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Eos

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Magnetic Fields and Iron Snow

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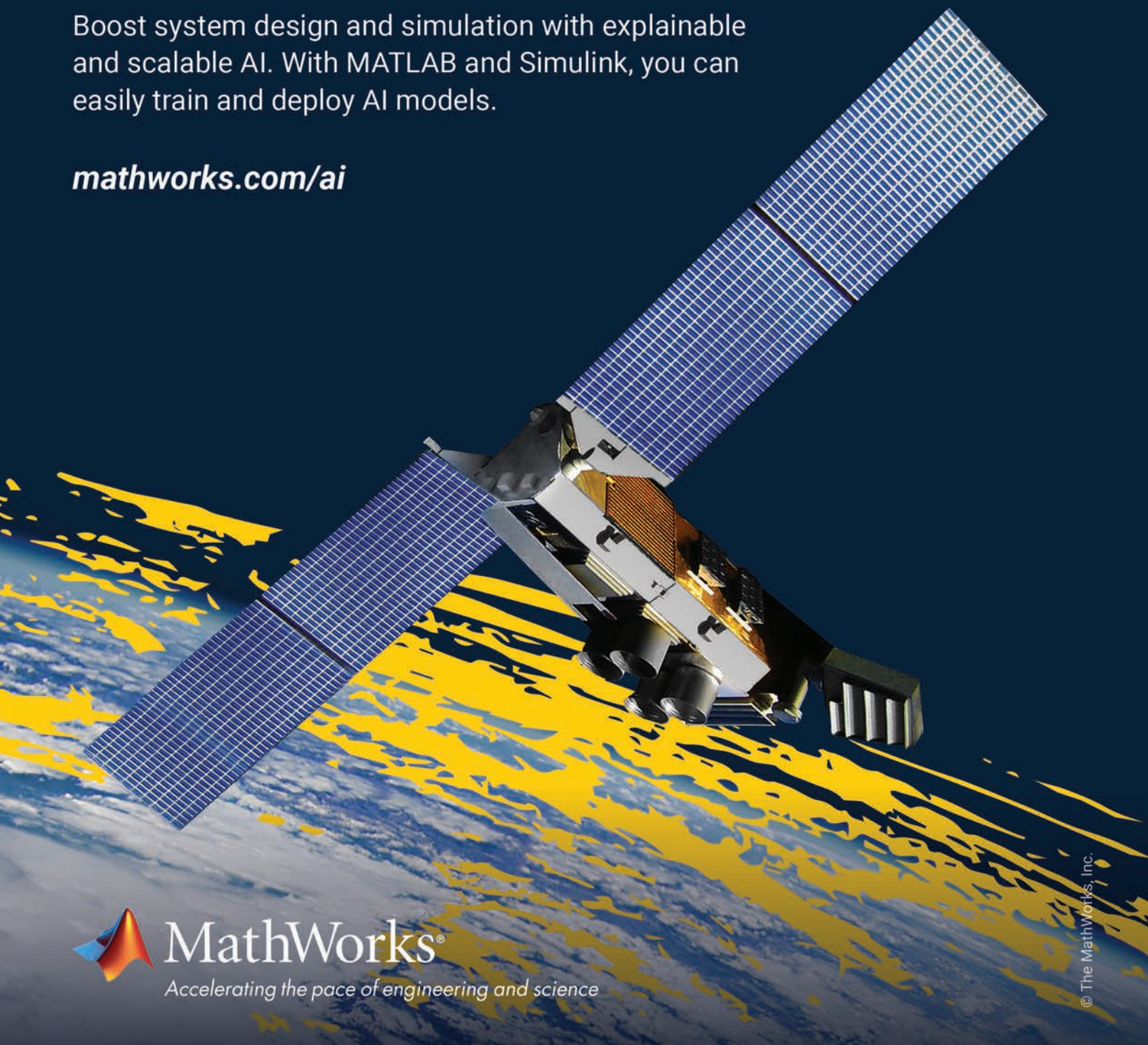

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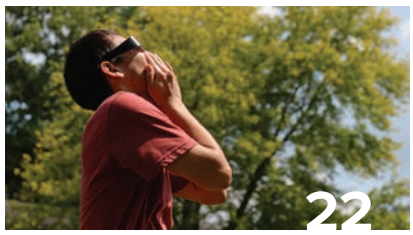
From the Editor

On 8 April, a total solar eclipse will cross North America from sea to shining sea—from Mexico's Pacific coast to Canada's Atlantic Maritimes. Scientists and skywatching enthusiasts are ready for the event with projects and programs to follow the Moon's shadow—and you can follow them with Katherine Kornei's "Eclipse Science Along the Path of Totality." But you don't need to be a researcher to be starstruck by the spectacle, as Kate Evans explains in "The Small Self and the Vast Universe: Eclipses and the Science of Awe." If you're in North America, grab *Eos* and a pair of eclipse-viewing glasses. If you're too far away to view this eclipse, visit Eos.org, and scan your social feeds for surprise and delight.



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Janice Lachance, Interim Executive Director/CEO

Olivine May Have Given Life a Jump Start

Olivine can form as the gemstone peridot, but it's anything but preciously rare. On Earth, it's the most abundant mineral in the upper mantle and a main component of the basalt rocks that form oceanic crust. Beyond Earth, scientists have found olivine everywhere from Mars, where it's been spotted by rovers, to asteroids. It's even present in cosmic dust.

Now, new research published in *Earth and Planetary Science Letters* has suggested that this cosmically cosmopolitan mineral can help turn formaldehyde, a toxic gas, into sugars (bit.ly/olivine-sugars). The finding could help explain how the earliest organisms obtained sugars, which they used for energy and to build genetic molecules such as RNA and DNA.

Today life creates its own sugars, as well as amino acids, fats, and nucleic acids—critical components that create and sustain many biologic processes. But the first cell couldn't have produced its own building blocks, which must have formed through reactions that didn't involve life.

Scientists have long thought that the formose reaction, which takes in formaldehyde and spits out a mix of different sugars, may have played a role in creating at least one component of the building blocks of life. Formaldehyde is a simple molecule consisting of a carbon atom bonded to two hydrogen atoms and one oxygen atom. Though rare on Earth's surface today, it is common in the universe and has been identified in asteroids, in comets, and even in the interstellar medium.

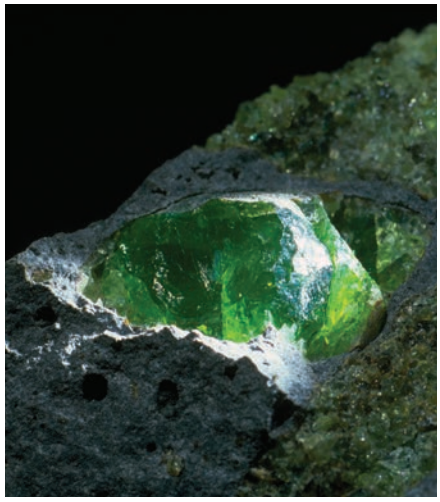
It's possible that impacts delivered formaldehyde to early Earth.

Before Life

The formose reaction begins with the formation of a molecule called glycolaldehyde from two formaldehyde molecules. Glycolaldehyde is the simplest molecule that follows the general chemical formula for sugars.

That first step is the hardest, said study author and astrochemist Vassilissa Vinogradoff of Aix-Marseille University in France. Without a catalyst, producing glycolaldehyde is a slow process, and this holds up the rest of the formose reaction. So it needs a boost, especially when the reaction takes place in water.

Once glycolaldehyde forms, Vinogradoff said, the formose reaction becomes self-sustaining. It consumes formaldehyde to regenerate glycolaldehyde and churn out more and more monosaccharides, or simple sugars. (The reaction's name itself is a portmanteau of formaldehyde and aldose, one category of monosaccharide produced by the reaction.)



Olivine, named for its green color, is the most common mineral in Earth's upper mantle and is widespread throughout the solar system. Credit: Smithsonian National Museum of Natural History, CC0 1.0 (bit.ly/cc01-0)

Given enough time, this cyclical reaction could produce "kilograms, tons, maybe megatons of sugars," said organic chemist Oliver Trapp of Ludwig Maximilian University in Munich, Germany, who was not involved in the study. Showing how this reaction could get started under natural conditions, he said, is a "remarkable step."

Vinogradoff and her colleagues wondered whether olivine-rich rocks, which would have been abundant on early Earth and elsewhere in the young solar system, might have been the catalyst for the planet's first formose reactions.

The researchers reacted formaldehyde with finely ground olivine-rich rock that they carefully cleaned to avoid contamination with organic molecules. (They also set aside some formaldehyde and olivine separately as controls.) The reaction chambers were filled with water and kept warm and oxygen-free. Such conditions are not unlike those that scientists think existed at hydrothermal vents on early Earth or within watery asteroids. After 2, 7, and 45 days, the team took samples and measured the reaction products using a technique called multidimensional gas chromatography.

"This reaction forms many, many, many compounds, and analysis is very, very difficult," said prebiotic chemist Yoshihiro Furukawa of Tohoku University in Japan, who was not involved in the study. "The authors used a state-of-the-art analysis."

The experiments revealed that in the presence of olivine, glycolaldehyde—and sugars—formed much more efficiently. Olivine also helped the reaction produce more complicated sugars such as glucose. Chemical models suggest that the surface of olivine interacts with formaldehyde molecules in a way that makes it easier for their carbon molecules to bond.

Because olivine is widespread, the right conditions for making sugars from formaldehyde could have occurred—and could still occur—throughout the solar system, from the seafloor of early Earth to the interiors of asteroids.

Olivine's ubiquity makes the finding relevant to not just one but several hypotheses for the origin of life. The mineral is already central to a hypothesis placing the origin of life at hydrothermal vents in Earth's primordial ocean. The warm, alkaline fluids at these vents come from a reaction between olivine and seawater.

"This reaction forms many, many, many compounds, and analysis is very, very difficult."

Other hypotheses involve the delivery of organic molecules from space. Furukawa and his colleagues recently identified sugars, including ribose, a key component of genetic molecules, in meteorites. Because certain asteroids contain olivine and formaldehyde, the new results could help explain the existence of such space sugars.

"Olivine is a common mineral," Vinogradoff said. "That's the interesting point." That it could catalyze such a potentially important reaction is something "we had not imagined before."

By **Elise Cutts** (@elisecutts), Science Writer

Almost a Year in, Drought in the Amazon Is Far from Over

The drought striking the Amazon that has worried researchers since last year is far from over, according to meteorological institutions in Brazil. Local authorities have reported that the drought has affected more than 600,000 people in the state of Amazonas alone.

Even seasoned scientists are surprised by the scope. "We don't remember hearing about the death of river dolphins in past droughts in the Amazon," said climatologist José Marengo, research and development coordinator of Brazil's National Center for Monitoring and Warning of Natural Disasters. Marengo was referring to the deaths of more than 250 river dolphins recorded between September and October 2023 in Lake Coari and Lake Tefé in northern Amazonas. In Tefé, water temperatures reached 39.1°C (102.3°F).

In a technical note released at the end of January, Brazil's National Institute for Space Research and National Institute of Meteorology and the Cearense Foundation for Meteorology and Water Resources said that a pattern of lower-than-expected rainfall will extend through this month (bit.ly/low-rainfall). The pattern is, in part, a result of unusually high temperatures in both the equatorial Pacific and tropical Atlantic oceans.

As a sign of that pattern, only three of the Amazon's 32 river basins entered February with positive rainfall volume, according to the National Institute for Amazonian Research (INPA). Another five basins had precipitation levels close to those expected for the period, but the rest—including portions of the Amazon River itself, the most extensive drainage system in the world—started the year with low rainfall. The Negro River, one of the most important navigation corridors in the region, received about half its expected rainfall for January (bit.ly/INPA-bulletin).

Researchers are currently working on an analysis of water loss in the Brazilian Amazon in 2023 compared with 2022. According to their data, in 2023 the rainforest lost 3.33 million hectares of surface water, an area slightly larger than the U.S. state of Maryland. The team is using Sentinel satellite imagery, and its analysis shows that most surface water loss in 2023 took place less than 50 kilometers from Indigenous villages and urban areas and within 25 kilometers of small towns.

Located in the upper Amazon basin, the Solimões River was severely affected by the drought that hit northern Brazil in 2023. Credit: Sandro Kakabadze/MapBiomas

"It is crucial to monitor aquatic environments because they are the first to be affected by dry spells," said Carlos Souza, a coauthor of the technical note and remote sensing researcher at the Amazon Institute of People and the Environment. The Amazon tipping point, he said, is a hypothetical situation in which forest degradation reaches a point of no return and the area degrades to a grassy savanna. Researchers said it may be reached if 20%–25% of the forest's original area is deforested. The phenomenon, Souza warned, "is a plausible hypothesis, and before a catastrophe of this nature hits, aquatic ecosystems ring the alarm."

Floodplains are also especially vulnerable to prolonged droughts, according to Souza. "When the soil undergoes long dry periods, it loses its microbiodiversity—which is important to process organic matter and release nutrients that contribute to soil productivity," he said.

Finally, agricultural businesses have been hard-hit by the Amazon drought. It has affected the quality and quantity of açaí being produced, for example, as well as those of pineapples and other crops.

El Niño and Climate Change

The El Niño–Southern Oscillation (ENSO) is a predictable weather pattern that regularly brings warmer sea surface temperatures to the west coast of South America. The problem with ENSO in 2023, explained Marengo, was that the phenomenon arrived early and followed a warming of the tropical Atlantic Ocean on the east coast of the continent. Both warming processes swirled simultaneously, feeding each other.

"The peak [of ENSO] that we would expect for January this year occurred last September—very much driven by an atypically warm Atlantic Ocean," Marengo said.

The patterns of these ocean-atmosphere processes are shifting—and shifting fast because of climate change.

In fact, a recent study released by World Weather Attribution pointed to climate change, not ENSO, as the main culprit for the current drought in the Amazon (bit.ly/climate-drought). In the study, an international team of 18 researchers used models to simulate the drought under current atmospheric conditions and under preindustrial average global temperatures.

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In the modeling, the team found that a drought caused by low rainfall (meteorological drought) became 10 times more likely under current conditions because of climate change, whereas a drought caused by evapotranspiration (agricultural drought) became 30 times more likely to happen because of climate change.

"Droughts are not only about lack of precipitation. It is low rainfall plus evapotranspiration," said coauthor Regina Rodrigues, a physical oceanographer at the Federal University of Santa Catarina. "Evapotranspiration depends a lot on atmospheric temperatures—and this is where climate change is more visible," she added.

"We are messing with something we should never disturb: the distribution of energy on our planet. We don't know what consequences it can have."

Indicator of More Extreme Events

When the drought is over, the Amazon will need time to recover, researchers warn.

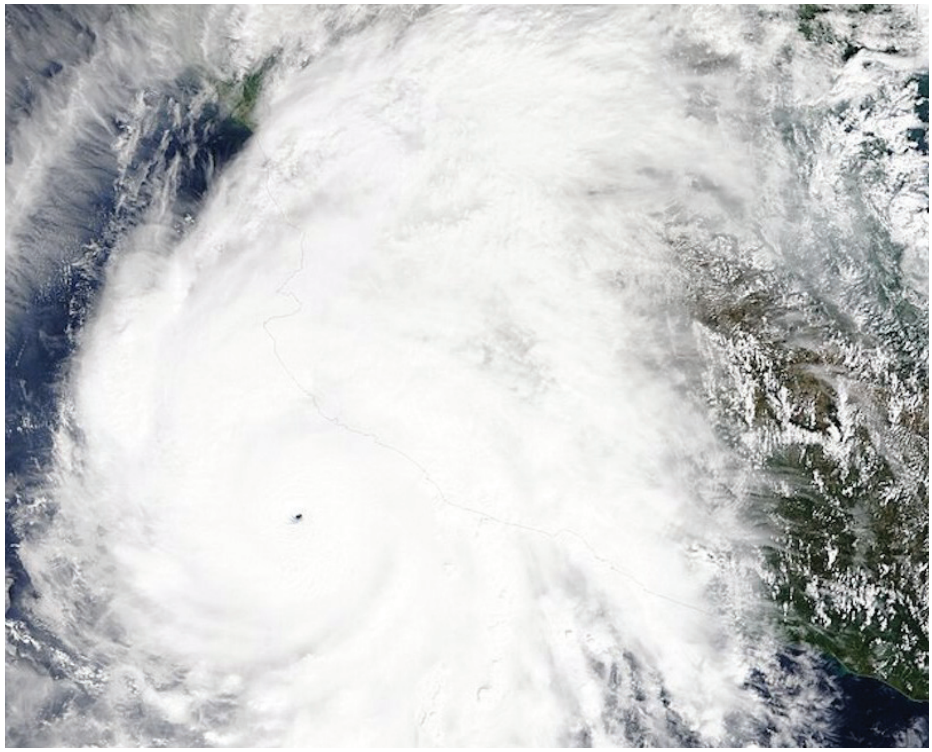
"The fact that the El Niño is set to last until April does not mean rainfall is going back to normal in May," said Renato Senna, a meteorologist who monitors Amazon basin hydrology at INPA's Coordination for Environmental Dynamics. Temperatures take time to change, he explained, because of a delay in ocean–atmosphere processes.

"Normally, [temperature change] processes start in the oceans and spread through the atmosphere, so atmospheric perturbations take a bit longer—a few weeks—to start and end than the oceanic ones," he said.

To Senna, the severity and extension of the current drought in the Amazon are just the tip of the iceberg for more extreme events to come. "We are messing with something we should never disturb: the distribution of energy on our planet," he said. "We don't know what consequences it can have."

By **Meghie Rodrigues** (@meghier), Science Writer

Is It Time to Make Category 6 Hurricanes Official?



Hurricane Patricia, which made landfall in southwestern Mexico in October 2015, clocked wind speeds greater than 192 miles (309 kilometers) per hour, the threshold for a proposed category 6 hurricane. Credit: Rapid Response/NASA

Five tropical cyclones in the past 9 years have had wind speeds far above the category 5 threshold, causing thousands of fatalities and billions of dollars of damage. Such ultrastrong, highly destructive hurricanes are becoming more likely as climate change increases the amount of energy available to storms.

"Storms are getting stronger and stronger, so category 5 underestimates actual risk."

In a study published in the *Proceedings of the National Academy of Sciences of the United States of America*, scientists suggest that the growing intensification of tropical cyclones may necessitate adding a sixth category to the Saffir–Simpson Hurricane Wind Scale (bit.ly/category-6). Doing so could be a useful tool not only to indicate hurricane risk but also to convey the increasing dangers of climate change.

"Storms are getting stronger and stronger, so category 5 underestimates actual risk," said James Kossin, coauthor of the paper and an atmospheric scientist at the University of Wisconsin–Madison.

Warming Winds

The Saffir–Simpson scale is the most widely recognized hurricane intensity scale, ranking storms from "tropical depression," with wind speeds less than 38 miles (61 kilometers) per hour, to "category 5 hurricane," with wind speeds greater than 157 miles (253 kilometers) per hour.

That scale may not capture the risk posed by the most intense storms as the world warms, the authors write. They suggest a sixth category that encompasses storms with winds greater than 192 miles (309 kilometers) per hour.

The authors use three lines of evidence to support the creation of a sixth category. First, multiple storms have already spilled over into the hypothetical category 6. Typhoon Haiyan, for example, which made landfall in the Philippines in 2013, had winds that reached 195 miles (314 kilometers) per hour. Haiyan was the costliest storm ever to hit the country and one of the deadliest, causing more than 6,000 fatalities. In 2015, Patricia—considered the strongest hurricane ever recorded—brought winds of up to 215 miles (346 kilometers) per hour to southwestern Mexico.

Second, climate change has likely contributed to the intensification of tropical storms, according to the Intergovernmental Panel on Climate Change, the United Nations body that assesses climate science.

The authors also analyzed the maximum potential intensity of storms in recent decades to demonstrate this. That metric refers to the highest wind speeds possible on a particular day, given that day's weather conditions. They found that in the Gulf of Mexico between 1979 and 2019, conditions were conducive to category 6 hurricanes about 10 days per year.

The number of days conducive to category 6 wind speeds has increased because of climate change, said Kossin.

Last, the authors modeled future hurricanes under various climate change scenarios and found that under each scenario, the risk of a category 6 hurricane increased. "Over the next decade, there will be category 6 [hurricanes]," said Michael Wehner, lead author of the paper and a climate scientist at the Lawrence Berkeley National Laboratory.

"The reality is that hurricanes have changed already. This creates the need to discuss whether the systems that we currently have in place are adequate for the future."

Communicating Climate Change

Communication of risks shouldn't focus only on the Saffir-Simpson scale, according to Michael Brennan, director of NOAA's National Hurricane Center (NHC). Most hurricane-related fatalities are caused not by wind but by water, including storm surges and rain.

"At NHC, we've tried to steer the focus toward the individual hazards, which include storm surge, wind, rainfall, tornadoes and rip currents, instead of the particular category of the storm," Brennan wrote in an email. "Category 5 on the Saffir-Simpson scale already captures 'Catastrophic Damage' from wind, so it's not clear that there would be a need for another category even if storms were to get stronger."

The question of whether a category 6 would be an effective communication tool requires a larger discussion, with input from social scientists, psychologists, emergency managers, and city planners, Kossin said. He said he hopes the suggestion to add a sixth category to the Saffir-Simpson scale will spark more discussion of how to warn people about all hurricane-related risks, including wind, storm surge, and rainfall, as hurricanes continue to intensify.

"What we're trying to highlight is not the immediate danger of an impending storm," Wehner said. "That kind of thing is already out there. What we're trying to communicate is that the risk of the most intense storms is increasing because of climate change."

Kevin Reed, a climate and atmospheric scientist at Stony Brook University who was not involved in the new study, said that expanding the Saffir-Simpson scale would indicate increased risks from individual storms and also highlight the worsening risks of climate change in general.

"The reality is that hurricanes have changed already," Reed said. "This creates the need to discuss whether the systems that we currently have in place are adequate for the future."

By **Grace van Deelen** (@GVD__), Staff Writer

New Satellite Will Help NASA Keep PACE with Earth Systems

On 8 February, NASA launched a new satellite tasked with monitoring microbes in the ocean and aerosols in the atmosphere. The mission, called PACE (Plankton, Aerosol, Cloud, ocean Ecosystem), will improve scientists' understanding of the carbon cycle.

The satellite houses three instruments: the Ocean Color Instrument (OCI) and two polarimeters to measure the atmosphere's aerosol composition.

Unlike other remote sensing satellites, which measure five to seven colors, the OCI measures the brightness of more than 200 colors, from ultraviolet to infrared. Scientists use the ocean's color to identify the abundance of phytoplankton, which live in the upper 200 meters of the water column. Greener waters typically mean that more of these chlorophyll-containing microbes are present.

Before now, scientists struggled to distinguish between different taxonomic groups of phytoplankton. The ability of the OCI to distinguish so many different colors promises to remedy that.

"The amount of light at each wavelength is directly impacted by how much of each type of plankton is in the water," explained Alison Chase, an optical oceanographer at the University of Washington and a member of the NASA PACE Science and Applications Team. This is because different pigments (like yellow to orange carotenoids) and cell structures absorb and scatter light differently, she said.

Different types of phytoplankton interact with the ocean and atmosphere in varying ways, said Jeremy Werdell, a project scientist for PACE and an oceanographer at NASA. Ultimately, however, phytoplankton "form the base of the aquatic food chain. They are responsible for bringing carbon dioxide out of the atmosphere," he said.

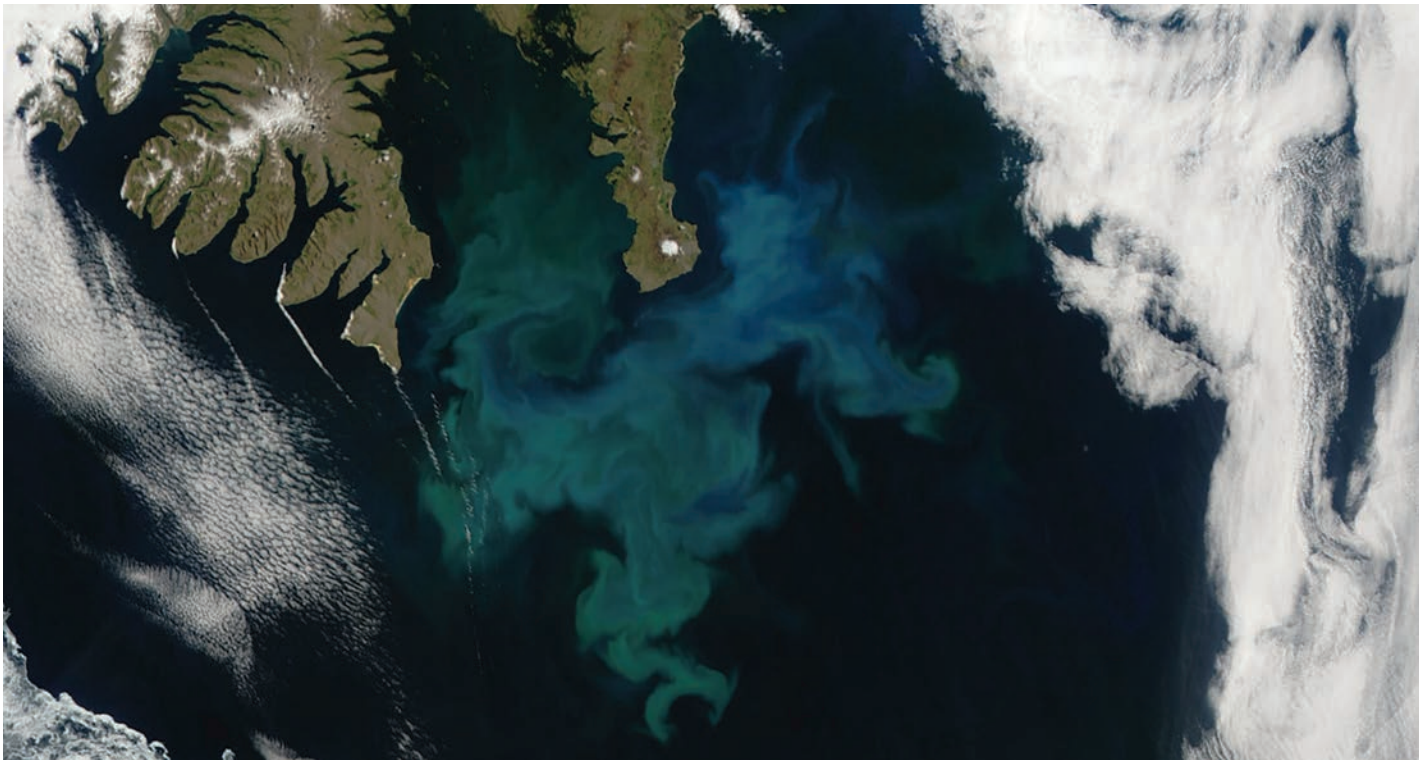
PACE could also help answer questions about the role of phytoplankton in the carbon cycle as the world warms. "We certainly don't know a lot yet about how different phytoplankton community groups at the surface impact carbon flux on large spatial scales," Chase said.

Larger phytoplankton species such as diatoms live in the upper ocean but rely on cold, nutrient-rich water that upwells from the deep, for example. Warming waters could affect ocean currents, limiting the flow of nutrients. If these conditions occur, "big phytoplankton won't have what they need to grow," Chase said.

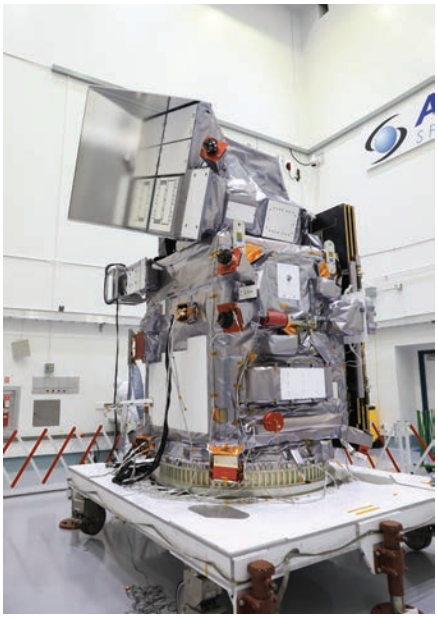
PACE will help scientists monitor these communities across entire ocean regions. Chase explained that those data can then be used to estimate carbon flux and predict what may happen to carbon levels if those communities change.

From Ocean to Sky

The ocean, clouds, and aerosols interact to modulate temperature in the atmosphere, Werdell said, and the PACE mission is monitoring Earth's skies as well as its seas. PACE's polarimeters measure how light is



The PACE (Plankton, Aerosol, Cloud, ocean Ecosystem) satellite monitors the ocean's color to identify phytoplankton such as this bloom swirling off the coast of western Iceland in June 2010. Credit: NASA/Goddard Space Flight Center/Jeff Schmaltz/MODIS Land Rapid Response Team



Scientists and engineers test PACE before its launch. Credit: Kim Shiflett/NASA

polarized as it passes through the atmosphere, which can indicate the amount, size, and shape of suspended particles and other properties of clouds.

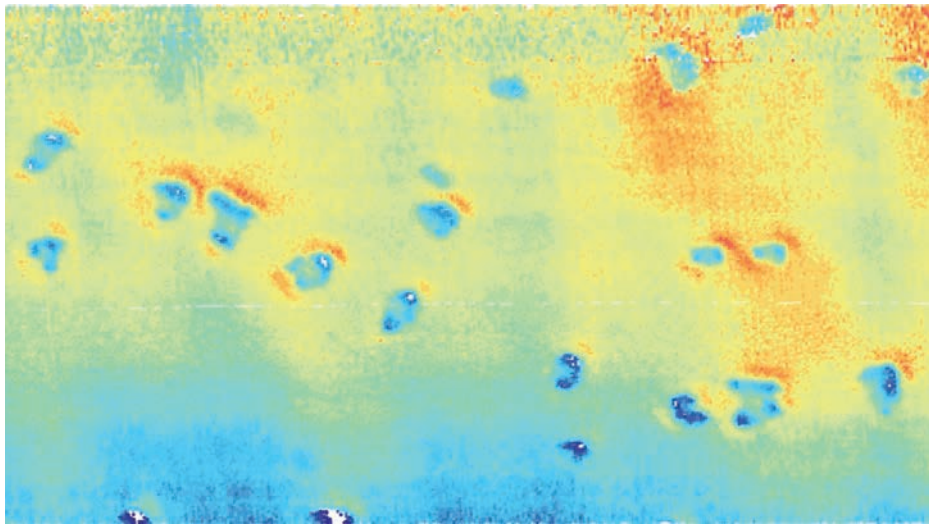
"Our understanding of those interactions is really one of the largest uncertainties in our ability to interpret [climate] models."

"Our understanding of those interactions is really one of the largest uncertainties in our ability to interpret [climate] models," said Werdell.

PACE will produce so much information that it will be a challenge to use it all at first, Werdell said. "The beauty of this mission, in my mind, is that it's information we can grow into in order to understand the interconnectedness of this full Earth system."

By **Emily Shepherd** (@emilyshep1011), Science Writer

Mysterious Seafloor Pits May Be Made on Porpoise



Seafloor pits like these may not have been created by methane leaks. Credit: Jens Schneider von Deimling

In the murky waters of the North Sea, shallow divots dot the seafloor. The pits are round or oval and range in width from a few meters to more than 60 meters, but they are consistently only 11 centimeters deep. Some pits appear to have merged, creating oblong Venn-diagram-shaped depressions.

Such pits usually form when fluids containing methane or other groundwater bubble out of the sediment. But new research published in *Communications Earth & Environment* suggests that thousands, and perhaps millions, of pits in the North Sea and elsewhere might actually be the work of foraging porpoises (bit.ly/porpoise-pockmarks). The work showed that these and other megafauna may play a large role in shaping the seafloor.

For years, geoscientist Jens Schneider von Deimling of Kiel University was skeptical that the North Sea pits were made by leaking methane. The floor of the North Sea is made of porous sand and has strong currents, which aren't conducive to methane accumulating in sediment.

"I didn't really see any mechanisms that accumulate methane," Schneider von Deimling said. Out on the water during a research cruise, he and his colleagues confirmed his suspicion. Mapping studies designed to detect methane in the sediment using a subbottom echo sounder, which is a form of sonar that bounces sound off the seafloor to image the shallow subsurface, turned up nothing. "We mined thousands of miles of data for shallow gas, and simply didn't find that," he said.

"I didn't really see any mechanisms that accumulate methane."

To get a better look at the pits, the team used a multibeam echo sounder that allows for surveys of the seafloor in high resolution. Whereas older multibeam technologies can miss pits entirely, this multibeam tool allowed the researchers to scrutinize the shape of the pits down to the centimeter scale.

"They had the opportunity to collect this really, really high resolution data, which is great because it means you can closely examine the structures," said Jess Hillman, a marine geoscientist at GNS Science in New Zealand who wasn't involved in the study.

This cetacean and its fellows may have been porpoisely pitting the seafloor under scientists' noses. Credit: Ecomare/Sytske Dijksen, Wikimedia Commons, CC BY-SA 4.0 (bit.ly/ccbysa4-0)

The multibeam echo sounder revealed that the pits were not conical, which is the case when a narrow stream of methane bursts through the sediment. "What makes them exceptional is that the depth doesn't change with its aspect ratio," Schneider von Deimling said. Regardless of their width, the pits are always roughly 11 centimeters deep.

A Porpoiseful Pit

On the hunt for what might be creating the pits, Schneider von Deimling called up a biologist and diver friend, who told him about how harbor porpoises scour the seafloor sniffing for sand eels.

The researchers used existing models to predict the habitats of eels and porpoises and overlaid oceanographic data of currents. (Porpoises and sand eels both live where currents are strong.) They found that the habitats overlapped with their study area. Back on the water with the echo sounder, the researchers found that wherever they had expected to find porpoises and sand eels, they also found more pits.

The bigger pits, according to the group, were porpoise pits that had been scoured by ocean currents.

Schneider von Deimling said he hopes someday to get photographic proof of a porpoise digging a pit, but he's not holding his breath. The waters of the North Sea are too murky to see much. "Also, the harbor porpoise is pretty shy," he said.

For now, the researchers are working with scientists in Ireland to confirm that their predictions of pit locations based on porpoise habitat apply to areas outside of the North Sea.

Hillman said that interdisciplinary studies such as this are a way for geoscientists to help biologists learn more about animal behavior. Understanding how seafloor pits are formed can be important for understanding submarine hazards. Pits created by methane seepage can be a sign of tectonic hazards. Faults bring fluids and gases up from depth and are often associated with these methane vents, Hillman said. If scientists know how to recognize pits that are made by living things, they could help quell concerns about tectonic activity.

The study results suggested that large animals may have had a greater impact on shaping the seafloor and mobilizing sediment than was previously thought, Schneider von Deimling said. Because bathymetric surveys aren't performed regularly and often have low resolution, the subtle changes in the seafloor had been obscured until now.

"They had the opportunity to collect this really, really high resolution data, which is great, because it means you can closely examine the structures."

"If you think over geological timescales, the function of [animals] perturbing the sediments might be quite important," he said.

By **Andrew Chapman** (@andrew7chapman), Science Writer

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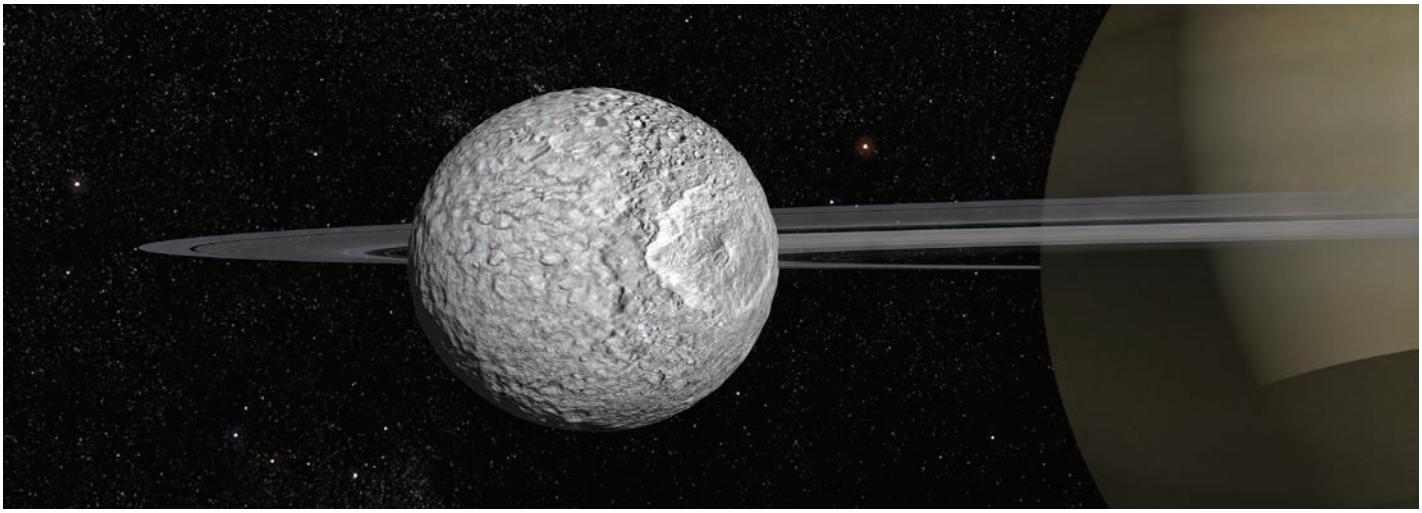
That's No Moon; It's an Ocean World



Mimas, a midsize moon of Saturn, likely has a subsurface ocean. Credit: Frédéric Durillon, Animea Studio/Observatoire de Paris–PSL, IMCCE

Saturn's moon Mimas, famous for its "Death Star" crater, likely harbors a subsurface ocean.

A new analysis of images taken by NASA's Cassini spacecraft revealed that tiny changes in Mimas's orbit can be explained only if the moon hosts an ocean beneath 20–30 kilometers of ice.

The research, published in *Nature*, adds an unlikely member to the small roster of ocean worlds in the solar system and furthers our understanding of Saturn's chaotic history (bit.ly/Mimas-moon).

"If even Mimas can get an ocean, then almost any object could hide an ocean," said Valéry Lainey, an astronomer at Observatoire de Paris in France and lead researcher on the discovery.

A Tiny Shift with Big Implications

In the solar system, only Jupiter's Europa, Callisto, and Ganymede and Saturn's Enceladus and Titan have confirmed oceans, but several more moons of Saturn, Uranus, and Neptune are the subjects of fierce speculation and proposed exploration.

But Mimas's small size and cratered surface make it an unlikely candidate for an ocean world.

"If you wanted to bet on which body gets a global ocean, you will never bet on Mimas," Lainey said.

Mimas, the innermost of Saturn's major moons, is not quite 400 kilometers (250 miles) across. Its pockmarks suggest that no new material has erupted and smoothed out the surface in a while. It's best recognized for its 130-kilometer Herschel crater, which makes it resemble the Death Star from the Star Wars franchise.

Measurements by the Cassini spacecraft revealed that Mimas rotates in an unexpected way. Instead of always showing the same face to Saturn the way the Moon does to Earth, Mimas's Saturn-facing hemisphere rocks back and forth in a cycle known as libration.

The strength of the libration made the authors of a 2014 study suspect that Mimas's interior either was completely frozen with an oblong core or had a subsurface ocean layer (bit.ly/measurements-of-Mimas).

"Given how different Mimas looks from confirmed ocean moons like Enceladus, most of us figured the frozen model was probably correct," said Alyssa Rhoden, a planetary scientist at the Southwest Research Institute in Boulder, Colo., who was not involved with this research.

Lainey and his colleagues reanalyzed the old Cassini data, supplemented with data from the Hubble Space Telescope. They used tens of thousands of Cassini images of Mimas and 18 other Saturnian moons and looked at not just changes to Mimas's rotation but its orbit around Saturn, too.

The researchers determined that the closest point in Mimas's orbit to Saturn, its periapsis, had drifted 9.4 kilometers (less than 6 miles) over Cassini's 13 years at Saturn, roughly 0.15° counterclockwise around the planet. The shift was tiny, but it was enough for the team's orbital simulations to home in on an answer.

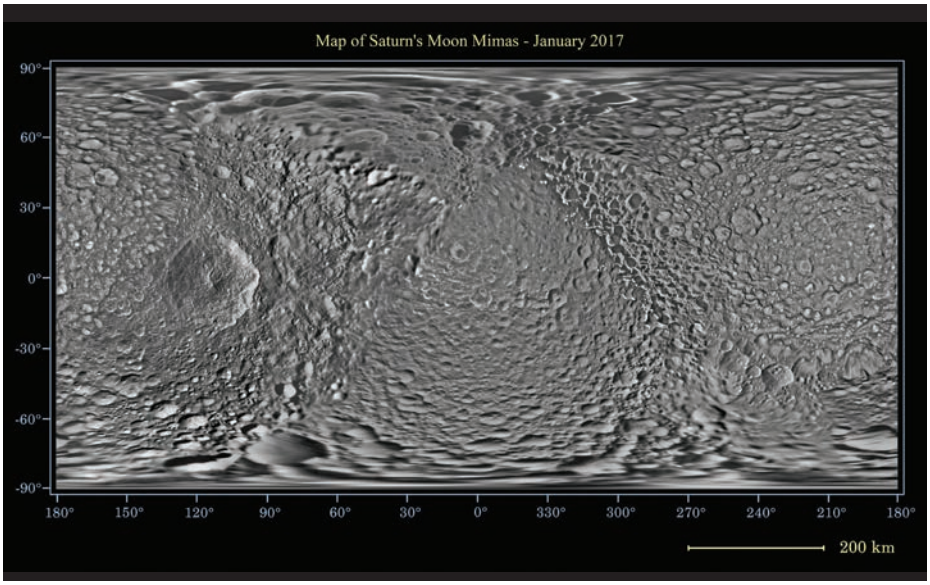
> **"If you wanted to bet on which body gets a global ocean, you will never bet on Mimas."**

"There is no way to explain both the rotation and the orbital motion of Mimas with a rigid core," Lainey said. "Whatever the size and whatever the shape of the silicate core, there is no way you can have a rigid interior. You must have liquid water and an icy shell that slips on the surface."

The team's simulation suggests that Mimas's subsurface ocean rests under 20–30 kilometers of ice. As much as 50%–60% of Mimas's total volume could be liquid water, Lainey said.

Combined with the 2014 study, this new research makes "a very strong case for an internal ocean within Mimas today," Rhoden said. "I wouldn't say it's 'confirmed' or 'definitive,' but I would say it's highly likely and worth dedicated exploration."

"We are past the point of an internal ocean in Mimas being simply possible—it's now plausible," said Matthew Walker, a planetary scientist at the Planetary Science Institute in Tucson, Ariz., who was not involved with this study. There's always the possibility that some unknown mechanism is causing the libration and orbital drift without an ocean, Walker said, so he would not discourage other scientists from investigating other options. Still, "it seems most likely that there is an ocean there," he said.



Mimas's heavily cratered surface suggests that unlike ocean world Enceladus, no material has emerged from the interior to smooth out the surface. The likely reason is that Mimas' ocean is too young and beneath too much ice. Credit: NASA/JPL-Caltech/Space Science Institute, Public Domain

Stealthy Ocean World

The analysis suggests that Mimas's ocean could be as young as 2 million years old. The team postulated that the relatively young ocean hasn't yet had time to change Mimas's surface in a visible way, the way Europa and Enceladus have done. Mimas could very well look more like Enceladus in a few million years, Lainey said.

The Saturnian system, with its rings and plentiful moons, has had an eventful history. Mimas's interior could have melted from additional tidal heat during a shift in gravitational alignment or the expulsion of a moon.

If a moon as small and as cratered as Mimas could have a subsurface ocean, ocean worlds might be even more common than previously thought.

"Mimas is almost certainly the most stealthy ocean world," Rhoden said. Other confirmed or suspected ocean worlds around Saturn and Uranus, for example, show more evidence than Mimas has of having oceans now or in their recent past—geysers, tectonic features, young surfaces, and/or high heat flows.

"Ocean moons at Uranus seem even more plausible in light of the Mimas results," Rhoden said.

"That Mimas quite probably does have an ocean under that cratered crust demonstrates that we cannot just rely on tiger stripes, double ridges, or chaos terrains to indicate to us the presence of an ocean," Walker said. By identifying ocean worlds through their orbital characteristics, "we can then use the surface geology of these worlds to tell us about the stages and life cycles of any ocean worlds that we observe."

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

Propose a Session for AGU24

Science is a story. A story of infinite possibilities. A story of continuous discoveries. A story of hopeful solutions.

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How to Address Publication Overload in Environmental Science

A staggering number of peer-reviewed papers are published each year in environmental science, climatology, ecology, geology, hydrology, companion social sciences, and related fields. The vast majority of these papers represent high-quality contributions to our understanding of the world. Yet they build on bodies of work that are already astonishingly large, making it ever more difficult for established scientists to keep up and for young scientists to get up to speed on foundations and frontiers within their fields.

This publication overload hampers our ability to advance scientific frontiers, address societally important challenges, and support early-career scientists. It can also lead to researchers duplicating work, rediscovering previously published ideas, or, worse, perpetuating mistakes—inefficient uses of limited resources. Furthermore, geographically localized studies, which may be incremental in scope but provide critical context and comparisons for broader or more global studies in applied environmental science, are often missed.

Considering that the pace of science and scientific publication is unlikely to slow, we need a better approach to synthesizing the wealth of available knowledge. We propose that—and describe how—one such approach could involve a human-driven, machine-aided online synthesis tool that evolves over time and seamlessly connects large amounts of related research and information while preserving the richness of detail found in individual peer-reviewed papers.

A Publications Avalanche

Today more than 3 million peer-reviewed papers are published each year—some 500,000 in the United States alone [*Jinha*, 2010; *Johnson et al.*, 2018; *White*, 2019].

The number of papers related to critical environmental concerns—drought, fire, and climate change, among others—is especially high. For example, using standard search engines to find academic peer-reviewed literature on "fire or wildfire" in the western United States turns up more than 20,000 papers, of which more than a thousand have been published per year since 2016.

Considering that the pace of science and scientific publication is unlikely to slow, we need a better approach to synthesizing the wealth of available knowledge.

These publication rates preclude staying up to date on all the work being done—even for within-field experts—which can hamper

hypothesis evolution and limit the adoption of new observation and modeling technologies.

The burden of publication overload is often greatest for early-career scientists, who are simultaneously trying to establish their expertise and their careers [*Atkins et al.*, 2020; *Thakore et al.*, 2014]. Becoming an expert requires reading, understanding, and integrating others' work, but knowing what to read, and in what order, can dramatically improve one's grasp of key concepts.

Without good mentors to help curate information, many early-career scientists are left to wander the halls of our digital libraries—often with the Google search bar their only guide—in the hope that they can identify and understand the key foundational and frontier knowledge they need. A lack of effective mentorship is a notable barrier to academic advancement and success, especially for individuals from underrepresented backgrounds [*Deanna et al.*, 2022].

Publication overload is also a barrier to scientists receiving recognition for their work. This is a community-wide problem, but, again, it may be particularly acute for early-career researchers. Even when scientists publish their work, it often goes unrecognized amid the "tide" of other new literature. The percentages of papers that are never cited are difficult to measure and vary by discipline, but estimates are often in the double digits.

Early in their careers, scientists often engage in more incremental research—for example, testing existing hypotheses in new locations or under new conditions, or applying and assessing emerging methodologies in innovative ways. This sort of incremental research is central to the scientific enterprise, but it is often published in discipline-specific journals rather than in higher-profile, multidisciplinary outlets. As a result, the new research is often overlooked, especially by readers in other fields and specializations, and thus greatly undervalued.

Existing Initiatives Are Only a Beginning

Publication overload is not new. Scientists have tried to remedy the problem with various synthesis products and approaches. For example, review articles such as the Tamm Reviews, which cover research in forest ecology and management, typically distill findings from numerous studies related to a given theme. In addition, journals such as the Wiley Interdisciplinary Reviews (WIREs) series focus almost exclusively on review papers. There are also standards for high-quality systematic reviews such as those provided by Collaboration for Environmental Evidence.

We have also built synthesis institutes. Good examples include the National Center for Ecological Analysis and Synthesis, the U.S. Geological Survey's John Wesley Powell Center for Analysis and Synthesis, and the National Socio-Environmental Synthesis Center. All of these are increasingly focused on producing synthesis products like review papers and databases.

A dynamic online metasynthesis tool that makes finding, understanding, and updating science equitable and efficient would be a transformative solution.

The National Science Foundation (NSF) has programs like Research Coordination Networks that support groups of investigators as they coordinate and synthesize related research, training, and educational activities. Finally, governmental and nongovernmental organizations produce other synthesis materials and reports, such as California's Climate Change Assessments and the Intergovernmental Panel on Climate Change's reports. Similar in function but decidedly different in approach, there are data provisioning websites like Google Earth that provide data and model outputs relevant to core questions in environmental science.

These existing tools and initiatives clearly contribute to information synthesis, although the array of syntheses and their various products can themselves be overwhelming. Of critical importance, these synthesis products are often static or limited in scope, meaning that users can easily mistake outdated syntheses for up-to-date understanding or misapply generalized findings to specific locations or circumstances where they aren't relevant.

In addition, subsequent findings may diverge from working hypotheses in preexisting synthesis papers or add specificity to flesh out general principles (e.g., quantifying how warming temperatures relate to earlier snowmelt in a particular location). However, because synthesis papers are rarely revisited, this sort of evolution in the current understanding is easily overlooked or lost.

Synthesis papers and reports also typically focus on specific topics, but links to reviews of related topics are not consistently included, particularly if topics cross disciplines. For example, a review paper discussing the effectiveness of wildfire fuel treatment methods may not mention or link to reviews of relevant science, such as how climate affects fire risk.

Artificial Intelligence, with Human Guidance

If existing human-generated synthesis products cannot save us from publication overload, can artificial intelligence (AI) help? Indeed, it can [*Matthews*, 2021].

Machine learning–enabled products that automate searches and distill information are already available: Iris.ai, Semantic Scholar, Connected Papers, Open Knowledge Maps, and Local Citation Network, to name a few.

Nonetheless, extracting meaningful searches of publications around specific topics in environmental science remains challenging [*Romanelli et al.*, 2021]. In part, this is because finding literature does not necessarily lead to understanding, particularly if searches yield hundreds of papers. Focusing on only highly cited papers may also be problematic, given that the reasons they are highly cited may not align with the goal of understanding [*Romanelli et al.*, 2021]. For example, high citation counts may simply track topics of current general interest rather than advances in expert knowledge. In some cases, high citation counts may result from scientific disagreements playing out in the literature or from papers serving as oft-cited examples of discredited assumptions.

Similarly, automated mapping of domain knowledge by AI algorithms that cluster papers around semantic terms can highlight topical areas and show how trajectories of publications on particular topics evolve through time (e.g., charting the number of papers related to dust on snow). But this clustering does not necessarily synthesize ideas about a topic [*Borner and Polley*, 2014; *Franconeri et al.*, 2021; *Lafia et al.*, 2021]. And highly generalized syntheses (such as what might emerge from ChatGPT) do not readily contribute to the more nuanced, detailed understanding that researchers need to help advance environmental science.

A dynamic online metasynthesis tool that makes finding, understanding, and updating science equitable and efficient would be a

Opposite: foreground, iStock.com/Trifonenko; background, Gustavo Queiroz/Pexels

transformative solution to these shortcomings. Such a tool could combine the strengths of human-driven science syntheses with technical advances in visualization and AI. It could also evolve as our knowledge deepens and synthesize research using customizable searches while still preserving and providing the detail and context found in individual peer-reviewed papers when prompted.

Classic review papers organize disparate ideas into conceptual models. They highlight convergence and divergence around core hypotheses. They evaluate the techniques used in observational data collection, data analysis, and modeling. And they place specific papers into conceptual frameworks that guide understanding.

The ideal tool would retain these strengths while more thoroughly connecting review papers and reports across disciplines and topics. By using recent advances in AI, including natural language AI (e.g., ChatGPT) and visualization techniques such as "on the fly" rendering, we can imagine tailored user interfaces involving AI-aided searches with graphics and text that make traversing knowledge landscapes easy and efficient.

These interfaces could, for example, guide more novice users to current conceptual models related to general topics (e.g., snow accumulation and melt) as starting points, whereas experts could specify a location- and scale-specific research hypothesis and be directed to related pages.

However, active leadership by scientists would be the critical feature. The primary design of the knowledge synthesis (i.e., the conceptual models, hypotheses, and how current techniques can be applied to advance these) would be generated and updated by domain scientists.

Building this tool will require collaboration and partnerships among scientists, visualization experts, database specialists, ontologists (language engineers), and machine learning experts. And, we argue, if this collaborative process is led by and involves scientists at every step, the resulting product would better fit the needs of our community. Although improved private-sector products may emerge, such as a "better" Google Scholar or more detailed ChatGPT, these will not necessarily maintain the strengths of human-driven science syntheses.

From Concept to Reality

What might our proposed tool look like in practice?

Overall, we envision linked, web-based pages that present conceptual diagrams and current working hypotheses and counter-hypotheses related to particular research questions, as well as examples of evidence that confirms or disputes these hypotheses for particular locations and time and space scales. We note that finding exceptions to general rules—or quantifying the magnitudes of effects—in particular settings is often how environmental science advances. This information would all be linked to peer-reviewed papers.

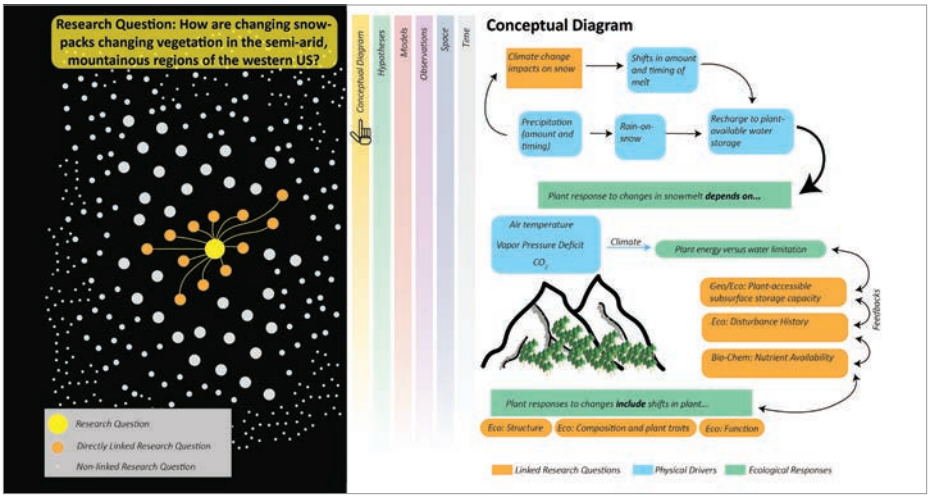

Fig. 1. This snapshot of a hypothetical page in the proposed online synthesis tool addresses how changing snowpacks affect vegetation in semiarid mountainous regions of the western United States. The navigation pane (left) would allow a user to traverse from the currently selected research question (yellow dot, center) to related questions and associated conceptual models (orange dots). The conceptual diagram pane (right) would present a visual overview of the central processes, variables, and interconnections that are typically considered in addressing the research question. This pane would link to related conceptual models and questions (orange). At center, the vertical bars in the dashboard pane would link to other pages (see Figure 2) highlighting information—grouped as hypotheses, models, observations, space, and time—and associated peer-reviewed papers relevant to the selected research question. The space and time pages would provide examples of papers that support or contradict a hypothesis, organized by location/period and time/space scale, respectively.

Because scientific knowledge is most valuable when it is current, the system would require a robust process by which it could keep up with changes in contemporary understanding.

Figures 1 and 2 illustrate potential front-end pages focusing on the question of how changing snowpacks relate to changing vegetation in semiarid, mountainous regions of the U.S. West. A dashboard would allow users to move quickly among pages covering different aspects of this broad research question, and a navigation pane would show connections between the selected question and other related questions, such as how snowpacks, which store water for vegetation, are changing in the region.

Because scientific knowledge is most valuable when it is current, the system would require a robust process by which it could keep up with changes in contemporary understanding. This process would be the system's key innovation. Developing the details of the updating process—including how often, by whom, and by what criteria it would be updated—would require careful thought and rigorous debate by the scientific community. And the system's success ultimately would depend on scientists' willingness to contribute. The more users there are, and the larger the updating community, the better the end product would be.

To maintain its credibility while also creating a flexible, dynamic, and accessible sys-

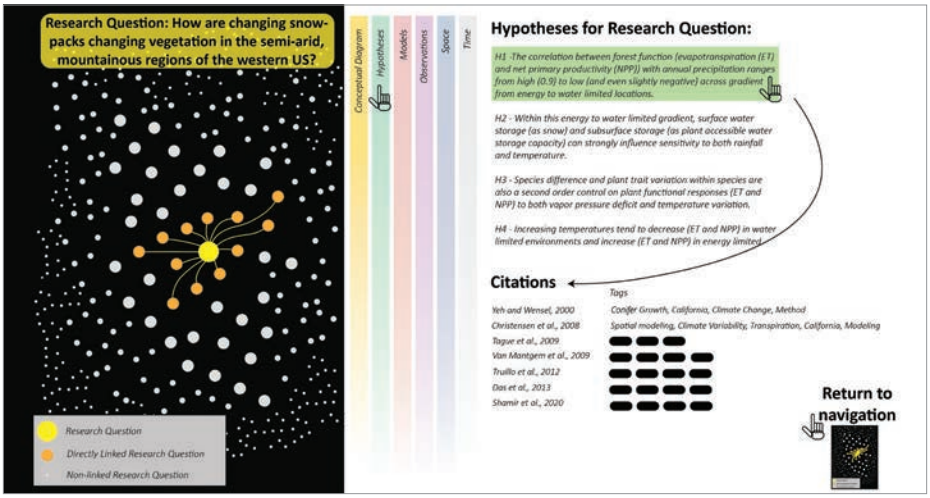

Fig. 2. This hypothetical page would be accessed via the "hypotheses" bar in the dashboard shown in Figure 1. This page would provide a list of current working hypotheses associated with the selected research question and list papers that support, clarify, or contradict each working hypothesis (highlighted in green); it would also tag citations to provide more contextual information. From this page, users could also select another category of information from the dashboard or click "return to navigation" to return to a main page where users could search for other connected hypotheses (a more detailed version of the box at left in Figure 1).

tem, we envision leveraging existing peer-review setups, which provide critical quality control on the science being published. The design of the conceptual diagrams and hypothesis would require direct science community involvement—working group engagement would be critical here. We anticipate using iterative working group processes such as those used by the Intergovernmental Panel on Climate Change and leveraging existing community organizations such as AGU to accomplish this task.

In developing the proposed tool, creating incentives to motivate participation will be important. For example, researchers who contribute to curation, conceptual model evolution, hypothesis development, or software development or who create, contribute to, and maintain the tool, should receive formal recognition [*Carter et al.*, 2021]. This push for recognition parallels similar trends in universities and funding agencies such as NSF that are expanding the scope of work they credit to include software and database development and other contributions.

The peer-reviewed paper, a 17th-century invention, has served science well.

However, as scientific understanding of all manner of topics and questions evolves, we need a new system to access knowledge that provides expert-driven synthesis across many studies while preserving the hard-won details of individual studies.

As a first step, we suggest that communities of environmental scientists convene working groups to focus on designing a tool similar to what we have proposed here and developing rules for how scientists would engage to support the tool's continual evolution, which are equally important. Concurrently, these groups must partner with artificial intelligence and other specialists to leverage advances in visualization and information updating and searching capabilities. Agencies and organizations such as NSF and AGU should support these efforts by convening and funding these working groups, prototype development, and other community engagement efforts.

Researchers who contribute to curation, conceptual model evolution, hypothesis development, or software development, or who create, contribute to, and maintain the tool, should receive formal recognition.

With the rapidly rising number of peer-reviewed papers and the proliferation of synthesis tools like ChatGPT, now is the time for environmental science communities to recognize the limitations (and strengths) of current and emerging scientific dissemination and synthesis products, and to lead in developing new tools. We need a radical solution to publication overload that will help researchers—established and early-career alike—to keep pushing scientific frontiers.

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By **William Brandt,** Scripps Institution of Oceanography, University of California, San Diego, La Jolla; and **Christina Tague** (tague@ucsb.edu), University of California, Santa Barbara

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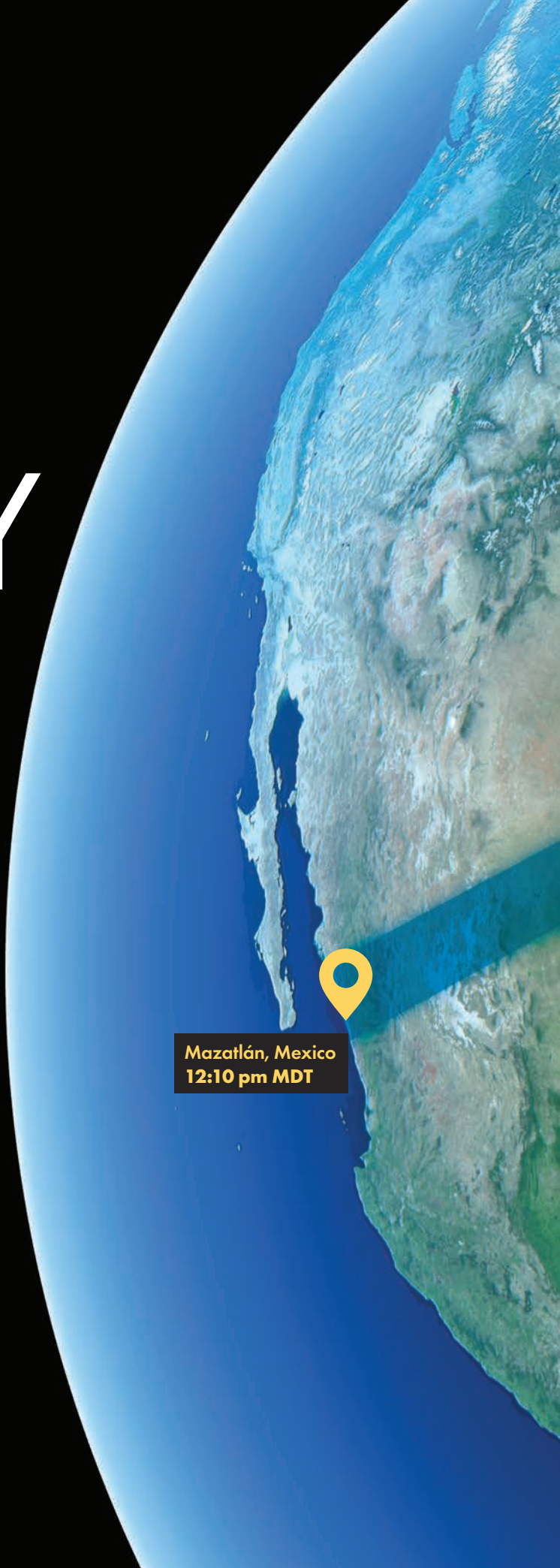
ECLIPSE SCIENCE ALONG THE PATH OF TOTALITY

WHEN A TOTAL SOLAR ECLIPSE SWEEPS ACROSS THE UNITED STATES ON 8 APRIL, SCIENTISTS AND ENTHUSIASTS ALIKE WILL BE THERE TO DOCUMENT IT.

By Katherine Kornei



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Orono, Maine
3:28 pm EDT
Rochester, New York
3:20 pm EDT
Cincinnati, Ohio
3:10 pm EDT
Paris, Arkansas
1:50 pm CDT

In general, scientists don't put much credence in cosmic coincidences.

But a total solar eclipse—a phenomenon made possible by the remarkable similarity between the apparent sizes of the Sun and the Moon—is likely to awe even the most data-driven researcher. And on 8 April 2024, millions of people across the United States will be treated to such a spectacle as the Moon's umbral shadow arcs from Texas to Maine.

Researchers and educators are gearing up for the event with a plethora of scientific investigations, many of which welcome the participation of amateur scientists.

Other solar eclipses have been visible from the United States in the recent past. On 14 October 2023, sky watchers in parts of Oregon, California, Nevada, Utah, Arizona, Colorado, New Mexico, and Texas were treated to an annular solar eclipse; viewers in the rest of the contiguous United States saw a partial solar eclipse.

But the roots of recent eclipse mania in the United States can be traced to 21 August 2017. On that day, millions of people converged on a roughly 110-kilometer-wide swath stretching from Oregon to South Carolina—the so-called path of totality—to witness the first total solar eclipse visible from coast to coast in the United States in 99 years.

Observers enjoyed fewer than 3 minutes of totality, but cities across the country held events to celebrate the Moon's brief—but perfect—passage. And scientists, professionals, and enthusiasts alike were busy collecting data afforded by the rare glimpse of the Sun's outer atmosphere, its corona.

Three total solar eclipses have occurred since 2017. However, they were witnessed by relatively few people because totality occurred largely over remote parts of the Pacific and Atlantic oceans.

The 8 April eclipse promises to be different: Roughly a third of its path of totality will stretch from southwestern Texas to northeastern Maine; major cities such as Dallas, Little Rock, Indianapolis, Cleveland, and Rochester are all within the path of totality.

Researchers and educators will once again eye the sky with eclipse-related projects.

A team at the University of Nevada, Las Vegas practices for NASA's Nationwide Eclipse Ballooning Project. Credit: Josh Hawkins/UNLV

The 50,000 Foot View

By the time the Moon's shadow first reaches the United States in southern Texas at 1:27 p.m. CDT, a pair of WB-57 high-altitude research aircraft will have taken off from Ellington Field near Houston. After heading west and climbing to an altitude of roughly 15,000 meters (50,000 feet), they will intercept the Moon's shadow just off the coast of Mazatlán, Mexico.

> **"They really loved the fact that they got to work together on a continent-sized group project."**

Amir Caspi, a solar astrophysicist at the Southwest Research Institute in Boulder, Colo., will travel to Texas to monitor one of the planes. Caspi is the principal investigator of a NASA-funded project that will use four cameras mounted on the aircraft's nose to observe the Sun's corona in visible and infrared light.

Heading high into the atmosphere on a maneuverable aircraft to observe a solar eclipse has many advantages, Caspi said. For starters, there's no chance of being clouded out. "Clouds are the bane of every eclipse chaser's existence," he explained. The flights will also make it possible to record midinfrared wavelengths of light that would otherwise be absorbed and scattered by water molecules in the atmosphere. "It opens up wavelengths that you just can't observe from below," Caspi said.

Finally, because the WB-57 jets can literally chase the eclipse, their onboard instruments will be afforded a view of totality lasting roughly 6 minutes and 20 seconds—about 50% longer than that of stationary observers on the ground.

Caspi and his colleagues hope their data will shed light not only on the enduring question of why the Sun's corona is so much hotter than the photosphere but also on why certain solar features known as prominences glow so brightly at midinfrared wavelengths.

After leaving Texas, the Moon's shadow will skirt across the southeastern corner of Oklahoma before heading into Arkansas at 1:45 p.m. CDT.

When that happens, Ross Carroll and his team will be ready. Carroll, a physicist at Arkansas State University in Jonesboro, and a cohort of undergraduate students are taking part in the Nationwide Eclipse Ballooning Project, a NASA-sponsored effort involving hundreds of amateur scientists spread across the path of totality.

On 8 April, Carroll's team will inflate a large latex balloon with helium, connect an

instrument payload, and release it near the city of Paris, Ark. The balloon will rise at a rate of about 300 meters (1,000 feet) per minute and, if all goes according to plan, hover at an altitude of roughly 26,000 meters (85,000 feet) as it intercepts the Moon's shadow. "That gives us a nice vantage point," Carroll said.

Another Arkansas State University team will be waiting downwind on Petit Jean Mountain at a ground station equipped with four radio antennas. Those antennas will receive not only a live video feed from the stratosphere but also precise location, temperature, pressure, and humidity data collected by the balloon's instruments.

One goal is to detect whether the passage of the Moon's shadow affects gravity waves in the atmosphere. Measuring slight changes in the undulations of a floating balloon could help answer that question, Carroll said.

Stationary Snapshots

At 1:53 p.m. CDT, the Moon's umbral shadow will enter Missouri. Shannon Babb, an aerospace educator working with the Civil Air Patrol, an auxiliary of the U.S. Air Force, will be waiting.

Mrunal Patil, a Civil Air Patrol cadet, shows off her set of air temperature measurements obtained during the 14 October 2023 annular solar eclipse. Credit: Cory Garvin/Civil Air Patrol

Babb is helping to coordinate several teams of Civil Air Patrol cadets in collecting solar eclipse data in Missouri and neighboring Illinois. The cadets, who range in age from 12 to 21, will take measurements of air temperature, wind speed and direction, and cloud cover during the eclipse. Those data will support GLOBE Observer, a network of amateur and professional scientists focused on collecting a wide variety of data about our planet.

The cadets will enter their data into an eclipse-focused GLOBE Observer app, and their observations will be aggregated with other data collected across the United States to better understand how eclipses affect the natural environment. Many of these young people also collected data during the 14 October 2023 annular solar eclipse, Babb said, and they're looking forward to doing it again. "They really loved the fact that they got to work together on a continent-sized group project."

Babb will also oversee teams of Civil Air Patrol cadets measuring how well very high frequency (VHF) radio waves propagate during the eclipse. First responders and search-and-rescue teams typically make use of those radio frequencies, which range from 30 to 300 megahertz, Babb said, but it's relatively unknown how those kinds of radio waves are affected by the changes in Earth's ionosphere that occur during an eclipse.

"There was anecdotal evidence that solar eclipses affected these radios in addition to the longer-band radios that have been really well studied," Babb said. Pairs of cadets using VHF radios will investigate how their radio transmissions change, if at all, during the eclipse.

Long before the Moon's shadow races across the very western corner of Tennessee and enters Kentucky at 1:58 p.m. CDT, Gordon Emslie will have made sure that his cell phone is charged. Emslie, a solar physicist at Western Kentucky University in Bowling Green, is the principal investigator of Sun-Sketcher.

This project encourages members of the public to use their smartphones to take a preprogrammed set of photographs of the Sun during totality. The goal is to image brief flashes of light caused by sunlight streaming through lunar valleys. Photographs of these so-called Baily's beads—named for a 19th-century British astronomer—can be combined with detailed information about the Moon's topography known from Lunar Reconnaissance Orbiter observations to infer the precise shape of the Sun.

"Whether the beads appear depends on how big the Sun is," Emslie said. The Sun's exact shape in turn depends on its internal structure and magnetic fields. Emslie hopes that data from tens of thousands of Sun-Sketcher participants will constrain the roundness of the Sun to better than about 5 kilometers. That would significantly improve current estimates of the Sun's shape, he said.

> **"Every eclipse gives you a chance to see things slightly differently."**

Watching the Waves

After passing over Indiana, the Moon's shadow will reach Ohio at 3:08 p.m. EDT.

Even if it's cloudy in the Buckeye State that day, John Blasing, an amateur physicist and a member of the Cincinnati Astronomical Society, will be collecting data. That's because he'll record radio waves, which travel through clouds just fine.

Blasing is working with Radio JOVE Project 2.0, which encourages participants to build their own radio antenna and use it to observe celestial bodies such as Jupiter and the Sun. The project sells kits that include a radio receiver, the supplies to erect an antenna, and software to process signals over a frequency range of roughly 16–24 megahertz. Setting up a radio observatory is a fun project that combines astronomy with physics and engineering, Blasing said. "There's a bit of cutting and fitting and soldering to do."

On the day of the eclipse, Blasing's radio telescope in the Cincinnati suburb of Cleves will record radio waves produced by both the Sun and the Milky Way. Comparing the intensities of those signals with data collected at other times will make it possible to study the effects of the eclipse on Earth's ionosphere, Chuck Higgins, a founding member of the original Radio JOVE Project, reported at AGU's Annual Meeting 2023 (bit.ly/AGU23-Radio-JOVE).

Ham radio operators are another group of radio aficionados getting involved in eclipse observations. To become a licensed ham

An observer in Texas sets up a phone to use the SunSketcher app during the 2023 annular solar eclipse. Credit: Clinton Lewis/Western Kentucky University

radio operator in the United States, individuals must pass a test demonstrating knowledge about electrical engineering and space physics, among other fields. They're a ready-made cohort of amateur scientists, said Nathaniel Frissell, a space physicist at the University of Scranton in Pennsylvania.

Frissell, whose call sign is W2NAF, said that he hopes that thousands of ham radio operators will be ready when the Moon's shadow enters Pennsylvania at 3:15 p.m. EDT. As the leader of the Ham Radio Science Citizen Investigation (HamSCI), Frissell coordinates crowdsourced science experiments involving radio observations. Several eclipse-related projects are being planned, including ones that build on observations made during the 21 August 2017 total solar eclipse and the 14 October 2023 annular solar eclipse.

"Every eclipse gives you a chance to see things slightly differently," Frissell said.

The hope is that data from HamSCI's participants will hopefully reveal small changes that occur in Earth's ionosphere during so-called ingress and egress, when the Sun is only partially blocked by the Moon.

Inviting All

When the Moon's shadow barrels into New York at 3:16 p.m. EDT, both Buffalo and Rochester will experience totality.

Dan Schneiderman, eclipse partnerships coordinator at the Rochester Museum & Science Center, has been busy helping to plan a plethora of eclipse-related activities for viewers in the Rochester area. There will be no shortage of opportunities to observe the event, Schneiderman said, because 50 local organizations have been designated community eclipse ambassadors and have each received 1,000 eclipse glasses and a telescope with a solar viewing filter, among other supplies.

> **"There's this multisensory experience you can have."**

Schneiderman is also helping to publicize crowdsourced science opportunities. One is Eclipse Soundscapes, a NASA-funded project in which participants collect audio data and other multisensory observations of an eclipse. There's more to an eclipse than just its visual impact, said Henry "Trae" Winter, one of the coleaders of the project based in Medford, Mass. "There's this multisensory experience you can have."

As part of the Eclipse Soundscapes team, an amateur scientist can record the sounds made by animals or changes in temperature that occur during the eclipse, Winter said.

The project is building on a much earlier study that measured how the behaviors and vocalizations of birds, mammals, insects, fish, and other animals changed during the total solar eclipse in 1932. One goal of Eclipse Soundscapes is to determine whether a minimum eclipse threshold—that is, the fraction of the Sun's disk that's blocked by the Moon—is necessary for animals to behave significantly differently.

LightSound is another eclipse-related crowdsourced science project that challenges its participants to think beyond visual observations. The project provides open-source plans to build devices that convert light intensity into sound; as light levels change during a solar eclipse, participants will hear tone changes. The roughly palm-sized LightSound device is intended to allow people who are blind or have low levels of vision to experience an eclipse. LightSound hopes to distribute 750 of the devices before the 8 April eclipse.

After passing through Vermont and New Hampshire, the Moon's shadow will zoom across Maine beginning at 3:28 p.m. EDT.

Shawn Laatsch, director of the Versant Power Astronomy Center at the University of Maine in Orono, is helping to coordinate people involved in the Citizen Continental America Telescopic Eclipse (CATE) 2024 project. The effort, which builds on a similar project conducted around the 2017 total solar eclipse, is looking to place roughly 35 telescopes along the path of totality to observe the Sun's corona in polarized light.

One specific goal is to better understand the so-called middle corona, the portion of the Sun's outermost atmosphere that begins roughly 700,000 kilometers (435,000 miles) beyond the Sun's surface and extends for about 4,000,000 kilometers (2,500,000 miles). Having observations from multiple vantage points along the path of totality will make it possible to construct 3D images of the middle corona, the team hopes.

After leaving Maine, the Moon's shadow will race across eastern Canada and out over the Atlantic Ocean; the entire event will last about 2.5 hours. Researchers and educators alike hope that amateur scientists will embrace the opportunity not only to partake in a special event but also to collect scientifically important data.

Participating in science is a valuable way to cement what is already an awe-inspiring experience, Laatsch said. "Hopefully, it'll inspire them to go further in astronomy."

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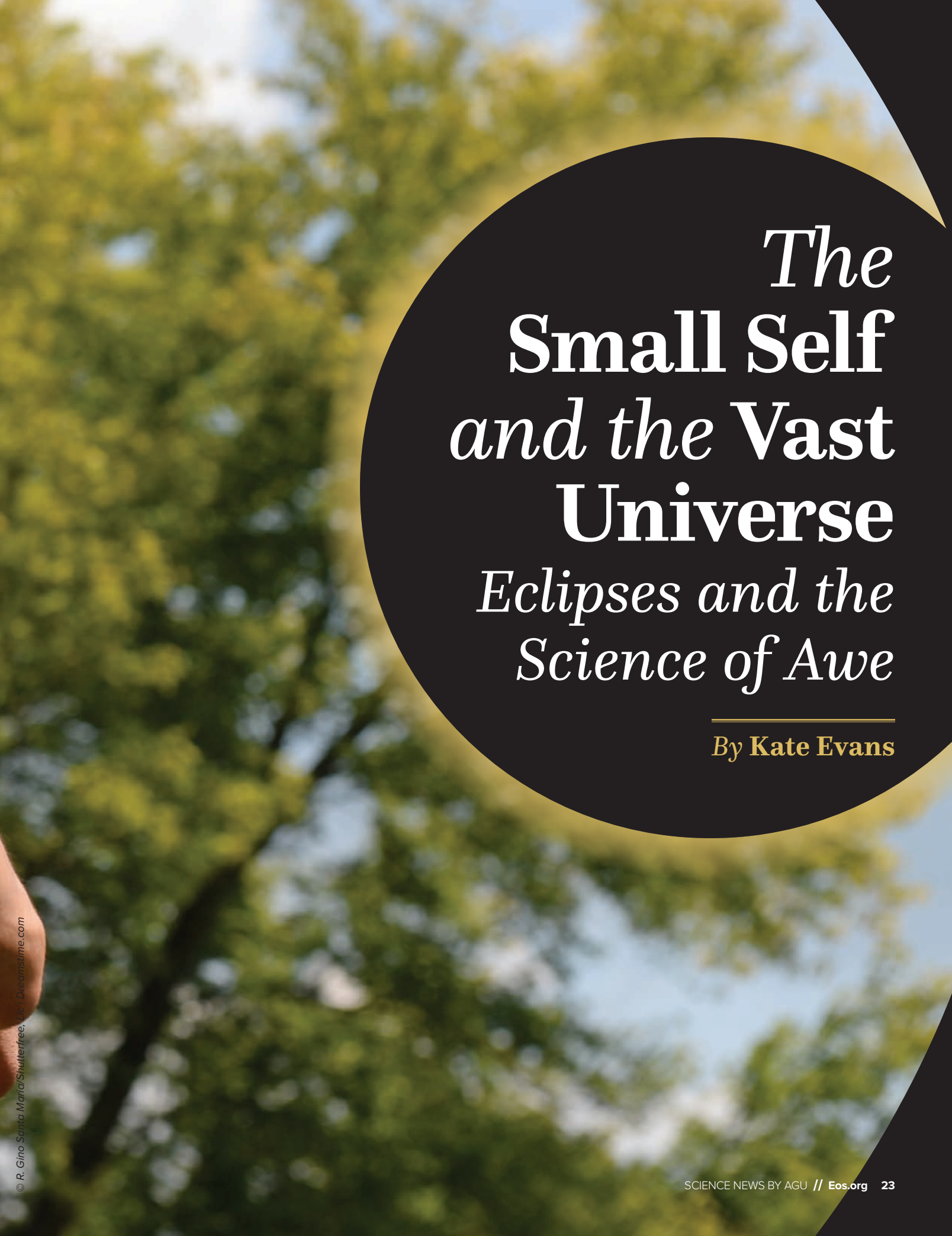

The Small Self *and the* Vast Universe

Eclipses and the Science of Awe

By **Kate Evans**

It sounded as if the Streets were running
And then—the Streets stood still—
Eclipse—was all we could see at the Window
And Awe—was all we could feel.
EMILY DICKINSON

When the Moon's shadow glides over the Sun and the world goes dark, birds call in alarm, bats emerge into the uncanny night, flowers close up their petals, and zooplankton rise to the ocean's surface.

And humans? Humans are overcome with awe. Many accounts of total solar eclipses use the word—like the poem Emily Dickinson wrote to a friend in 1877, which probably refers to an eclipse that had passed over her Amherst, Mass., home 2 years earlier.

What is awe? What does it feel like? Why does it exist? And what is it about a total solar eclipse that seems perfectly designed to provoke it?

In an essay in her 2020 book *Vesper Flights*, nature writer Helen Macdonald tries to find words for the ineffable. It's 2006, and to get into the path of totality, she has traveled to ancient ruins on the Turkish coast, where she's about to experience "a flood of primal awe":

> *I stare at the sky as the sun slides away, and the day does too, and impossibly, impossibly, above us is a stretch of black, soft black sky and a hole in the middle of it. A round hole, darker than anything you've ever seen, fringed with an intensely soft ring of white fire. Applause crackles and ripples across the dunes. My throat is stopped. My eyes fill with tears. Goodbye, intellectual apprehension. Hello, something else entirely....*
>
> *And then something else happens, a thing that still makes my heart rise in my chest and eyes blur, even in recollection. For it turns out there's something even more affecting than watching the sun disappear into a hole. Watching the sun climb out of it.*

Writing 50 years earlier, biologist and author Rachel Carson wondered, "What is the value of preserving and strengthening this sense of awe and wonder, this recognition of something beyond the bounds of human existence? Those who dwell, as scientists or laymen, among the beauties and mysteries of the earth are never alone or weary of life."

Investigating Awe

Researchers have taken a renewed interest in the science of emotions in the past 4 decades.

It took them a while to get around to awe, said Dacher Keltner, a psychologist and codirector of the Greater Good Science Center at the University of California, Berkeley. "I think people might have felt a little leery of being a scientist studying the sublime or the spiritual. It almost sounds New Agey," he said. Yet awe is foundational to our experience of music, literature, art, and spirituality, he explained. "It's a central emotion in other disciplines, and we just had forgotten it."

"I think people might have felt a little leery of being a scientist studying the sublime or the spiritual. It almost sounds New Agey."

When Keltner turned his attention to awe, it was so rich in surprises that he spent the next few decades trying to understand it. (In 2023, he published an entire book about it, *Awe: The New Science of Everyday Wonder and How It Can Transform Your Life*.)

Awe is a slippery, mysterious emotion that—like the experience of totality—is difficult to describe. In a 2003 paper, Keltner and a colleague wrote that awe is located "in the upper reaches of pleasure and on the boundary of fear." Paradoxically, it can be triggered both by threat and by great beauty or virtue. But two things are central to the full experience of awe: the perception of vastness and the "inability to assimilate an experience into current mental structures."

In other words, Keltner wrote, "awe is the feeling of being in the presence of something vast that transcends your understanding of the world."

To study awe, Keltner and his colleagues did experiments with people in different settings: They conducted detailed surveys about past experiences of awe; analyzed people's facial expressions, vocalizations, and brain activity in the lab; and observed their behavior and self-perception while gazing up at big trees, white-water rafting, and standing beneath a full-sized replica of a *T. Rex* skeleton.

Together these studies have taught us a lot about the physical and mental characteristics of awe, he said.

"It has this vocalization of like, 'Whoa!'" Keltner said—an ancient, wordless sound made by everyone from that guy in California exulting over a double rainbow to isolated communities in the Himalayas exposed to undersea footage for the first time. People's mouths drop open, they tear up, they feel chills and goose bumps, their hair stands on end. They want to huddle with other humans, like the social animals we are. Then comes what Keltner called "the boundary-dissolving sense of being part of something much larger."

"As you encounter vast mystery, your self starts to get really small," he said. "You feel humble, your ego diminishes, then physiologically, you really open up to the world and to other people.... And then you want to do good—be a better person, be more truthful. That's the unfolding that we documented both outside and then in the labs."

Community and Connection

Before Macdonald saw her first total solar eclipse (in Cornwall, England, in 1999; it was cloudy), she imagined viewing it in "romantic solitude." Other people would just get in the way of her communion with nature, she thought. But when the light dimmed, and the crowds ringing the coast all raised their flashing cameras at once, she felt only connection.

"I'd wanted a solitary revelation but had been given something else instead: an overwhelming sense of community, and of what it is made—a host of individual lights shining briefly against oncoming darkness," she recounted in *Vesper Flights*. "When you stand and watch the death of the sun and see it reborn there can be no them, only us."

Awe can actually be heightened by the presence of others, said Keltner—whether it's viewing a natural spectacle like ocean phosphorescence or a tornado, listening to sublime music, or raising our combined voices in prayer or song. "When we put our minds together, it's transcendent. When you're all focusing on the same thing, and your bodies and your voices are starting to synchronize… there's a power to it that you can't get just looking at the solar eclipse by yourself."

That enhanced sense of community and connection is probably the reason awe exists, said Keltner. "Feeling awe, you'll sacrifice for the tribe, you'll work for it, you feel more identified with it. It integrates you into social networks."

Studies by Keltner and his team bolster the theory that awe-inspiring experiences foster our desire to work together and share resources. In one, participants who had just spent a minute gazing into towering eucalyptus trees were more likely to assist a person who dropped a bundle of pens into the dirt than another group who were directed to look at a mundane building. In another, Dutch children aged 8–13 were more likely to help refugees after watching an awe-inspiring video. "Being in the presence of vast things calls forth a more modest, less narcissistic self, which enables greater kindness toward others," Keltner wrote.

"Being in the presence of vast things calls forth a more modest, less narcissistic self, which enables greater kindness toward others."

But what sorts of vast things? Keltner and his team gathered "narratives of awe" drawn from accounts of encounters with nature, psychedelic trips, spiritual revelations, and pilgrimages. They also collected awe stories in 20 languages from 2,600 people in 26 countries—and although it turns out there is significant cultural variation (in Japan, for instance, awe is more commonly imbued with a feeling of threat), there are commonalities, too.

At first, the scientists assumed that nature-based experiences would be most likely to trigger awe—eclipses, natural disasters, the northern lights, the Grand Canyon. Nature was important, the study showed, but was eclipsed by something else: Around the world, people are most commonly awed by *other people*. This type of awe can take the form of the "collective effervescence" we may feel in religious ceremonies, sporting matches, stadium concerts, festivals, political rallies, or weddings and funerals.

For instance, Māori performing arts—like the haka, a ceremonial chant and dance, and the karanga, a welcome—are explicitly designed to incite *ihi*, *wana*, and *wehi*, three components of awe. "*Ihi* is a psychic power that elicits [an]…emotional response from the audience," wrote scholar Nathan Matthews (Ngā Puhi) in the essay "The Physicality of the Māori Message Transmission." "The response is referred to as *wehi*; a reaction to the power of the performance. *Wana* is the condition created by the combination…it is the aura that occurs during the performance and which encompasses both the performers and the audience."

In 2013, Beyoncé "felt the *ihi*" when a backstage crew in Auckland welcomed her with an impromptu haka, and she responded with her own spontaneous *wehi*—shaking her head, slapping her thighs, erupting in joyous laughter. Nicola Hyland (Te Atihaunui-a-Pāpā rangi, Ngāti Hauiti), a senior lecturer in theater at Te Herenga Waka—Victoria University of Wellington, wrote about "this interchange of *ihi* and *wehi* that evoked the *wana* of the performance.… The intangible *wana* is electric. When I witness a haka performed live (and often even in recordings), it feels as though my insides are roaring. The hairs on my arms stand on end, my heart throbs, and I almost always weep. A powerful internal physical violence, a tearing, a drawing in—but also healing and cathartic.… It is clear that Beyoncé felt something like this."

Most often of all, Keltner's study found, awe is evoked by "moral beauty"—witnessing great courage, kindness, strength, self-sacrifice, or overcoming.

"It was one of the most uplifting surprises of the whole project," Keltner recalled, "that we care so much about other people—and that when we see human goodness, we're moved as powerfully as at a rock concert or Taylor Swift" show.

Chasing Totality

For some people, though—like Australian clinical psychologist Kate Russo—nothing else approaches the immersive and intoxicating awe elicited by "intersecting the Moon's shadow wherever it may be cast on the surface of the Earth.… It's quite profound for some people. People will say it's even more powerful than the birth of their first child."

For Russo, chasing totality has become both an addiction and a way of life.

Her first eclipse was the same one as Macdonald's, in 1999—though Russo had taken a trip to France, where the skies were clear. It blew her mind. "No matter how prepared you are, you are never prepared for it. I just was overcome with that unexpected emotional overwhelm. The world is a different place afterwards. It has to be. And then you just think, when is the next one?"

Russo has now seen 13 total solar eclipses. At first, she was a tourist, using her holidays to travel to wherever caught her eye in the path of totality, from Madagascar to a boat heading west into the Pacific from the Galápagos Islands.

In 2012, the Moon's shadow crossed Russo's home state of Queensland, not far from where she'd grown up. She'd been living in Northern Ireland for years but moved back to Australia 6 months before the eclipse. She soon realized that the communities in its path were woefully unprepared for the experience.

Newspaper articles explained the physics of eclipses but didn't mention their emotional impact. Residents talked about getting out of town to miss the madness, and the city of Cairns was planning a marathon that would begin at the moment of totality.

"I was like, this is just bonkers. Anyone who's seen an eclipse will know that that's never gonna work," Russo recalled thinking of the preparations. Closing off streets for the marathon would restrict people trying to move into the path, she said, and the runners themselves would be hopelessly distracted from either the race or the celestial event unfolding all around them.

Russo now runs an eclipse-planning business to help towns and cities prepare—and she's a passionate evangelist for experiencing totality at least once in your life. "It's almost like my life's mission to be able to share it with as many people as possible," she said.

Russo plans to conduct the first field study of total-eclipse-induced awe in April 2024. In Texas, she and a collaborator will use mobile electroencephalographic headsets to record the brain waves of people viewing a total solar eclipse for the first time in an attempt to measure the rapturous overwhelm of totality.

And totality matters, Russo was eager to explain. Annular or partial eclipses are certainly interesting and maybe even awe-inspiring.

But being fully enveloped in the Moon's central shadow is next-level, Russo stressed. "That is the most incredible, freaky, goose bumps, hair-on-the-back-of-your-neck-standing-up thing, those few minutes when it's 99.99% covered. You have to go all in. You have to get into the path," she said.

Communing with the Corona

The other thing eclipse chasers obsess over is the cloud cover.

Ryan Milligan, an astrophysicist at Queen's University Belfast, has traveled to 10 total solar eclipses. Eight of those were what he calls "successful"—there were clear skies. In 2020, however, Milligan wasn't so lucky. He had managed to get himself to southern Chile at the height of the COVID-19 pandemic, and yet when the moment of totality came, thick clouds covered the sky. The same thing happened in 2015 when Milligan was in the Faroe Islands. "It's soul destroying. It's just—it's crippling," he said.

Clouds obscure many of the awe-inspiring features of a total eclipse, he explained: the oncoming sweep of the Moon's shadow "like a column of darkness hurtling toward you at 1,000 miles an hour," the 360° sunset, planets and stars suddenly appearing, and the Sun's filaments and prominences looping like flames from behind the black face of the Moon.

"Everyone tries to look for an ideal location with a nice backdrop, but I'm like—weather's everything," Milligan said. When the skies are clear, the awe payoff is huge, he added. "It's a real, visceral, primeval experience. Everything's wrong, the light is wrong, the shadows are wrong—it's perfectly safe, obviously, and you know what's happening. But it's a real overwhelm, a really powerful hit. And it's such a fleeting experience."

"No matter how prepared you are, you are never prepared for it."

In April 2023, Milligan drove from Belfast to Dublin; flew to Munich, then Bangkok, then Singapore, then Perth; and then drove 1,250 kilometers up the west coast of Australia—all to experience 60 seconds of totality.

"I wouldn't do that for a partial eclipse, I wouldn't do it for a meteor shower," he said. "You wouldn't do it for any other astronomical or celestial event other than the total solar eclipse."

As a solar physicist, Milligan has an extra layer of appreciation for that rare moment when all but a tiny fraction of the Sun's light is obscured. For a handful of minutes, you can take off your protective glasses and see, with the naked eye, our star's corona and chromosphere—two layers of its elusive upper atmosphere.

Milligan has been studying the solar chromosphere for 20 years, but the only glimpse he ever gets of it is the "beautiful red ring" it leaves around the Moon during a total solar eclipse. "When you get to see that, you're like, 'That's where I work!'" he said.

The rest of the time, sitting in front of a computer, "it's easy to feel detached from the reason you got into astronomy in the first place—that you want to explore space, you want to understand the universe," he said. A regular dose of totality keeps that awe and wonder alive.

Microdosing Awe

In 2017, Nicholas Scarsdale was a graduate student researching exoplanets at the University of California, Santa Cruz. He and a group of friends—"surface physicists, several biochemists, a couple of mathematicians"—met in Philadelphia, piled into two cars, and proceeded to drive 14 hours to South Carolina to see the so-called Great American Eclipse.

As the big moment approached, Scarsdale's crew wound up in a small town. A stage and food trucks were set up on a soccer field, and the group joined about 200 other people waiting for totality.

When it came, Scarsdale and his friends were "a bunch of big nerds…standing in a field just going, *whaaaaat is haaaaappening*," he remembered. Hands on their heads, eyes bugging out, jaws dropped. "Just, like, absolutely stunned. It's so hard to fathom, or to express, what it's like for the Sun to just go out. The human element of wonder really overwhelms any sort of intellectual knowledge. You're just like, *wow*—you can't help but just be present," Scarsdale said.

He was immediately hooked and looks set to become an eclipse chaser himself. "If I had an infinite amount of money, the first thing I would make sure I do is wind up viewing every single total solar eclipse for the rest of my life," he said. "Even for somebody who isn't spiritual, I think it evokes a sense of spirituality—like, I am here, in this moment, just experiencing this one single thing."

For city-born Scarsdale, other awe-inspiring moments that have come close include his first views of the Milky Way in dark skies, Saturn's rings through a telescope, and the monolithic rock of Half Dome in Yosemite National Park—views that "challenge your everyday intuition for how things are in the world," he said.

These kinds of experiences are good for us, Keltner concurred. "Just get out and find awe, and you'll be better," he said.

Preliminary evidence from a review article in *Perspectives on Psychological Science* suggests that awe releases oxytocin, reduces inflammation, decreases our focus on ourselves, and gives us a greater sense of meaning.

But you don't need to chase totality to the other side of the world to experience awe, Keltner emphasized. You can microdose on it every week, if you're paying attention. Awe is all around. One of his recent studies found that "every third day, on average, people feel that they are in the presence of something vast that they do not immediately comprehend."

Keltner encourages people to take regular "awe walks." Try to tap into your sense of wonder, he advises, and imagine you're seeing your surroundings for the first time.

"You don't need to wait for the eclipse," Keltner continued. "The night sky can be great. The sunset can be great. Watching clouds can be great. Yeah, the eclipse is extraordinary. But there's a lot of extraordinary awe around us."

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Read the article at Eos.org

To Meet Climate Goals, Protect the Tongass and Chugach Forests

Nearly half of all bald eagle habitats found in national forests are in the Tongass and Chugach forests. Credit: Erwin Weston, U.S. Forest Service/Flickr, CC-BY 2.0 (bit.ly/ccby2-0)

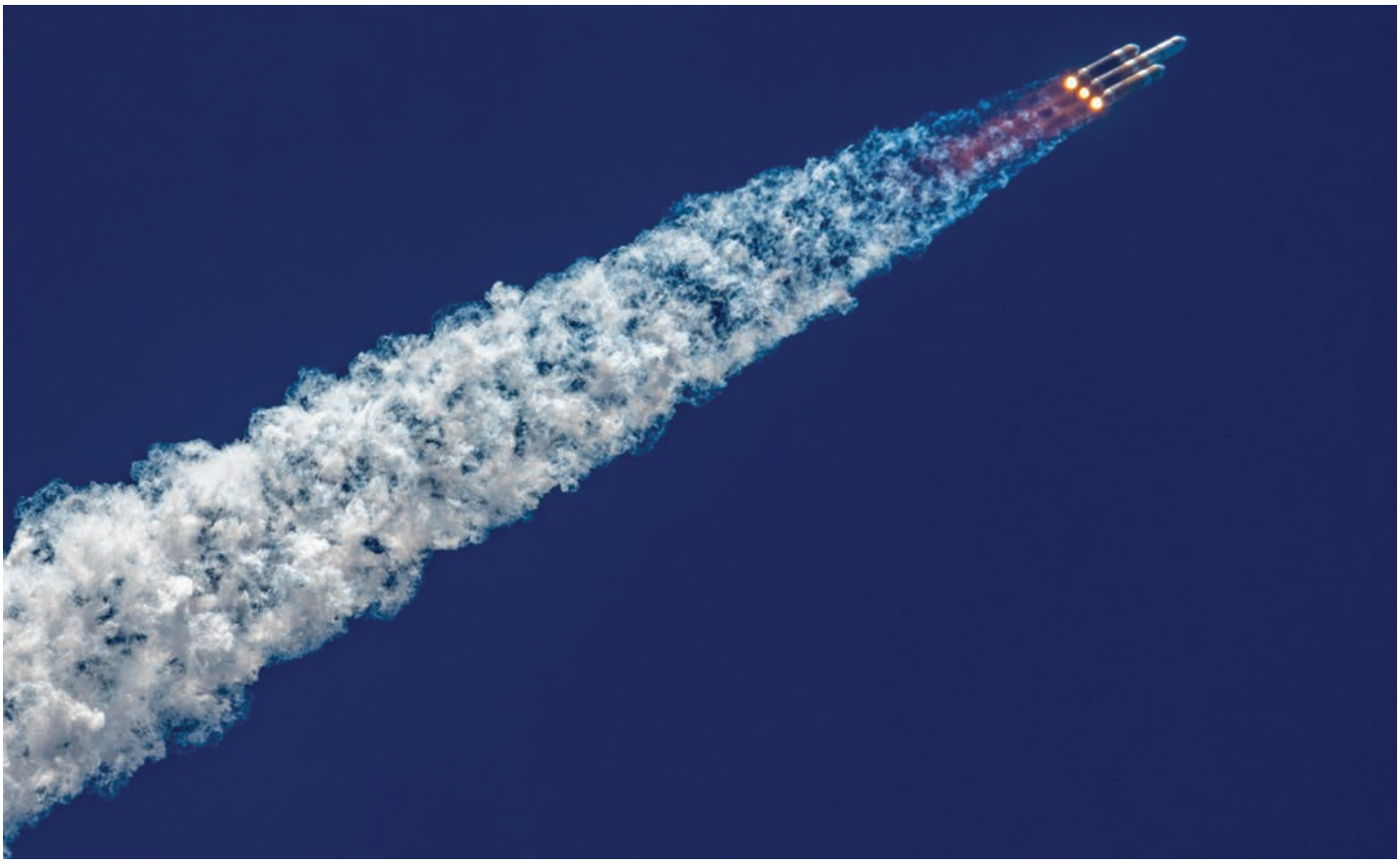
Forests are a powerful natural tool for climate change mitigation, often acting as massive carbon sinks to counteract greenhouse gas emissions while also protecting biodiversity. However, because of deforestation and global warming, many forests have been ravaged by wildfires or have more dead than living trees—and have now flipped from carbon sinks to carbon sources. A new study by *Law et al.* sought to determine which U.S. national forests have the highest potential to act as carbon sinks and preserve biodiversity if adequately protected.

To do this, the team used remote sensing and geospatial modeling data to compile information about forest landscape integrity (or low degradation by humans), carbon stocks, wildlife habitats, and fire activity. The researchers also included climate projections from Coupled Model Intercomparison Project Phase 6 in their analysis.

The Tongass and Chugach national forests in Alaska scored highest on measures of wildlife habitat extent and landscape integrity. The two also scored highly on total tree carbon stock, particularly the Tongass, which alone stores more than 10% of all tree carbon stocks that occur on national forest land. Combined, the two forests store more than a third of carbon stocks in national forests with high landscape integrity. They also have a high number of apex predators, including bald eagles, brown bears, and gray wolves, indicating a healthy and intact ecosystem. Finally, the Tongass and Chugach also scored low on risk of wildfire because they are colder and wetter than many other forests in the United States.

The authors concluded that these combined traits make the Tongass and Chugach forests particularly high priorities for protection. The forests are large and intact, as increasingly few forests will be, and they are naturally buffered against future disturbance from fire and climate change if their integrity is preserved. (*AGU Advances*, https://doi.org/10.1029/2023AV000965, 2023) **—Rachel Fritts,** *Science Writer*

Uncertainty Abounds About Seeding the Sky to Fight Climate Change



Injecting alumina into the atmosphere could potentially reduce global warming. Studies are now being used to understand how such injections might affect stratospheric ozone. Credit: Glenn Beltz/Flickr, CC BY 2.0 (bit.ly/ccby2-0)

As greenhouse gas levels increase in Earth's atmosphere, scientists are considering ways to temporarily limit rising temperatures. One idea is to inject aerosols into the stratosphere to reflect incoming sunlight, thereby reducing global warming and its associated risks. Most previous research has focused on using gaseous sulfur dioxide, which is also released in volcanic eruptions. However, the injection of sulfur dioxide into the stratosphere is associated with side effects including ozone depletion and local stratospheric heating.

Recent studies have shown that the use of solid materials such as alumina, calcite, or even diamond particles could more effectively cool the climate while reducing side effects. But our understanding of how solid material injection affects the stratospheric ozone layer is limited. Current understanding is based on scant, decades-old experimental data on alumina particles emitted into the stratosphere via solid-fuel space rocket exhaust.

In new research, *Vattioni et al.* show that stratospheric conditions resulting from space shuttle exhaust plumes are not comparable to alumina injection scenarios for climate intervention.

They found that although injected alumina may be better than sulfur dioxide in terms of reduced local stratospheric heating, there are "significant uncertainties" in estimating such injections' impact on the ozone layer. The scenarios they tested would inject about 5 megatons of alumina particles into the stratosphere per year, which would compensate for about a quarter of the present-day radiative forcing caused by anthropogenic greenhouse gas emissions. The researchers estimate that the global mean ozone loss from these scenarios could range from negligible to as much as 9%, which is about twice the historical peak of ozone loss from chlorofluorocarbons in the 1990s.

The authors note that more research is needed on the potential surface reactions of solid particles in the atmosphere. In particular, such research would focus on learning more about surface reactions under present and future stratospheric temperatures, trace gas concentrations, and relative humidities. Improving this understanding could help reduce the uncertainty over how solid particles might behave when injected into the stratosphere. (*Geophysical Research Letters*, https://doi.org/10.1029/2023GL105889, 2023)

—Sarah Derouin, *Science Writer*

Iron Snow Ebb and Flow May Cause Magnetic Fields to Come and Go

Just as snow crystals form and then melt as they fall to lower warmer altitudes, scientists believe a phenomenon called iron snow happens in the molten iron cores of some planetary bodies: Cooling near the core–mantle boundary creates crystals of iron, which melt as they fall deeper into the hot core. This movement may create magnetic fields in some smaller bodies like Mercury and Jupiter's moon Ganymede, but its dynamics are not well known.

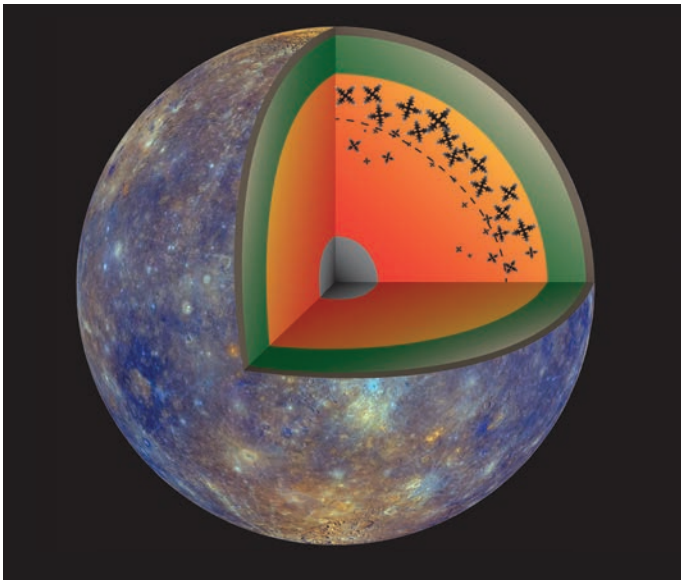
In a first-of-its-kind experiment, *Huguet et al.* modeled iron snow in a lab using water ice and found distinct cycles of crystal formation and inactivity.

The researchers' simple experimental setup involved a tank of water cooled from below, with a layer of salt water at the bottom to prevent ice crystal adhesion. As the lower layers of freshwater cooled, they produced ice crystals, which floated upward and melted once they reached warmer water. This created a current that, along with latent heat created by crystal formation, eventually warmed lower layers of water and halted ice crystal formation. When the water cooled sufficiently again, the process started over.

The researchers found that these "bursts" of crystal formation repeated about every 1,400 seconds in their experiments. This rate was controlled by heat diffusion in the cooling layer, with some variability likely because of the heterogeneity of crystal nucleation.

Their model indicated that planetary bodies with molten iron cores may go through similar bursts of iron snow formation that create internal fluid flows in the molten iron, driving a periodic dynamo that generates a planetary magnetic field. Thus, magnetic fields may appear and disappear at semiregular intervals in these bodies.

Several questions about this process remain, the authors note, including what degree of supercooling is necessary for crystals to form, how iron snow particles move collectively, and how these movements affect large-scale flows within the core. (*Geophysical Research Letters*, https://doi.org/10.1029/2023GL105697, 2023) **—Nathaniel Scharping,** *Science Writer*



Iron snow can occur in planetary bodies such as Mercury, seen here, when cooling near the core-mantle boundary causes iron crystals to form. These crystals grow, then sink into the hot core and melt. Credit: Image by Ludovic Huguet; map texture from NASA/Johns Hopkins University Applied Physics Laboratory/Carnegie Institution of Washington

How Does Heat Rise Through Europa's Ocean?

Europa, one of Jupiter's many moons, may be capable of supporting life because its icy surface likely obscures a deep, salty ocean. If present, Europa's ocean is probably in direct contact with its mantle rocks, and interactions between rock, water, and ice could provide energy to sustain life.

Lemasquerier et al. modeled Europa's ocean to examine how heat from the mantle drives ocean circulation and affects the thickness of its icy surface.

The mantle heat that drives ocean circulation on Europa comes in two forms. Radiogenic heating is caused by the decay of radioactive materials in the mantle and is uniformly distributed. Tidal heating is caused by the deformation Europa undergoes as it orbits Jupiter and experiences the planet's strong gravitational pull. Tidal heating is uneven; it's higher at Europa's poles and lower at the points of the moon that are opposite and facing Jupiter.

Using simplified idealized modeling that did not consider salinity and ocean–ice feedbacks, the researchers examined how heat might transfer from Europa's seafloor, through its ocean, and up to its icy shell. They found that if tidal heating is dominant in the mantle, the latitudinal heat variations from the floor would be transferred up through the ocean, affecting ice thickness and leaving it thinnest at the poles. However, if radiogenic heating is the dominant type of heating in the mantle, then the ocean would have a relatively small impact on ice thickness.

The 2024 Europa Clipper mission could help confirm these findings and offer new insights into the link between Europa's mantle heating, its ocean circulation, and the thickness of its icy crust. (*AGU Advances*, https://doi.org/10.1029/2023AV000994, 2023) **—Rebecca Owen,** *Science Writer*

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- Familiar with Esri products (i.e., ArcPro, ArcEnterprise, ArcGIS Online) and other open-source GIS software (i.e., QGIS).
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The Department of Earth Sciences, University of Toronto, Canada, invites applications for the **Roger E. Deane Postdoctoral Fellowship** in any field of the Earth Sciences. The Department is interested in supporting innovative research and excellent early career geoscientists to work in collaboration with one or more faculty members.

Applicants must contact potential supervisors in advance to discuss areas of common interest and proposal ideas. Applicants must obtain approval from a proposed supervisor to apply. Only applicants who have secured a potential supervisor willing to supervise will be considered. Faculty who may be eligible and available to supervise are listed here:

https://www.es.utoronto.ca/people/faculty/
Note that not all supervisors are taking on new lab personnel. Contact potential supervisors prior to applying.

ABOUT THIS AWARD: This endowed award was created thanks to a bequest from Dorothy M. Deane, widow of the late Prof Roger E Deane, an alumnus of the Department of Geology, University of Toronto (U of T). Prof Deane obtained a PhD in 1949 under the supervision of Prof Alexander Maclean, and returned to U of T as a faculty member in 1955, pursuing research in the areas of glacial geology and Pleistocene paleoenvironments. Prof Deane served as the inaugural Director of Research at the U of T Great Lakes Institute which eventually contributed to the founding of the U of T School of the Environment. Prof Deane died in a tragic boating accident near Tobermory, Ontario in 1965 while undertaking field work.

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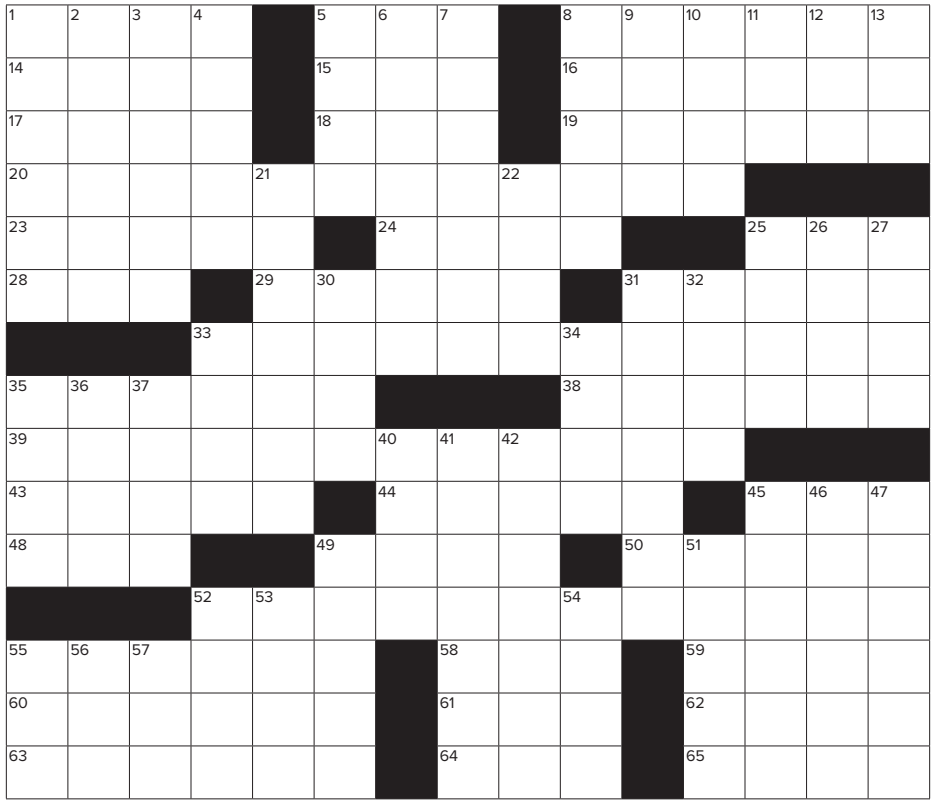
Sky Dance

By Russ Colson, Minnesota State University Moorhead



ACROSS

1 Go quickly
5 Alien beings
8 Former Navy fighter jet, Grumman F-14 ___
14 Word appearing twice in the Golden Rule
15 Decay
16 Sufficient
17 Brash self-confidence or burglar booty
18 Crystalline H_2O
19 Mixed selection of songs
20 Predicting this event played a key part in Mark Twain's *A Connecticut Yankee in King Arthur's Court*
23 Tehran resident
24 Word connecting "Sun" to "rises" in a Hemingway title
25 Vehicle model or mammal with rear-curling horns
28 Film director Lee
29 Hyperion, Cronos, or Phoebe
31 Deer with broad, flattened antlers
33 In the Amblin Entertainment logo, Elliott's bicycle passes across the Moon in a ___ ___
35 Model Ys or units of magnetic flux
38 In the Galápagos, Darwin observed adaptations of the marine ___
39 Stars that winked out during ___ by the Moon allowed ancient people to realize that the Moon remains present even when not seen
43 Degree recipients or several 0.9-degree increments
44 Lather, ___, repeat
45 Hard drive with no moving parts (abbr.)
48 "Let us not seek to satisfy ___ thirst for freedom by drinking from the cup of bitterness and hatred" Martin Luther King Jr.
49 Top of a canyon, edge of a wineglass, and a basketball hoop
50 Titter (variant)
52 Celestial events that block the Sun's light have been taken as harbingers of positive or negative transformation: ___ or ___ ___
55 Nothing is so ___ as gentleness, said Ralph Sockman
58 Santa ___ winds
59 Acid counterpart
60 "It's true hard work never killed anybody, but I figure, why take the ___?" joked Ronald Reagan
61 Type of lighting used for energy efficiency
62 Companion to "happily" and "after"
63 Los Angeles baseball player
64 Paleozoic, Classical, or Modern
65 Stop along a highway

DOWN

1 Setting for *War and Peace*
2 Garment not used or frayed
3 __ 17, or __ Luft III of *The Great Escape*
4 Navajo dwelling
5 Economically transformational canal completed in 1825
6 Organ composition
7 Exceptional, or related to the theme of this puzzle
8 Pace
9 Prior to twos and threes
10 Companion to "à la"
11 Start for a dead end
12 Maastrichtian, Enlightenment, or Stone
13 Your, long ago
21 Weddings, bar mitzvahs, baptisms, and Sun dances
22 Song lyrics: __ it romantic or __ it ironic
25 Parks or Luxemburg
26 Amazon product number
27 Start for data, phor, some, or morphic
30 Established org.
31 Model T charger, or 1963 Lee/Kirby creation
32 Burden of responsibility; "The ___ is on you"
33 Celtic warrior god, or anagram of dull
34 Amazonas y el Grande
35 "...and I'll take that burger ___ ___"
36 Beige
37 Start for "city" yielding "in short supply"
40 Like the Atacama, Sahara, or Gobi
41 Type of kettle drum or anagram for bimetal
42 Crazier
45 To gather and bind (wheat)
46 Touch, sight, hearing, etc.
47 Atacama, Sahara, or Gobi
49 Communication acknowledgment, e.g., by battle droids in *The Phantom Menace*
51 "Ah, distinctly I remember it was in the bleak December; And each separate dying ___ wrought its ghost upon the floor" Edgar Allan Poe
52 Disk-shaped musical bell
53 "___ upon a midnight dreary, while I pondered, weak and weary" Edgar Allan Poe"
54 Child's first word?
55 Terminal degree in science
56 Longer words are cumbersome. They can be shortened, ___
57 Cool, neat, fire, nifty, swell, groovy

See p. 8 for the answer key.

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