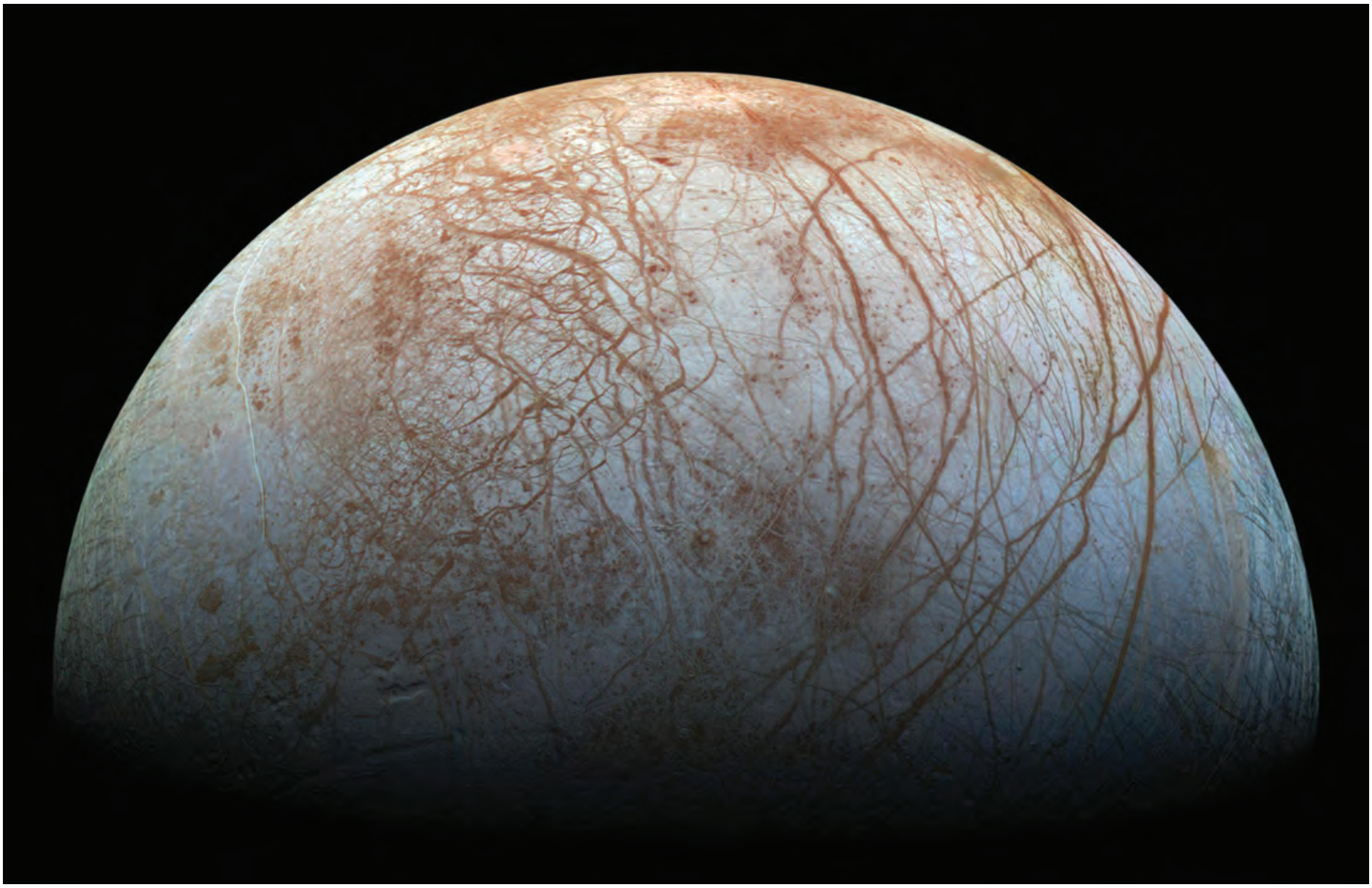
Zipping Up Data to Zap Them Back from an Icy Moon



Icy moons like Europa, seen here in this composite of images taken by the Galileo spacecraft in the 1990s, may support life and are targets for efforts to design instrumentation capable of analyzing biosignatures and transmitting data all the way back to Earth. Credit: NASA/JPL-Caltech/SETI Institute

In the search for life beyond Earth, icy ocean moons like Jupiter's Europa and Saturn's Enceladus are promising possibilities that host potentially habitable environments. Evidence of these environments—and of possible geobiological activity—may be observable at these moons' surfaces because of deposition of subsurface fluids by erupting plumes, in pressurized fractures in ice, or through the convective churning of ice.

Organic molecules in living organisms have unique biochemical signatures that can be instrumentally detected, and NASA is currently designing instrumentation for the Ocean Worlds Life Surveyor (OWLS) suite, which could be used in future missions that will land on and sample ice from the surfaces of Europa and Enceladus.

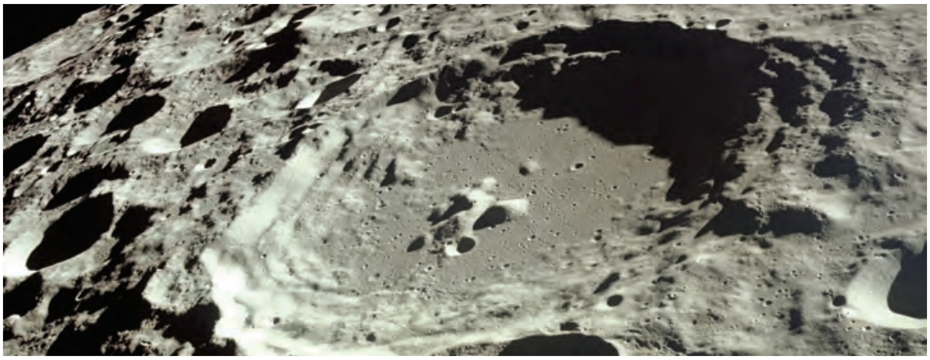
OWLS will include a capillary electrophoresis–mass spectrometry (CE-MS) instrument that can separate, identify, and quantify distinct chemicals as part of sample characterization. All this sampling, analysis, and cataloging produce large amounts of raw data, however, with each CE-MS sample generating 100 or more megabytes. The problem is, How do you transfer all those data from distant moons back to scientists on Earth?

In a new study, *Mauceri et al.* investigate how best to compress and prioritize these data to reduce transmission requirements while keeping the important information from the on-moon instrument intact. To do so, the researchers created onboard software called autonomous capillary electrophoresis mass-spectra examination (ACME).

Using laboratory samples, the team tested how effectively the ACME system could detect signal peaks—corresponding to concentrations of different molecules—within raw CE-MS data. The researchers also simulated how information from the sampling exercise could be compressed and transmitted. They found that ACME could summarize and compress raw data by 2–3 orders of magnitude while preserving the most scientifically relevant information.

The researchers note that ACME can also prioritize which data to transmit by assessing the presence of potentially important compounds in a sample. In the future, these capabilities will help researchers target key areas for sampling and maximize the scientific returns of missions to icy moons. (*Earth and Space Science*, https://doi.org/10.1029/2022EA002247, 2022) **—Sarah Derouin,** *Science Writer*

Decrypting Lunar Craters Quickly and Easily



Apollo 11 astronauts took this photo of the Moon's Daedalus crater in 1969. Credit: NASA

The surface of the Moon tells the story of the inner solar system. Every meteorite that hits leaves its mark, and together those craters hold a record of the events that have occurred on and around the Moon over the past 4 billion years.

But the record can be hard to read. The ages and spatial densities of craters are critical metrics for decoding the Moon's impact history, but analyzing these properties can be time-consuming and sometimes requires bringing samples back to Earth.

Fairweather et al. show that machine learning could be a quick and easy way to improve our understanding of lunar craters. By training an algorithm on more than 50,000 images of previously characterized craters, the researchers were able to estimate the ages and densities of many more of the Moon's multitudinous marks.

At first, the machine learning algorithm's estimates differed substantially from those that other researchers had derived by hand. But with a bit of manual curation, the team brought its automated estimates of crater age and density in line with previous estimates.

Lighting conditions presented one issue. If craters were partially shaded by rocks or located on unevenly lit slopes, the algorithm had trouble analyzing them accurately. Excluding such craters improved the accuracy. The presence of rocks or buried craters also led the algorithm to overestimate crater ages by 10%–45%, but it could determine accurate ages for young lunar surfaces and impact craters once rocks, buried craters, and other unwanted objects were removed from the images.

The researchers caution that although machine learning can provide a wealth of information about the Moon's surface, the algorithms still require careful oversight. (*Earth and Space Science*, https://doi.org/10.1029/2023EA002865, 2023) **—Saima May Sidik,** *Science Writer*

Specious Timescales from Sedimentary Layers

Layers of sedimentary rock are often studied to re-create Earth's history. But rocks aren't always the most reliable historians. New research shows that environmental conditions can substantially affect how—and how fast—sediment accumulates, misleading scientists who are trying to estimate the time periods of events in Earth's past.

Barefoot et al. studied sedimentation rates and patterns by mimicking a natural system using an experimental basin. The researchers simulated floods of various amplitudes and measured how these floods affected sediment accumulation.

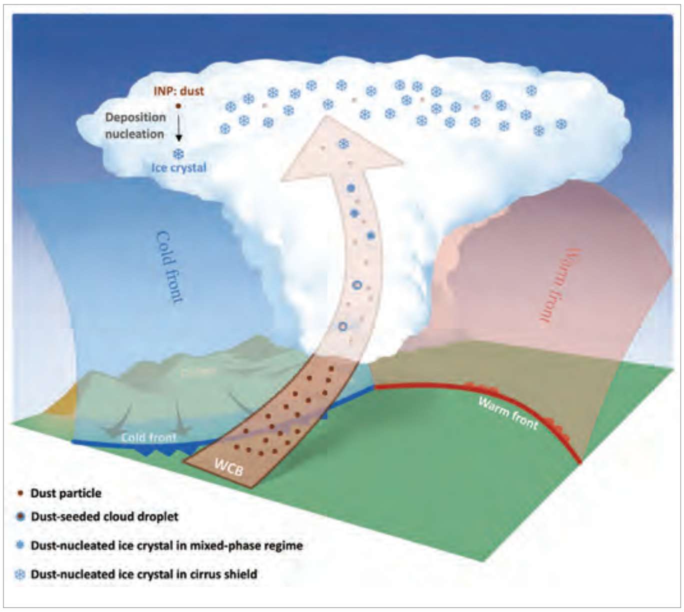
Low-amplitude floods distributed sediment in patterns marked by roughness, with many localized ridges and hills separated by valleys, the researchers found. That meant that when floodwaters rose in a high-amplitude event, there were plenty of topographic nooks and crannies to capture sediment over a broad area, allowing it to build up in a thick, smooth layer. When the opposite transition occurred and low-amplitude floods occurred again, there were only localized rough patches to catch sediment, and the resulting layers were thin.

Many layers of different thicknesses are evident in this stack of sedimentary rocks located at Seiser Alm, a plateau in the Dolomite Mountains of Italy. Credit: Friedrich Haag/Wikimedia Commons, CC BY-SA 4.0 (bit.ly/ccbysa4-

These depositional differences—localized versus widespread, thick versus thin—can be obscured when scientists later look at portions of the resulting sediment stratigraphy, leading to misinterpretations of the timing and duration of deposition for given layers. During a transition to a high-amplitude flood regime, for example, assuming linear sediment accumulation rates could result in overestimates of depositional duration by up to 30%, the scientists report.

Processes and feedbacks other than those studied here also affect how sediments are deposited and preserved. But, the researchers say, this work represents a step toward more accurately quantifying measurements of time gleaned from stratigraphic records. (*Geophysical Research Letters*, https://doi.org/10.1029/2023GL103925, 2023) **—Saima May Sidik,** *Science Writer*

How Kicked-Up Dust Forms Cirrus Clouds



High-altitude ice particles, some of which crystallize around storm-lofted dust, form cirrus clouds. Credit: Zeng et al., 2023

Cirrus clouds are high-altitude (8- to 17-kilometer) clouds composed of ice particles. These clouds significantly affect Earth's climate by scattering incoming sunlight and absorbing the planet's emitted infrared radiation. In a new study, *Zeng et al.* discovered new details about how these wispy, hairlike clouds form in large storm systems.

Ice forms cirrus clouds in two ways. In homogeneous nucleation, drops of liquid water spontaneously freeze when they encounter appropriate conditions. In heterogeneous nucleation, a secondary particle, such as a mote of dust, provides a site around which the ice crystal forms. The heterogeneous pathway operates in a wider range of conditions, but it requires the presence of adequate debris.

In the past, researchers thought that ice crystals in cirrus clouds formed mostly through homogeneous nucleation because of low temperatures and the lack of ice-nucleating particles at high altitudes. In the new study, the scientists suggest that heterogeneous nucleation may play a larger role than previously appreciated.

The researchers tested the role that dust-infused baroclinic storms (DIBS) play in cirrus cloud formation. These strong storms lift dust particles from Earth's surface into the atmosphere through warm conveyor belts. Prior research using satellite data revealed that cloud tops of DIBS have unusual, cirrus-like properties. In the new study, the scientists used satellite data and modeling to show that extremely high ice crystal concentrations in DIBS cirrus clouds are formed through heterogeneous freezing.

The study drew on data from a May 2017 DIBS event in East Asia recorded by four separate weather satellites. The imaging, spectroscopic, radar, and lidar data indicated that the 2017 storm produced extremely high ice particle concentrations of 1–10 particles per cubic centimeter, with particle sizes in the range of 10–30 micrometers.

These data were used in the Weather Research and Forecasting model coupled to chemistry. The authors ran the model in two configurations: one simple model that depended only on temperature and a second, more complex model that included additional factors like the surface area of nucleating particles.

They found that the more sophisticated parameterization matched cloud observations more closely than the simple model: The new, more complex model yielded ice particle concentrations that were 10–100 times higher and particle sizes that were 2–3 times smaller. These findings indicate that ice crystals in DIBS are formed through heterogeneous nucleation of dust particles, the authors say, and point to a mechanism of cirrus cloud formation in DIBS that should be incorporated into future climate models. (*Journal of Geophysical Research: Atmospheres*, https://doi.org/10.1029/2022JD038034, 2023) **—Morgan Rehnberg**, *Science Writer*

Climate Change Is Drying Out Earth's Soils

When soil moisture is low, evaporation is limited. The conditions of this moisture-limited regime can exacerbate extreme weather events, including droughts and heat waves. In a new study, *Hsu and Dirmeyer* quantify how global warming affects soil moisture. Although climate change will dehydrate soil, they found, it is not clear how dry is too dry.

The team examined several Coupled Model Intercomparison Project Phase 6 (CMIP6) climate models and found that if carbon dioxide increased by 1% every year, after about 125 years, soils would dry and the world would become much more moisture limited. Still, the models disagreed on the threshold at which Earth would become a more moisture-limited system—a value called critical soil moisture. That threshold depends on myriad factors both on land and in the atmosphere.

Water Resources Mission Area, USGS

Critical soil moisture has wide-ranging effects on the water cycle, climate, ecosystems, and society. Getting a solid grasp on that value would improve climate models and paint a fuller picture of Earth's future. (*Earth's Future*, https://doi.org/10.1029/2023EF003511, 2023) **—Rachel Fritts**, *Science Writer*

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R Y E K R I M T Y U A E C I V G C V N Y C W G L O B N A O H
S Y O X L V H R V K Y G E L C F Z A E U O I O C S P L Q U T
Y O R N T E F K Z O S F E O Z G L B O H S V E I Q O V Z H M
S X C O C E A N O G R A P H Y W O E W J E A W N O H S C G S
T Z P S S I B U R O I H G L T R F C Z C N L Q Y C P Y C D N
E O F G Y T A Z Z D J A Y F P X A E I W C X H G A E E Z D Y
M N Q Y H I X Z R J N U M D D L A P O R U E P C K E L J C C
Z I I L O E V H H Y W N O N L R J R Y Y I O E W G N B M V D
B X N E F X K H M B R Y R I T Q L X H Z T C R O W C A E N H
D G X M V E D E W S C G S H E D W W S P R M E E Z E T Q P H
V O O U P O D D O Z P T R M S O L K F A T C Z Z C L I N K P
F X K N U E T O B X O L U V O D I L F F B R Y E Z A B Q P U
E N I V B J L J S E V F J Y I C S T G F I I E D K D A N M W
H W U U L F N J C D M S D G D Y P W W D F O Q G T U H T Z R
I C E S H E E T S B Y P V J E K O M K O G E N C D S J P I A
Z C R Y U X Y Z K E V I N K A U S S N E R B B I E W L J R C

UNION
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GEOSCIENCES ASSISTANT PROFESSOR IN ENVIRONMENTAL CHANGE (FALL '24)

The Geosciences Department at Union College invites applicants for a **tenure-track position at the assistant professor level** beginning **Fall 2024**. We seek an outstanding geoscience scholar and teacher who will establish an innovative research program motivated by environmental change with clear societal relevance. Potential areas of research could include, but are not limited to, atmospheric sciences and extreme weather, cryosphere dynamics, coastal processes and hazards, alternative energy resources, or urban and built environments. Research may involve field work, laboratory analyses, experimentation, interpretation of large data sets, and/or computer modeling. We are especially interested in candidates who are enthusiastic about providing undergraduate research opportunities, mentoring of students, and cultivating a diverse learning community. The successful candidate will offer an introductory Geoscience course accessible to both majors and non-majors (thereby contributing to the new general education curriculum: https://www.union.edu/common-curriculum/general-education-union) and two upper-level classes (all classes with lab sections) that complement our existing areas of expertise (**see** https://www.union.edu/geosciences). The position is within the Department of Geosciences, but may also contribute to our programs in Environmental Science, Policy, and Engineering, and a new major in Environmental Engineering.

The Department of Geosciences at Union College is committed to teaching and mentoring students in the classroom and in our active research programs. The Department is well equipped for the analysis of water, rock, and sediment and is home to LA-ICP-MS, stable isotope, ion chromatography, and sediment core laboratories, as well as shared analytical facilities within the sciences (including, SEM, HPLC, and XRD) available for research and teaching (see https://www.union.edu/geosciences/geology-equipment). The College is situated in close proximity to both the Adirondack and Catskill Mountains (see https://muse.union.edu/adirondack/), the Mohawk River, numerous lakes, and urban and suburban areas. This provides a fascinating and diverse regional geology that drives vibrant field research and teaching.

Union College is a small, highly selective liberal arts college with strengths in science and engineering located in Schenectady, NY, a culturally rich and economically diverse city in New York State's Capital Region within three hours from New York City, Boston, and Montreal. The salary for this position will be $80,000-82,000, commensurate with experience. Union offers an exceptional benefits package that includes medical, dental, vision insurance, life and disability coverage, and generous retirement and tuition benefit packages. For more information, please visit our website: **https://www.union.edu/human-resources/benefits**.

Union College is an equal opportunity employer and strongly committed to student and workforce diversity. Increasing diversity on campus is a critical priority for Union College, one that is integral to our mission of preparing students for a globally interconnected world. We strongly encourage applications from members of traditionally underrepresented groups. We value and are committed to a host of diverse populations and cultures including, but not limited to, those based on race, religion, disability, ethnicity, sexual orientation, gender, gender identity, national origin, and veteran status. Our goal is not only to increase diversity but also to support a diverse environment in which people from varied backgrounds can succeed and thrive. We expect all faculty members to contribute to a thriving, diverse, and inclusive learning community, while promoting a sense of belonging among students, other faculty, and staff colleagues.

All candidates must have a Ph.D. degree (or equivalent) in a geoscience-related field. Successful candidates will demonstrate the potential to develop an independent research program, as evidenced by scholarship and productivity during graduate and/or postdoctoral activities. Preference will also be given to those who have a demonstrated interest in undergraduate research and teaching. Successful candidates will detail an interest, understanding, and commitment to advancing diversity, equity and inclusion – with preference for a demonstrated ability to contribute to inclusion of groups that are underrepresented in the geosciences through education, research, and/or service.

Interested candidates should submit the following via our portal at **http://jobs.union.edu**. We will begin review of applications on Sept. 20, 2023 and will continue until the position is filled, the application portal will close **Oct. 20, 2023**. Please submit the following with your application: 1) Cover letter, 2) CV, 3) Statement of research experience and interests, 4) Statement of teaching philosophy, experience, and the proposed upper-level courses that complement our existing courses, and 5) Statement of contributions to diversity, equity, and inclusion. You will be asked to include names and contact information for three references through our online application system at **jobs.union.edu**. An email will be sent automatically to references requesting a letter of recommendation. For additional information or questions please contact D.P. Gillikin at **geologychair@union.edu**

PRINCETON UNIVERSITY

POSTDOCTORAL RESEARCH ASSOCIATE IN OCEAN BIOGEOCHEMICAL MODELING

The Atmospheric and Oceanic Sciences Program at Princeton University, in association with NOAA's Geophysical Fluid Dynamics Laboratory (GFDL), seeks **postdoctoral research associate** to work in the area of ocean and benthic biogeochemical modeling and marine carbon dioxide removal (mCDR).

The seafloor serves as the only long-term storage of oceanic carbon, and consideration of the exchanges between the water column and benthic sediments is a major knowledge gap in understanding carbon cycling near coasts and continental shelves, as well as the durability of proposed mCDR solutions. This work will be conducted as part of a large and exciting collaboration with researchers at Northeastern University, University of Maryland, University of Maine, Rutgers University, and University of Connecticut, and will focus on the role of benthic biogeochemical cycles and benthic food web on two mCDR strategies: kelp aquaculture and cessation of trawling. Work will consist of the development of a simple benthic biogeochemical model that can be coupled to the GFDL Carbon, Ocean Biogeochemistry, and Lower Trophics (COBALT) model, and experiments in a range of domains (1-dimensional to global) assessing the benthic-pelagic coupling on the ocean carbon cycle. The incumbent will work with an active group at Princeton and GFDL studying the connections between biogeochemistry, ecosystems, and climate (**https://www.gfdl.noaa.gov/marine-ecosystems/**).

A Ph.D. is required in either oceanography, biogeochemistry, computational earth system science, or related field. Candidates with interest in or experience in ocean biogeochemical modeling, particularly model development, are especially encouraged to apply. Initial appointment is for one year with the possibility of renewal for one additional year subject to satisfactory performance and funding.

Complete applications, including a cover letter, CV with a list of publications, a statement of research interests (no more than 2 pages including references), and contact information of 3 references should be submitted by **September 5, 2023 11:59 EST** for full consideration, though evaluation will be ongoing. Princeton is interested in candidates who, through their research, will contribute to the diversity and excellence of the academic community. Applicants should apply online at **https://www.princeton.edu/acad-positions/position/31281**.

For more information about the project and application process, please contact Jessica Luo (**jessica.luo@noaa.gov**) or Charlie Stock (**charles.stock@noaa.gov**).

This position is subject to Princeton University's background check policy. Princeton University is an equal opportunity/affirmative action employer and all qualified applicants will receive consideration for employment without regard to age, race, color, religion, sex, sexual orientation, gender identity or expression, national origin, disability status, protected veteran status, or any other characteristic protected by law.

PRINCETON UNIVERSITY

POSTDOCTORAL RESEARCH ASSOCIATE - HEAT AND HEALTH APPLICATIONS OF STATISTICAL DOWNSCALING

Princeton University's Atmospheric and Oceanic (AOS) Sciences Program, in cooperation with NOAA's Geophysical Fluid Dynamics Laboratory (GFDL), the National Integrated Heat Health Information System (NIHHIS) [heat.gov], and the NOAA/NESDIS/National Centers for Environmental Information (NCEI) Regional Climate Services Program-Eastern Region, seeks applications for **a postdoctoral or more senior research scientist** to conduct research to advance the development and delivery of place-based climate information products and services that help NOAA's health sector stakeholders (e.g., public health agencies, epidemiologists) make science-informed decisions.

The health impacts of rising temperatures in a changing climate are expected to be many, including greater incidence of heat-related illnesses, water- and vector-borne diseases, reduced food security, and mental health impacts (National Climate Assessment, 2018)[1]. This opportunity seeks applicants with a strong interest in the application of climate science and CMIP6 climate model output to understand these impacts and potential solutions. Candidates who have, and are interested in further developing, skills in applying actionable science that transfers knowledge gained from climate models to applied researchers and decision makers are encouraged to apply. A Ph.D. in physical geography, statistics/biostatistics, environmental, climate, atmospheric, physical sciences is required. Candidates should be skilled in the application of statistical methods, including uncertainty analysis, and be familiar with North American climate and the application of climate science to practitioners. We expect the post-doc to engage regularly with governmental and non-governmental colleagues and stakeholders, and to co-produce climate model output aligned with health sector needs. Programming skills in R or Python are required, as are strong communication skills. Other beneficial experiences include prior work with downscaled multi-decadal climate projections and/or machine learning methods, and interdisciplinary experience bridging climate science with public health or other policy-relevant applications. This is a full-time, term-limited position for one year with the possibility of renewal subject to performance and available funding, for a maximum of three years.

This position is based at NOAA GFDL/Princeton University. The successful candidate's project will be primarily coordinated with GFDL's Statistical Downscaling team, with continuous interdisciplinary dialog among colleagues. Project specifics will be determined by the candidate's experience and alignment of project goals with NOAA priorities. For additional information on potential projects and the project team, visit **www.gfdl.noaa.gov/heat-and-health-downscaling** or contact Keith Dixon (**keith.dixon@noaa.gov**), Ellen Mecray (**Ellen.L.Mecray@noaa.gov**) and Hunter Jones (**hunter.jones@noaa.gov**).

Applicants should apply online at **https://www.princeton.edu/acad-positions/position/31521**. Complete applications include a cover letter, CV, publication list, and 3 letters of recommendation. Applications should be accompanied by a statement of research interests outlining the candidate's vision for a research topic using statistically downscaled climate projections to respond to the needs of the heat and human health sector, including the assessment and communication of uncertainties across disciplines. Application deadline is **October 15, 2023, 11:59 pm EST**. Review of applications will begin immediately and continue until the position is filled. Princeton is interested in candidates who, through their research, will contribute to the diversity and excellence of the academic community. This position is subject to Princeton University's background check policy.

Princeton University is an equal opportunity/affirmative action employer, and all qualified applicants will receive consideration for employment without regard to age, race, color, religion, sex, sexual orientation, gender identity or expression, national origin, disability status, protected veteran status, or any other characteristic protected by law.

[1]USGCRP, 2018: Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II [Reidmiller, D.R., C.W. Avery, D.R. Easterling, K.E. Kunkel, K.L.M. Lewis, T.K. Maycock, and B.C. Stewart (eds.)]. U.S. Global Change Research Program, Washington, DC, USA, 1515 pp. doi: 10.7930/NCA4.2018.

U.S. NAVAL RESEARCH LABORATORY

YOU are the Future of Ocean Prediction

OCEAN DYNAMICS AND PREDICTION BRANCH

Who are we?

Researchers seeking to understand and represent the fundamental dynamics of the ocean with the long-term goal to transition prediction systems for operational use.

Where are we?

U.S. Naval Research Laboratory located at Stennis Space Center, MS

What positions are available?

- **Postdoctoral Fellowships** – Annual 2023 salary is $79,363. Renewable up to 3 years. *Benefits: Medical, Dental, Vision, Life.*
- **Permanent Researchers** – Annual salary for full time federal civilian positions ranges from $80,000 to $150,000, commensurate with experience. *Benefits: Medical, Dental, Vision, Life, Pension, Retirement*.
- **Variable work schedules with partial telework options** (No remote work)
- **Student opportunities also available**
- NRL is an equal opportunity employer

Who are we looking for?

People with knowledge in any of oceanography, meteorology, computer science, mathematics, and related fields. Skills in any of ocean modeling, data analysis, computer programming, and data assimilation.

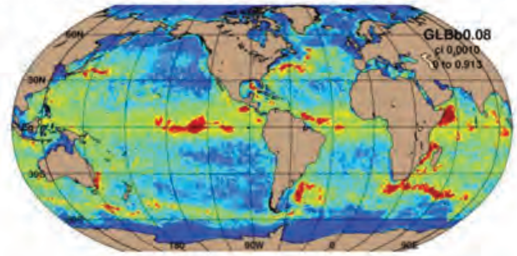
Interested? Contact us

Send your resume or any questions to:
7320jobs@nrlssc.navy.mil

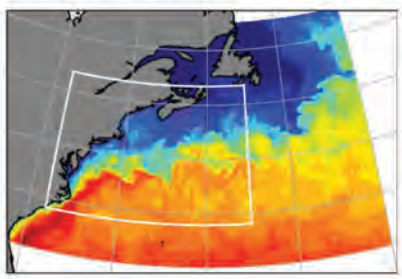
Scan or click QR code for information on research areas, publications, and available opportunities.

The Ocean Dynamics and Prediction Branch at the Naval Research Laboratory located at Stennis Space Center, MS has immediate positions available for postdoctoral and permanent researchers.

Our research areas include:



- Thermohaline circulation
- Ocean dynamics
- Surface wave prediction
- Air-sea interactions
- Nearshore hydrodynamics
- Marginal sea upwelling
- High latitude ocean dynamics
- Arctic sea ice modeling
- Turbulence modeling
- Mesoscale dynamics
- Submesoscale structures
- Submesoscale eddy dynamics
- High resolution coastal modeling
- Frontal processes
- Predicting small scale features
- Probabilistic prediction
- High performance computing
- MPI computational coding
- Ocean internal wave modeling
- Coupled ocean/acoustics
- Nearshore hydrodynamics
- Cryosphere forecasting
- Automated unmanned control systems
- Autonomous controlled systems
- Satellite observations
- In situ observations
- Data assimilation
- Covariance modeling in assimilation
- Variational assimilation



For information on projects, publications, and research opportunities, use QR code in the bottom left or go to www7320.nrlssc.navy.mil

More About Us

We collaborate with researchers across the globe from government agencies to academia, and the research results are published in peer reviewed journal articles. The research and development at NRL require close collaborations between interdisciplinary scientists.

With access to major high-performance computing resources, we utilized over 300 million CPU hours in the last year. Research results transition to operational systems at ocean forecast centers and are used in daily decisions covering a broad range of applications around the globe. This is an opportunity to work with the nation's largest group of dedicated ocean prediction researchers. The work involves building numerical systems that forecast ocean dynamics, developing techniques to process satellite and in situ information, and assimilating observations into numerical models.

Be part of the future of ocean prediction.

Email us at 7320jobs@nrlssc.navy.mil

UNIVERSITY OF GEORGIA
Warnell School of Forestry & Natural Resources

Position Announcement
Assistant Professor of Hydrology

POSITION AND RESPONSIBILITIES: This is a 9-month (0.75 EFT), tenure track appointment with 45% research, 50% teaching, and 5% service responsibilities at the Assistant Professor level in the Warnell School of Forestry and Natural Resources at the University of Georgia. The selected candidate will be expected to develop a broad and inter-disciplinary research program in hydrology and water resources. Research interests may include hillslope processes, ecohydrology, water quality, or anthropogenic effects on aquatic systems (e.g., climate and land-use changes, reservoir operations, sediment transport and channel dynamics, stream and wetland modification and restoration, groundwater extraction). We seek a candidate interested in multi-disciplinary research working with other faculty across a range of disciplines including soil science, ecology, civil and environmental engineering, forest ecophysiology, aquatic science, geology, geomorphology, marine sciences, landscape architecture, and environmental law and policy. Aquatic scientists at UGA often collaborate through the River Basin Center and the Institute for Resilient Infrastructure Systems. The candidate would also contribute to the University of Georgia's Water Resources Program that offers both undergraduate and graduate certificates in Water Resources. The selected candidate will mentor graduate students, serve on School and University committees, and actively participate in professional scientific societies. The selected candidate will normally teach three courses each academic year. The candidate is expected to teach a) a Junior-level class in Soils and Hydrology, b) a split-level (graduate and upper-division undergraduate) course in advanced hydrology, and c) a graduate-level course of their design. Other teaching responsibilities will depend on the selected candidate's interests and areas of expertise.

QUALIFICATIONS: Applicants must have a Ph.D. in an area of hydrology or water resources or related field. Strengths in oral and written communication must be evident, for example through conference presentations and publication record in peer-reviewed journals. Evidence of activity in research design and grant development is preferred. Demonstrated multidisciplinary collaborative work is preferred with expectations for similar continued efforts with faculty in Warnell and across the University. Evidence of teaching activities and excellence in teaching is preferred.

THE STATE & UNIVERSITY: Georgia is well-known for its quality of life, both in terms of outdoor and urban activities (www.georgia.gov). The University of Georgia (www.uga.edu) is a land/sea/space grant institution comprised of 17 schools and colleges. Athens is a diverse community of approximately 150,000 people located less than 75 miles from Atlanta. UGA enrolls about 38,500 undergraduate, graduate, and professional students. The Warnell School is a professional school with 64 faculty, 100 support staff, 325 undergraduates, and 195 graduate students (www.warnell.uga.edu). The School offers Bachelor of Science, Master of Forest Resources, Master of Natural Resources, Master of Science, and Doctor of Philosophy degrees in the areas of Forestry, Fisheries & Wildlife, Parks, Recreation & Tourism Management, and Natural Resource Management & Sustainability. The school manages 23,000 acres of forestland across the state in support of its teaching, outreach, and research missions.

Assistant Professor of Earth Sciences, Geochemistry - Dartmouth College

The Department of Earth Sciences at Dartmouth College invites applications for a full-time tenure track position at the rank of Assistant Professor in the general area of geochemistry. We are particularly interested in low temperature geochemists and biogeochemists with research in the broad area of modern surface processes and/or land-water interactions. We will prioritize applicants who focus on understanding fundamental processes with a state-of-the-art laboratory, modeling, and/or field research program, provide synergy with existing research activities at Dartmouth, and actively support the Department's commitment to promoting diversity.

As the person in this position will continue Dartmouth's strong traditions in graduate and undergraduate research and teaching, effective classroom teaching is essential for this position. Teaching responsibilities consist of three courses spread over four ten-week terms. The teaching assignment for this position includes a course on low temperature aqueous geochemistry. To create an atmosphere supportive of research, Dartmouth offers faculty members grants for research-related expenses, a quarter of sabbatical leave for each three academic years in residence, and flexible scheduling of teaching responsibilities. The Department of Earth Sciences is home to 13 faculty members in the Faculty of Arts and Sciences and enjoys excellent graduate (Ph.D. and M.S.) and undergraduate programs. We are especially interested in applicants who have a demonstrated ability to contribute to Dartmouth's diversity initiatives in STEM research, such as the Women in Science Program, E.E. Just STEM Scholars Program, and the Academic Summer Undergraduate Research Experience (ASURE). Beyond our department, our graduate students and postdoctoral scholars are supported by the Guarini School for Graduate and Advanced Studies, including their diversity and inclusion initiatives

The Department of Earth Sciences and Dartmouth are committed to fostering a diverse, equitable, and inclusive population of students, faculty, and staff. Dartmouth recently launched a new initiative, Toward Equity, that embraces shared definitions of diversity, equity, inclusion, and belonging as a foundation for our success in institutional transformation. The specific efforts of the Earth Sciences department are highlighted on our website. We are especially interested in applicants who are able to work effectively with students, faculty, and staff from all backgrounds and with different identities and attributes. Applicants should provide a statement addressing how their teaching, research, service, and/or life experiences prepare them to advance Dartmouth's commitment to diversity, equity, and inclusion. This statement will be evaluated as part of the selection process.

Qualifications: Applicants should have a PhD in Earth Sciences, Geology, or a closely related field, or be ABD with degree received before the start of the appointment. Effective classroom teaching is essential for this position.

Application Instructions: Please submit all materials electronically via Interfolio: http://apply.interfolio.com/130093

1. Cover letter
2. Curriculum vitae, including contact information for three references
3. Statement of teaching experience and interests
4. Statement of research interests and objectives
5. Statement addressing how the applicant's teaching, research, service, and/or life experiences prepare them to advance Dartmouth's commitment to diversity, equity, and inclusion
6. Writing samples: reprints or preprints of up to three (3) of your most significant publications

Review of applications will begin on October 1, 2023 and continue until the position is filled.

Equal Employment Opportunity Statement: Dartmouth College is an equal opportunity/affirmative action employer with a strong commitment to diversity and inclusion. We prohibit discrimination on the basis of sex, race, color, religion, age, disability, status as a veteran, national or ethnic origin, sexual orientation, gender identity, gender expression, or any other category protected by applicable law, in the administration of its educational policies, admission policies, scholarship and loan programs, employment, or other school administered programs. Applications by members of all underrepresented groups are encouraged.

If you are an applicant with a disability and need accommodations to assist in the job application or interview process, please email ADA.Institutional.Diversity.and.Equity@Dartmouth.edu. In the subject line, please state "Application Accommodations" and include the job number r title. Someone from the ADA Compliance Office will be in touch within 2 business days.

For additional employment opportunities at Dartmouth College, please visit the Dartmouth Interfolio Job Board, the Office of the Provost, and the Office of Human Resources.

Offers of employment are contingent upon consent to a pre-employment background check with results acceptable under Dartmouth policy. Please visit the Office of Human Resources for details.

All Dartmouth College employees, whether working on-site or remotely, must be fully vaccinated against COVID-19 or receive an approved medical or religious exemption from vaccination through Dartmouth's Division of Institutional Diversity and Equity (IDE). Compliance with the Dartmouth COVID-19 Employee and Appointee Vaccination Policy is a condition of employment, and every offer of employment is contingent upon submission of appropriate documentation evidencing either vaccination against COVID-19, or the receipt of an approved exemption. Failure to meet this condition of employment may result in Dartmouth, in its sole discretion, delaying employment or rescinding its offer of employment.
Visit https://dartgo.org/vaxpolicyto review the Policy and for details and information on requesting an exemption and/or reasonable accommodation.

Word Search: Ocean Worlds

T V S E R E H P S O Y R C W E B D G Z Z J A X X Y N D C S Z
R O I D C A G I I H C P H Q Z D I K M V M F Q L M Y X C K T
L T E A R T H O W H Q K F D J V Z T F G R W B F T F J W Q M
M P L Z C Q M R O K Q O F G F B D C S H W F J B R E T A W H
W G N D Z X A B Q E P R G K M Y K J V U L W S F N F X E Q V
J O E N J B S H W Z N L R A C G K I M Q C N S A W C Q G A G
V S R O H R Q M I F O V A W E C S F C Y A W I D Y F O J P P
I V P L L Y O F D D M R X N R Z P M I E B G L N W K V R K F
E C C K D P R U S Q M J K W E G K U C C C Q P A R O Q C L S
L A U N D H G J O H Z V P T T T V O A S P Z T I K L L T E D
S U S D Q R E E E E R I U P I R A S Q O H F L V F V L O H E
O H T N Q O R R O I P L S J B U E R G S G P O O G U N N Q K
L N P B O F D K I G B W C E R U R G Y M X I P J H A N P Y C
A Q K M M O A T C T H Z V F O L I A A S N G H P C M C U K T
R Y E K R I M T Y U A E C I V G C V N Y C W G L O B N A O H
S Y O X L V H R V K Y G E L C F Z A E U O I O C S P L Q U T
Y O R N T E F K Z O S F E O Z G L B O H S V E I Q O V Z H M
S X C O C E A N O G R A P H Y W O E W J E A W N O H S C G S
T Z P S S I B U R O I H G L T R F C Z C N L Q Y C P Y C D N
E O F G Y T A Z Z D J A Y F P X A E I W C X H G A E E Z D Y
M N Q Y H I X Z R J N U M D D L A P O R U E P C K E L J C C
Z I I L O E V H H Y W N O N L R J R Y Y I O E W G N B M V D
B X N E F X K H M B R Y R I T Q L X H Z T C R O W C A E N H
D G X M V E D E W S C G S H E D W W S P R M E E Z E T Q P H
V O O U P O D D O Z P T R M S O L K F A T C Z Z C L I N K P
F X K N U E T O B X O L U V O D I L F F B R Y E Z A B Q P U
E N I V B J L J S E V F J Y I C S T G F I I E D K D A N M W
H W U U L F N J C D M S D G D Y P W W D F O Q G T U H T Z R
I C E S H E E T S B Y P V J E K O M K O G E N C D S J P I A
Z C R Y U X Y Z K E V I N K A U S S N E R B B I E W L J R C

Search up, down, forward, backward, and on the diagonal in the grid above to locate the words listed below.

Callisto
cryosphere
Earth
Enceladus
Europa
Ganymede
habitable
ice sheets
ice volcanoes
Jovian
life
moons
oceans
ocean worlds
oceanography
orbiter
planetary science
probe
solar system
spacecraft
Uranus
Voyager
water
world heritage

See p. 40 for the answer key.

PICARRO

Hero Award *Winner*

Recognizing the World-Changing Work of Scientists Using Picarro Analyzers

Ido Rog

Using bioengineering to improve soil health and enable sustainable agriculture

Ido Rog of the University of Zurich and Agroscope in Switzerland, and the Weizmann Institute of Science in Israel has made many discoveries related to carbon regulation of plants, trees, and forests using Picarro analyzers.

In addition to his ecophysiological research, he worked with underprivileged communities to develop sustainable agricultural practices.

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Learn more about Ido's work, visit:
https://info.picarro.com/hero-ido-rog

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