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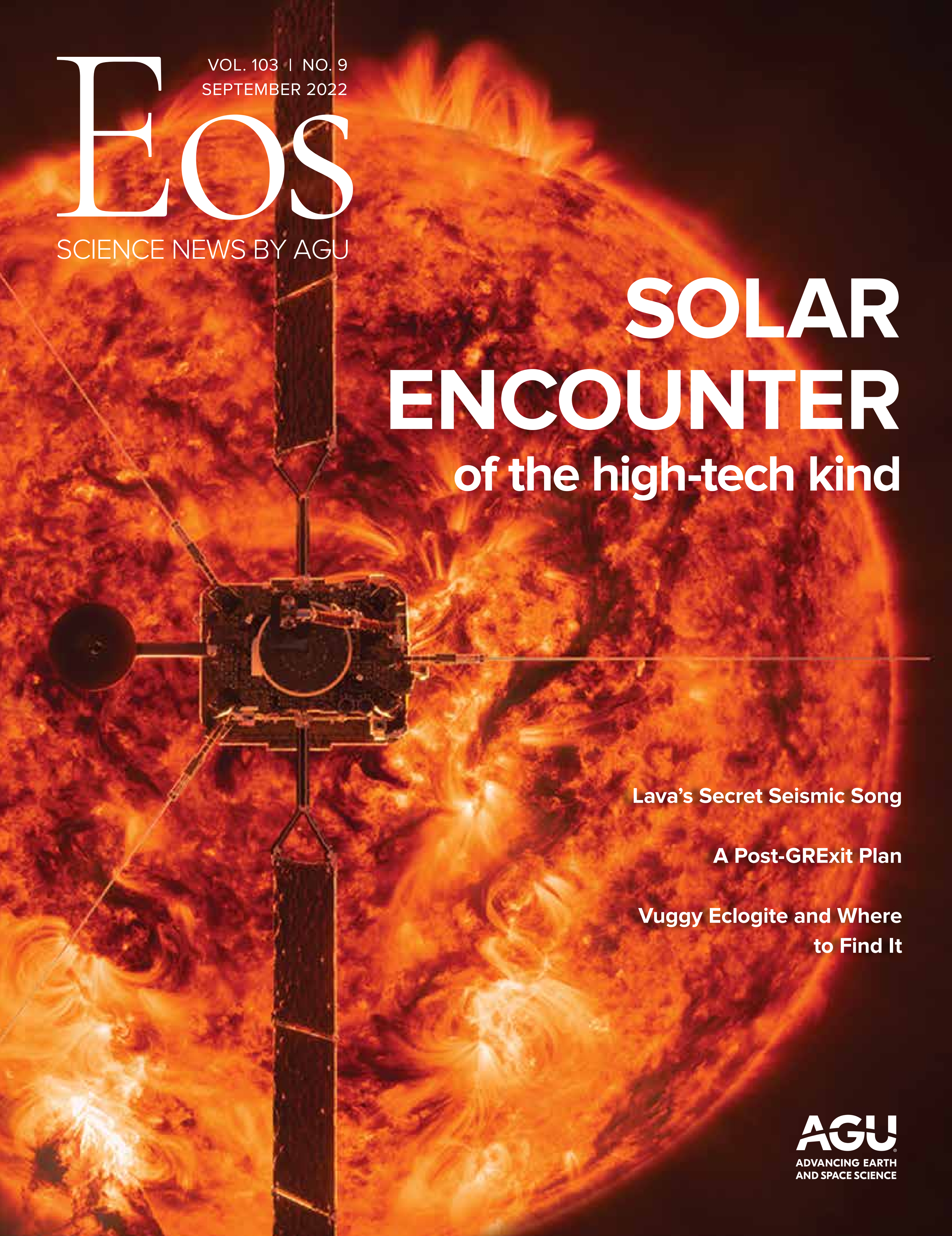

SOLAR ENCOUNTER
of the high-tech kind

Lava's Secret Seismic Song

A Post-GRExit Plan

Vuggy Eclogite and Where to Find It

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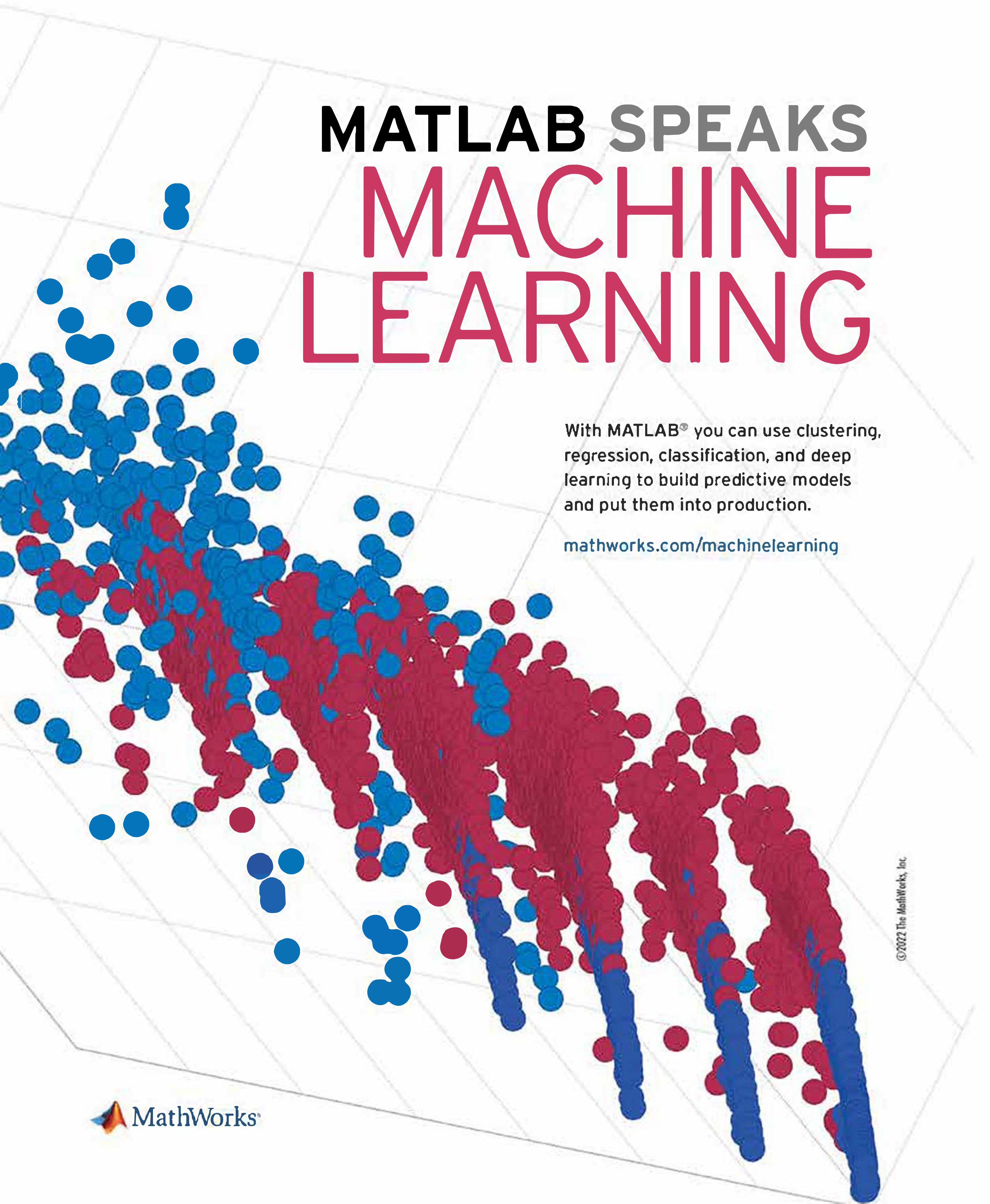
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Brighter Skies Ahead

We are quickly approaching an auspicious time for solar science. An impressive cadre of Sun-targeted missions has recently come online to replace or support an aging fleet of spacecraft, just as solar max is about to set in. In our September issue, *Eos* is staring straight into this bright future.

In February 2020, Solar Orbiter launched from Florida, carrying 10 state-of-the-art instruments to make the closest ever observations of the Sun. Daniele Telloni and colleagues, in "A New Journey Around (and Around) the Sun," describe for us "the groundbreaking observations that Solar Orbiter has made already," such as the "short-lived, small-scale flickering bright spots, nicknamed 'campfires,' in the solar corona." Not only will this joint European Space Agency–NASA mission shed new light on the unsolved mysteries of the Sun, but also it's revealing a new side of Venus from its 2020 flyby. Turn to page 20 to read all about it.

We dive into the Sun—in the only way we can—in our next feature, "Shake, Rattle, and Probe," on page 26. Helioseismology is a burgeoning discipline that allows physicists to better understand the structure of our star. They also have, as you'll read, some of the best mission names—GONG, BiSON—and science metaphors (I won't spoil these) to allow us to visualize the Sun's roiling interior.

Finally, as we ramp up to solar max, we talked to researchers about what's in store for study with all the new technology available. In "11 Discoveries Awaiting Us at Solar Max," on page 34, get excited about peering inside coronal mass ejections, creating "Sun to mud" predictions, and better understanding magnetic fields throughout our solar system.

I'd like to pause here and mention that shortly after completing his insightful look into innovative solar science in this issue, Daniele Telloni joined our panel of *Eos* Science Advisers. We welcome him along with around a dozen new advisers who came on board this summer for a 2-year term—find them in the masthead to the right. If you are an AGU member and would like to represent your discipline's section by directing the *Eos* editing team to innovative and exciting coverage in the Earth and space sciences and evaluating proposals submitted by scientist-authors, talk to your section leadership about volunteering with us.

We need more experts passionate about developing a worldwide culture that trusts in science, and Science Advisers contribute enormously to that mission during their time with *Eos*. Our thanks go out to the Science Advisers who rolled off this summer, and to those with us now helping to create great issues like this one!

Heather Goss, Editor in Chief

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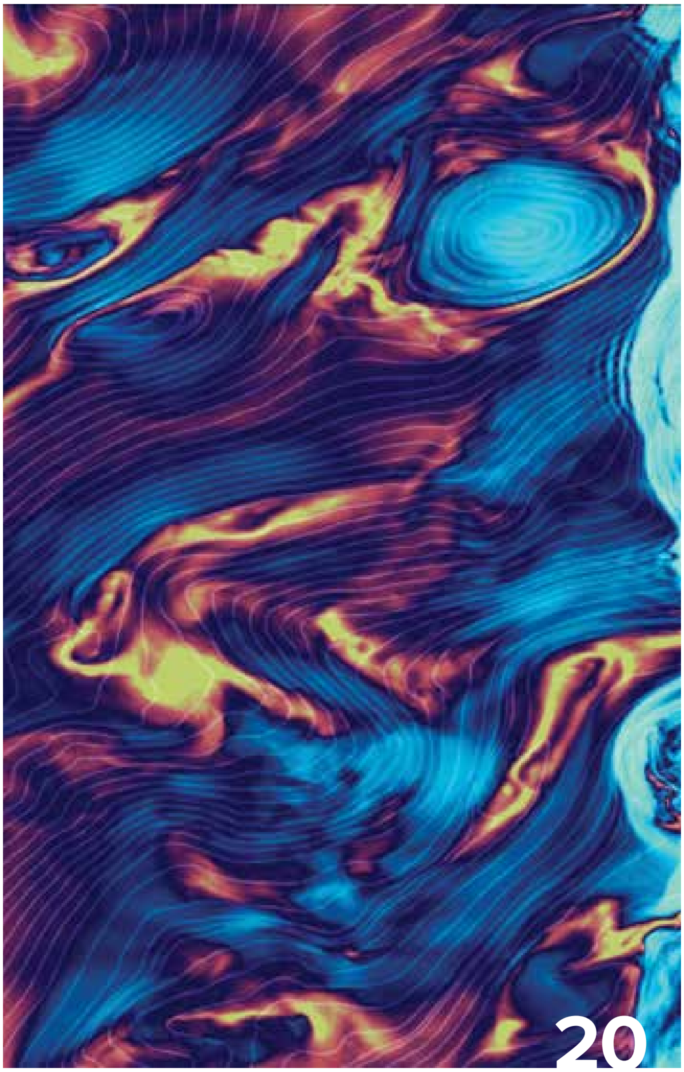
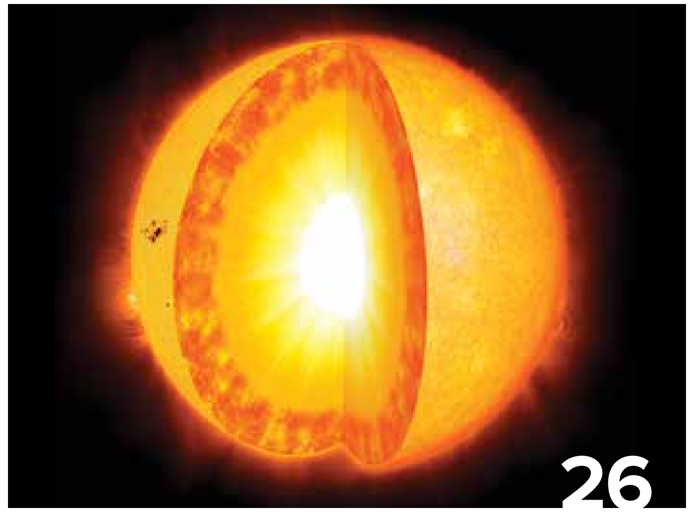
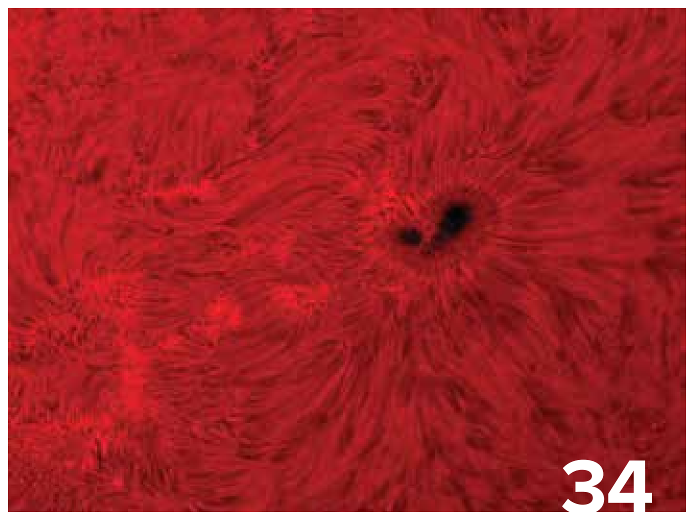
Randy Fiser, Executive Director/CEO



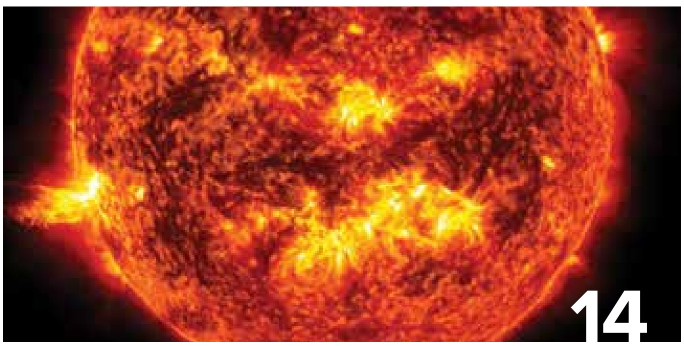




Features

On the Cover

The Solar Orbiter spacecraft stares at the Sun in this artist's illustration. Credit: European Space Agency/ATG medialab



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Coronal Dimmings Shine Light on Stellar CMEs

Solar Dynamics Observatory/NASA

You could be forgiven for missing what comes after a coronal mass ejection (CME). Colossal outbursts of plasma hurtling into space at hundreds to thousands of kilometers per second, CMEs are a spectacle.

But researchers are now turning their gaze away from a CME's jettison to what's been lost. After a CME, extreme ultraviolet light in the corona dims noticeably at the ejection site. Finding darkened spots could hold a key to observing elusive stellar CMEs.

New research using coronal dimming to identify CME candidates in stars found 21 occurrences of coronal dimmings in 13 different stars.

If these dimmings indicate CMEs, the latest work represents the largest number of stellar CMEs detections reported.

Before this research, scientists could "probably count 'convincing detections' with our hands," said astrophysicist Julián David Alvarado-Gómez at the Leibniz Institute for Astrophysics Potsdam, who was not involved in the work. "And some scientists would probably remain skeptical about some of them."

Pinpointing stellar CMEs could be important for finding habitable exoplanets. Stellar flares could "totally blow away the atmosphere of an exoplanet," said Astrid Veronig, the lead researcher of the latest work and chair of Solar and Heliospheric Physics at the Institute of Physics at the University of Graz in Austria.

Coronal Dimming

Over the past 3 decades, researchers have detected evidence of stellar CMEs from M-class stars. And in a 2019 paper in *Nature Astronomy,* Costanza Argiroffi published a detailed account of a monstrous CME from a star 450 light-years from Earth (bit.ly/stellar-CMEs).

Veronig and her colleagues took a different approach: coronal dimming.

Coronal dimmings are lower-density regions in a star's corona that occur after those areas are depleted of plasma following a CME. If these dimmings indicate CMEs, the latest work represents the largest number of stellar CME detections reported.

Veronig found certain stars that dimmed more than once, like the rapidly rotating AB Dor with five events, the young AU Mic with three events, and the nearby Proxima Centauri with two events.

"Proxima Centauri is the most interesting because it's our closest star and it's known to have exoplanets," said Veronig, who published the work in *Nature Astronomy* last year (bit.ly/dimming-CMEs).

Sun as Star

To start, the researchers first considered coronal dimming on our Sun. Looking at the Sun as if it were a far-off star, they analyzed the extreme ultraviolet light curves from instruments on NASA's Solar Dynamics Observatory (SDO). They compared fluctuations in the light curve with images of CMEs and coronal dimmings caught by spatially resolved instruments on SDO.

The scientists found that CMEs from the Sun precede coronal dimmings that decrease broadband extreme ultraviolet emissions by a few percent. The probability that the signature they observed was related to a CME was 95%.

Next, Veronig and her team looked for stellar dimmings. Combing through historical extreme ultraviolet data collected by the Extreme Ultraviolet Explorer from NASA, as well as soft X-ray wavelengths from the European Space Agency's X-ray Multi-Mirror Mission and NASA's Chandra X-ray Observatory, they found about 200 star candidates.

The stars had to be Sun-like, known to flare, and measured for long-enough periods (e.g., 10 hours) to qualify.

Unlike solar dimming of a few percent, stellar dimming decreased emissions by up to 56%. Stellar light curves are noisier than the Sun's, so only big events came through.

After a CME, extreme ultraviolet light in the corona dims noticeably at the ejection site.

"Now we've shown it is possible, can [scientists] go further and extract more information from it?" Veronig said of the new technique. Satellite missions planned by NASA, like the proposed Extreme-ultraviolet Stellar Characterization for Atmospheric Physics and Evolution (ESCAPE) mission,

would make spotting stellar coronal dimmings easier.

Building Momentum

Alvarado-Gómez called the work a "crucial contribution" to understanding space weather around other stars but worried about an underlying assumption that other stars behave like our Sun. "Dimmings alone are not sufficient to unequivocally find a CME event," he said.

"Now we've shown it is possible, can [scientists] go further and extract more information from it?"

Assistant professor of physics and applied physics Ofer Cohen at the University of Massachusetts Lowell called the technique promising but warned that detecting coronal dimmings can't tell us about a CME's characteristics or spatial position on the stellar disk. Cohen did not participate in the research.

The results support a simulation paper by Meng Jin at the SETI Institute and the Lockheed Martin Solar and Astrophysics Laboratory (bit.ly/coronal-dimming). Digging deeper into these promising findings from the latest paper and advancing modeling, said Jin, "will provide a critical reference for further instrumentation and methodology to better detect stellar CMEs that significantly influence the habitability of exoplanetary systems."

By **Jenessa Duncombe** (@jrdscience), Staff Writer

A Hail of a Night in Mexico

The sudden crash of hail hitting Hector Dorantes's balcony on the night of 12 June made him quickly look out his window in the Benito Juárez municipality, on the western side of Mexico City. Hundreds of leaves were falling from the trees to the ground, which was covered in what appeared to be a blanket of snow. Minutes after the downpour, the phone rang.

"Are you OK?" his neighbor asked. The hail had done more than carpet the ground: "The supermarket just collapsed."

Dorantes left his home immediately, but as he took his first step onto the street, his foot sank into a 20-centimeter-deep layer of marble-sized hailstones. As he approached the nearby shopping complex, the honks of stopped traffic and the sirens of ambulances and fire trucks kept blaring. When he arrived, the scene stunned him. "It was a disaster," he said.

Approximately 20 metric tons of hail collapsed the 1,000-square-meter roof of the local supermarket. And although there were no injuries, more than a dozen other incidents were reported that night in the Álvaro Obregón, Benito Juárez, Iztapalapa, and Coyoacán municipalities.

Four trees, each between 10 and 20 meters tall, fell and damaged the power grid in several parts of the city. Nine water obstructions

The most recent research indicates that the occurrence of hailstorms will decrease with climate change, but their severity will increase over time.

stopped traffic for up to 4 hours in Benito Juárez and Álvaro Obregón, the most affected municipalities. In addition to the supermarket, 12 structures and roofs of houses and businesses were damaged in both municipalities.

To deal with the damage on the night of 12 June and the early morning of 13 June, a total of 1,200 responders from the city's

The collapse of the reinforced-sheet-metal roof of the Mega supermarket was the most serious damage caused by the hailstorm in Mexico City on 12 June. No injuries were reported. Credit: Hector Dorantes

Water System, Fire Department, Comprehensive Risk Management and Civil Protection, and the Secretariat of Works and Services were needed.

Although hail is frequent in Mexico City during the spring-summer transition, citizens were surprised by the sheer volume of it that covered the highways and houses on 12 June.

Dorantes, who had never seen anything like it before, immediately thought of one thing. "It should be because of climate change," he said.

He was not the only one who thought about it. In the days following the hailstorm, people from both civil society and the scientific community began to discuss whether climate change might have had something to do with what happened.

A Perfect Storm

For Paulina Ordóñez, an Earth physicist at the Center for Atmospheric Sciences and Climate Change at the National Autonomous University of Mexico, the only way to resolve the question would be to conduct an attribution study to understand whether the duration, impact, or probability of a meteorological phenomenon could be affected by human-induced climate change.

In the case of hailstorms, evidence is still scarce because of the difficulty of studying the phenomenon. The most recent research indicates that the occurrence of hailstorms will decrease with climate change, but their severity will increase over time.

"Climate change is undisputed; the increase in global temperature in proportion to the concentration of greenhouse gases is a fact.... It's not that the hailstorm in the city is not related. We just don't know it yet," Ordóñez said.

Although the hail might have been a consequence of the rainy season, staff of the Early Warning System of the Comprehensive Risk Management and Civil Protection of Mexico City anticipated a high-pressure system over the west of the city produced by a number of factors, said Guillermo Ayala, director of the agency.

On 7 June—5 days before the hailstorm—the Megalopolis Environmental Commission registered a high concentration of ozone. This, combined with temperatures of up to 30°C and intense solar radiation, increased the region's stationary winds, which in turn caused the contamination in the city not to dissipate, producing the ozone concentration.

The ozone produced a "large bubble of high pressure" that ended precisely on Sunday, 12 June, explained Ayala. When that happened, winds and moisture from the Pacific Ocean and the Gulf of Mexico interacted with a cold front coming from the north, generating a "temperature shock" that produced the hail, Ayala said.

The Mexico City Fire Department arrived minutes after the Mega incident to ensure that the problem did not escalate. Credit: Hector Dorantes

"Would this storm have been the same 100 years ago? Most likely not."

We're Asking the Wrong Questions

Mexico City is not the only part of the country that has been recently affected by severe weather events. Just 1 day after the capital's hailstorm, the government of the state of Jalisco confirmed that the city of Guadalajara had experienced its heaviest rainfall in 30 years. In a total of 40 flooding events, 92 houses had water levels above 50 centimeters, and 92 cars were stranded.

At the same time, the city of Monterrey is experiencing its worst drought since 1988. As a consequence, the state government of Nuevo León has been supplying only 6 hours of water a day to its inhabitants since the beginning of June.

José Martín Cortés, a meteorologist at Universidad Veracruzana, said that the severe weather in Jalisco and Nuevo León, which involved new record levels of precipitation and drought, was more attributable to anthropogenic climate change than was the hail in Mexico City. As with Mexico City, however, Guadalajara and Monterrey are among the most urbanized areas in the country.

Still, for Jorge García, a climate physicist at Columbia University, the problem is that the question being asked ("Is this severe weather caused by climate change?") is wrongly formulated from the start. Extreme weather events have always existed; none of them are specifically, solely "caused" by climate change.

But climate change has affected the atmosphere in which all of these events happen, and that influences the severity of the events. Mexico is one of the fastest warming countries in the world (0.3°C per decade); this causes the atmosphere to be able to hold more moisture, which, when combined with the winds inside clouds, strengthens the already perfect conditions for strong hailstorms to form, García explained.

So instead of asking whether anthropogenic climate change caused the hailstorm, García said, "what we can ask ourselves is how climate change affected the amount of hail and the probability of having this storm that turned the whole city white. Would this storm have been the same 100 years ago? Most likely not."

By **Humberto Basilio** (@HumbertoBasilio), Science Writer

Tree Mortality Risk Surges in Australian Rain Forests

Over the past 35 years, tree mortality risk in Australia's tropical regions has doubled, according to new research. Such mortality would radically reduce biodiversity as well as carbon residency time, a threat faced by tropical rain forests around the world.

"Moist tropical forests are some of the most biodiverse and productive ecosystems on the planet," said David Bauman. The lead author of the study and a postdoctoral researcher at the French National Research Institute for Sustainable Development and the University of Oxford, Bauman noted that just 13 hectares (32 acres) can support more than 530 species of trees. "They're critical allies in mitigating climate change, but they're also vulnerable to climate change," he said.

The Daintree Rainforest was one of the sites of a 49-year study of tropical rain forests in Australia. Credit: Dinkum/Wikimedia, Public Domain

"Moist tropical forests are some of the most biodiverse and productive ecosystems on the planet."

Bauman and his colleagues attributed high tree mortality risk to the increasing vapor pressure deficit (VPD) associated with climate change. VPD describes the difference between the amount of moisture actually in the air and the amount of moisture the air can potentially hold. As the climate warms, VPD, sometimes nicknamed "atmospheric drought," limits plant growth.

"With increasing temperatures, vapor pressure deficit will rise, and that's why this paper is relevant," said Pieter Zuidema, a professor of tropical forest ecology at Wageningen University and Research in the Netherlands. "It shows that these mechanisms will continue to increase tree mortalities over time."

The results were published in *Nature* (bit.ly/tropical-tree-mortality).

A Rare Long-Term Monitoring Data Set

Bauman and his coauthors analyzed tree dynamics from 24 old-growth forest plots in northern Queensland, covering 49 years. The data set, made available by Australia's Commonwealth Scientific and Industrial Research Organisation, encompassed climate gradients and many species of trees. The length of the monitoring study, however, is what sets it apart.

"Long-term monitoring of forest populations is rare," said Benjamin Poulter, a research scientist at NASA's Biospheric Sciences Laboratory. Poulter noted the study's "incredible 49-year-long record of tree growth, establishment, and mortality."

The broad, long-term analysis revealed a loss in biomass, making Australia's tropical rain forests unique in recent years. "Observations from forest inventory plots in the Amazon or in African tropical forests generally show an increase in biomass over the last few decades, but this wasn't the case with the Australian plots, where we saw decreases," said Lucas Cernusak, a coauthor and an associate professor at James Cook University in Australia.

Scientists said results from the Australian study may help guide research and even policy outside Australia. If similar patterns of tree mortality are documented in other forests, their rate of biomass gain might decrease, and eventually the rate might drop. This means less carbon storage in the forest and more carbon in the atmosphere.

"The first and most important step is to cut emissions and decarbonize our systems," Bauman said.

Another step is to conserve old-growth forests, he added. Data from long-term monitoring, like those Bauman was able to analyze in Australia, can help in this effort.

Poulter concurred. "Sustained investment in long-term forest monitoring is essential to understand the processes that are causing tropical tree mortality. Expanding the networks to new geographic locations, and to include different disturbance and recovery histories, will help inform conservation and management," he said.

By **Rishika Pardikar** (@rishpardikar), Science Writer

How Can Silicone Wristbands Help Firefighters?

As fire season picks up, firefighters tasked with protecting lives, property, and nature are especially prone to deleterious, long-term health effects like cancer. Among the first steps in evaluating health risks posed to firefighters is understanding sources of toxic chemical pollutants.

A team of scientists led by Heather Stapleton, an environmental scientist at Duke University affiliated with the Duke Cancer Institute, used a combination of silicone wristbands (like the once ubiquitous cause-awareness bracelets) and surveys to track exposure and activities of structural firefighters who typically respond to building and car fires. In their first study on the topic, published in *Science of the Total Environment,* the scientists measured 134 different chemicals on wristbands worn by firefighters for 6 days in three different scenarios—on duty and fighting fires, on duty with no fires, and off duty (bit.ly/firefighter-wristband). In each scenario, different chemical species spiked. Working together, scientists and firefighters can begin to parse relative differences in pollutant sources and connect them with human health.

Working Together

Worried about the well-documented cancer risks faced by structural firefighters, the Durham Fire Department in North Carolina approached the Duke Cancer Institute, resulting in collaborative efforts to confront their concerns. Stapleton and her coauthors focused on one aspect of the fire department's queries: What are the differences in the firefighters' exposure to chemical pollutants while on and off duty?

Stapleton's team designed the study with firefighter input, alighting on a combination of silicone wristbands and surveys, said Jessica Levasseur, a doctoral student and the study's lead author. "You don't want to add anything to [firefighters] that can put them at greater risk." Silicone can record the presence of certain chemicals, and firefighters can put on their wristbands and forget about them, she said.

To understand the wristband data, said Stapleton, "we needed to know more about their daily activities." The surveys, conducted at the end of each 6-day scenario, let firefighters easily document whether they responded to a fire while on duty and track their off-duty pursuits.

Connecting Exposures to Health

The wristbands revealed increased concentrations of certain compounds when the firefighters fought fires, said Levasseur. These compounds included carcinogenic polycyclic aromatic hydrocarbons (PAHs) produced by burning organic matter (think forest fires or combusting gasoline, especially fire engines idling in a forest) and some potentially hormone disrupting flame retardants (often found in furniture and home electronics).

For other chemicals, "there is a clear occupational exposure that is independent of the fires," said Pierre Herckes, an atmospheric scientist at Arizona State University who was not involved in this study.

Exposure to some phthalates, which carry fragrances and make materials like plastic packaging and tubing more flexible, was higher in off-duty wristbands, indicating that these exposures occurred at home, Levasseur said. "We're not commenting on what got into people's bodies, but we're saying that this is what they were exposed to while they were wearing the wristband."

For their next study, Stapleton and her team are conducting blood and urine sampling at the beginning and end of a 4-month study period to identify changes in firefighters' bodies that might reflect cumulative exposure. Combined with wristband and survey data, this information can connect pollutant sources and exposure to biological changes.

> **"Firefighters can put on their wristbands and forget about them."**

Wildland Versus Structural Fires

Wildland firefighters—those who fight wildfires—are fewer in number and often work seasonally. As a result, they are harder to track, and less is known about their cancer risk, said Jeff Burgess, a professor of public health at the University of Arizona who was not involved in the Duke study. He's currently leading cohort studies including both structural and wildland firefighters in the United States and is planning to incorporate wristbands into the ongoing wildland firefighter studies in collaboration with Stapleton and others.

Wildland firefighters often fight fires with neither respiratory protection nor heavy personal protective gear, said Burgess.

In particular, wildland firefighters wear flexible, lightweight clothing with bandanas over their faces, said Jeff Hughes, a recently retired Orange County, California, fire captain who has fought both types of fires. "When you're running up and down the hills carrying a ton of weight...wearing [respiratory protection] over your face is a challenge," he explained.

Wildland firefighters also fight campaign fires—large wildfires whose suppression requires a highly coordinated response. Whereas structural fires tend to last a few hours at most, campaign fires can last for more than a month, with teams working for 2–3 weeks at a time, Hughes said.

Structural fires like this one in Massueville, Que., Canada, expose firefighters to both natural and artificial pollutants. Credit: Sylvain Pedneault/Wikimedia, CC BY-SA 3.0 (bit.ly/ccbysa3-0)

The 2013 Rim Fire in Stanislaus National Forest in California burned more than 250,000 acres (101,000 hectares) and took 9 weeks to fully contain. Credit: U.S. Department of Agriculture, CC BY 2.0 (bit.ly/ccby2-0)

Wildland and structural fires (as well as firefighting techniques and equipment) can sometimes overlap. Fires in the wildland-urban interface (WUI) often begin as brush fires but can engulf entire neighborhoods. When structural firefighters respond to brush fires, they're usually sans heavy-duty protection but end up working long hours as both nature and the built environment burn.

The recent Coastal Fire in Orange County, for instance, began as a vegetation fire but became a WUI fire when buildings were consumed by the flames. Responding firefighters came dressed for a brush fire, said Hughes, but ended up exposed to the pollutants typical of a structural fire. Moreover, the Coastal Fire burned many electric cars, adding chemicals from lithium-ion batteries to the air.

"It's a big dose [of chemicals]," said Hughes.

In assessing health risks to firefighters, the way forward may be the kind of community-engaged research that Stapleton and Burgess are pursuing. "The questions [about exposure] come from the firefighters," said Burgess, "[and] the firefighters are able to use that information to make...their jobs safer."

By **Alka Tripathy-Lang** (@DrAlkaTrip), Science Writer

Holey Eclogite!

When oceanic plates end their time atop Earth by plunging into the mantle, they don't die—they reincarnate. At high pressures and temperatures, their minerals morph into green pyroxene and red garnet characteristic of eclogite—a hallmark rock of Earth's interior.

During these transformations, water exits the downgoing slab and heads upward into the overriding plate's mantle. As these rocks experience crushing pressures, any preexisting porosity—the space between the minerals—might be smooshed. This is one reason geologists must suspend disbelief to enjoy movies like *The Core,* in which giant, perfectly formed crystals grow into cavernous spaces deep underground.

However, professors Samuel Angiboust of École Normale Supérieure of Lyon, France, and Tom Raimondo of the University of South Australia recently reported a curious finding from the western Italian Alps: a slice of former seafloor, subducted to great depths...and riddled with coin-sized holes sometimes filled with festive red and green eclogitic minerals. Though these holes, or vugs, are much smaller than the spacious chambers in the movie, they're still a surprise. Their existence hints at fluids that once held these pockets open many tens of kilometers below Earth's surface—the only place where these particular pyroxenes and garnets can grow. Moreover, by examining the minerals at scales comparable to the thickness of a human hair, Angiboust and Raimondo found that the pore spaces must be isolated to keep fluid imprisoned.

"I noticed the surface of the outcrop...was punctuated with hundreds of these little holes, and I wondered, 'What the heck is this?'"

Hard Rocks

In 2009, Angiboust and a field partner were mapping eclogites off a trail in the European Alps. After a break, Angiboust reached down to pick up his pack. "I noticed the surface of the outcrop...was punctuated with hundreds of these little holes, and I wondered, 'What the heck is this?'" But he didn't think much of it until he was hiking farther north in Switzerland and came upon more vuggy eclogite (yes, "vuggy" is a technical term). Making this observation again forced him to consider why such a feature existed in the first place, he said.

Unfortunately, trying to collect these weird little holes proved problematic because eclogites are among the hardest rocks on Earth. A trusty rock hammer won't do. Instead, Angiboust used an electric saw and battery supply to excise a mere 50 grams (about 0.1 pound) of rock. "It was the most difficult thing I've ever sampled," he said.

Sluggish Elements

Angiboust found large faceted garnets atypical of garden-variety eclogite growing on the walls of the vugs. When he showed Raimondo the samples, Raimondo was immediately intrigued and began to consider how to look at the minerals' tree ring–like elemental zones. In particular, as garnets grow, they tend to record distinct changes in certain elements depending on what's nearby—like a fluid—as well as whether other minerals are concurrently growing anew or falling apart, Raimondo explained. By mapping certain elements that are especially sluggish once they're securely locked within a garnet, scientists can reconstruct a rock's stepwise evo-

Close-up of an outcrop of an eclogite from the Monviso area of Italy showing a vug, or hole, containing red garnet crystals, labeled "Grt," and green pyroxene crystals, labeled "Omp," which stands for omphacitic pyroxene. Credit: Angiboust and Raimondo, 2022 lution, evidence of which is often erased or cryptically recorded.

According to Angiboust and Raimondo's modeling, the medium in which the faceted garnets must have grown most likely came from water-rich fluids released by the breakdown of hydrous minerals like chlorite, lawsonite, and glaucophane. "The fluid doesn't know where to go, and it gets collected within bubbles," Angiboust said. Within these water-filled bubbles, pyroxene needles and the big garnets grew, recording the changing fluid chemistry as they experienced increasingly higher temperatures and pressures.

Once you know to look for the vugs, "you notice what you're looking for."

Cold and Fast

Mary Leech, a San Francisco State University professor whose research focuses on ultrahigh-pressure eclogites, has not observed these types of vugs. She explained that to find such voids filled with eclogitic minerals, she'd expect the rocks in which they're preserved to be exceptionally strong and protected from deformation. This is, in fact, precisely the setting in which Angiboust has now twice observed the features.

"I'm convinced these are actually quite commonplace," said Mark Cloos, a professor at the University of Texas at Austin who has found several examples of vugs filled with high-pressure minerals in his own studies in California. Once you know to look for the vugs, he said, "you notice what you're looking for."

Angiboust agreed and said, "you can easily overlook something…because you don't have your eyes trained." Also, if the fluid has a chance to escape, he said, "the vug is going to collapse." These reasons may explain why so few holey eclogites have been recorded.

Leech pointed out that the fluids required to keep the vugs open would also tend to drive chemical reactions that would convert the garnets and pyroxenes back into water-rich minerals as the eclogites returned to the surface.

The upward path of the minerals, then, should be either fast or cold, or both, said Esti Ukar, a research scientist at the Bureau of Economic Geology at the University of Texas at Austin who was not involved in this study. Rapid exhumation and relatively cold conditions, she explained, could conspire to minimize the extent of chemical reactions described by Leech.

Scientists found vugs in various Alpine locations where now-metamorphosed seafloor is exposed, including near the Matterhorn, close to the Swiss municipality of Zermatt. Credit: Alka Tripathy-Lang

Direct Measures

No matter how they got to the surface, the existence of holey eclogites hints at what rocks deep in the Earth might look like. Typical methods of investigating Earth's interior that are used by geophysicists and experimental petrologists provide indirect inferences of deep Earth's permeability—the degree to which pore spaces are connected.

"Trying to establish the permeability of [subducted] crust is really, really challenging," said Raimondo. By piecing together all of these intricate, high-resolution records directly from samples that were so deeply buried, scientists can now extrapolate the permeability of otherwise concealed crust.

By **Alka Tripathy-Lang** (@DrAlkaTrip), Science Writer

Volcanic Lava Lake Belts Out Its Secrets in Seismic "Songs"

One of only a handful in the world, this lava lake lies in a crater within Hawaii's Kīlauea volcano. Credit: Chao Liang

Although there are about 1,350 potentially active volcanoes around the world, only a handful feature lava lakes. One of those lava lakes resides in a crater of Hawaii's Kīlauea volcano.

Kīlauea famously erupted in 2018, leading to the collapse of its summit. Preceding this eruption, the volcano showcased other, less dramatic eruptions, but much is still unknown about what happened within the volcanic system leading up to these events.

New research published in *Science Advances* turned to Kīlauea's lava lake for answers (bit.ly/Kilauea-lava-lake). The lake gives a direct window into the magma, said Josh Crozier, lead author of the new paper and a researcher now at the U.S. Geological Survey's (USGS) California Volcano Observatory.

"A lava lake is like opening a manhole in the sewer system: We can see the pressure that's built up and how fast it is flowing," Crozier said. "Once something physically disturbs the magma chamber or the lava lake, it sloshes around, and we can measure that with seismometers."

The researchers carefully examined resonant signals collected by the Hawaiian Volcano Observatory from 2008 to 2018, which allowed them to deduce what was happening inside the volcano without directly probing the hazardous and extreme environment. Crozier and coauthor Leif Karlstrom, an Earth scientist at the University of Oregon, focused on "very long period" (VLP) signals, at frequencies below 5 hertz. These "much gentler and resonant shakings" are produced by other seismic signals made by volcanoes, according to USGS. The authors found that the resonance characteristics encoded in the seismic signals collected around Kīlauea are determined by the shape and properties of the volcano's magma chamber, like temperature and gas content.

The volcano's plumbing system, which keeps fresh magma coming into the lava lake, produces a seismic resonance somewhat analogous to the musical sound produced by a drum, said Karlstrom. "If you hit a drum, how long does it last before the sound stops? That's determined by the shape of the drum and what's inside," Karlstrom, who is also a musician, said. "In the case of volcanoes, we're using seismic displacement—not sound"—to provide information about the volcano's inner dynamics and characteristics.

The different kinds of seismic signals can be compared to various instruments in the "song" of information coming from a volcano, said Crozier. "That's the thing we are still working on to understand. We've now been given data on it—we can kind of see the score now, instead of just hearing some nice noises."

"Some volcanoes are pop songs where there is a predictable structure, and others might be more complicated."

A Tune Toward Prediction

Although volcanologists have historically made successful eruption forecasts, such as the warning that went out during the 2018 Kīlauea eruption, there are big errors in current models. Changing signals heralding the buildup of gas or new magma coming in from the depths of the volcano could be considered choruses in the song of the seismic signals coming from the volcano.

Crozier said the hope is to be able one day to understand when the next chorus is going to pop up. "Some volcanoes are pop songs where there is a predictable structure, and others might be more complicated," he said.

Both Crozier and Karlstrom explicitly said this study is not going to lead to new ways to predict volcanic eruptions overnight, but eventually, it could help scientists make more informed interpretations of Kīlauea's seismic signals.

Einat Lev, a volcanologist at Columbia University's Lamont-Doherty Earth Observatory who was not involved in the paper, agreed.

"I actually think that the more we understand about how magmatic systems evolve between eruptions, the better equipped we will be to predict eruptions," she said. "While the specific model employed in this paper is designed for lava lakes, the insight about the evolution of the system is likely more generally applicable to other volcanoes."

By **Andrew J. Wight** (@ligaze), Science Writer

Ocean Acidification May Drive Diatom Decline

Diatoms are a type of single-celled alga invisible to the naked eye. Their opal shells are built with silicic acid, a dissolved form of silica. Like other algae, diatoms need light to survive and favor the sunlit zone of surface waters before dissolving and sinking to the seafloor.

As the most dominant primary producers in marine food webs, diatoms convert carbon dioxide (CO_2), water, and light into food and oxygen for other organisms. Diatoms generate around 20% of Earth's oxygen and transport CO_2 to the deep ocean for long-term storage.

Being sensitive to their surroundings, diatoms can reveal clues about environmental change. Scientists analyze living diatoms to understand current trends and fossil diatoms to unravel events from millions of years ago, as geological evidence has shown that diatoms date to at least the Lower Cretaceous.

Researchers conducted one of the mesocosm experiments in the waters surrounding the Norwegian archipelago of Svalbard. Credit: Kerstin Nachtigall

"Given how diatoms play critical roles in marine food webs and Earth's carbon cycle, a decline in diatoms in the world's oceans could have substantial consequences."

The Current Threat of Climate Change

Climate change has many effects on aquatic environments, including ocean acidification (OA), the process of seawater pH decreasing (acidifying) due to a greater uptake of CO_2 from the atmosphere. This acidification affects the survival of marine life, resulting in such phenomena as coral bleaching, declining oyster reproduction, altered clam metabolism, and compromised immune responses in sea urchins. The food webs associated with these organisms are not always able to adjust to swift population declines.

Ecological collapses associated with ocean acidification have occurred before. During the Paleocene-Eocene Thermal Maximum (PETM) about 55.8 million years ago, for example, coral reefs disappeared, and deep-sea microbes nearly disappeared in an extinction event associated with ocean acidification. Geologists look back at these times to understand what is happening now. Research has shown that CO_2 levels are rising at an alarming rate, even faster today than they did during the PETM.

Diatoms Are Not Immune

Diatoms have usually been considered less vulnerable to OA compared with calcifying organisms like corals, but they are not entirely immune, recent research has suggested. In a study published in *Nature*, Jan Taucher of the GEOMAR Helmholtz Centre for Ocean Research Kiel and his co-researchers completed experiments, a meta-analysis, and Earth system model simulations to predict how OA could globally affect diatoms in the future (bit.ly/silica-export).

They conducted five in situ mesocosm experiments (involving a kind of oversized "test tube") with natural plankton communities in different biomes, finding that OA would increase the elemental ratio of silicon (Si) to nitrogen (N). This shift appeared to be caused by the slower dissolution of silica as seawater pH decreases, a theory supported by the researchers' analysis of global sediment trap data.

Taucher explained that the slower dissolution of diatoms' opal shells limits the abundance and distribution of the microbes: "These shells sink deeper before being converted back to dissolved Si. This leads to a redistribution of Si, i.e., less silicic acid in the surface ocean… meaning that less of this nutrient remains in the surface ocean," which is where diatoms can access the sunlight they need to survive.

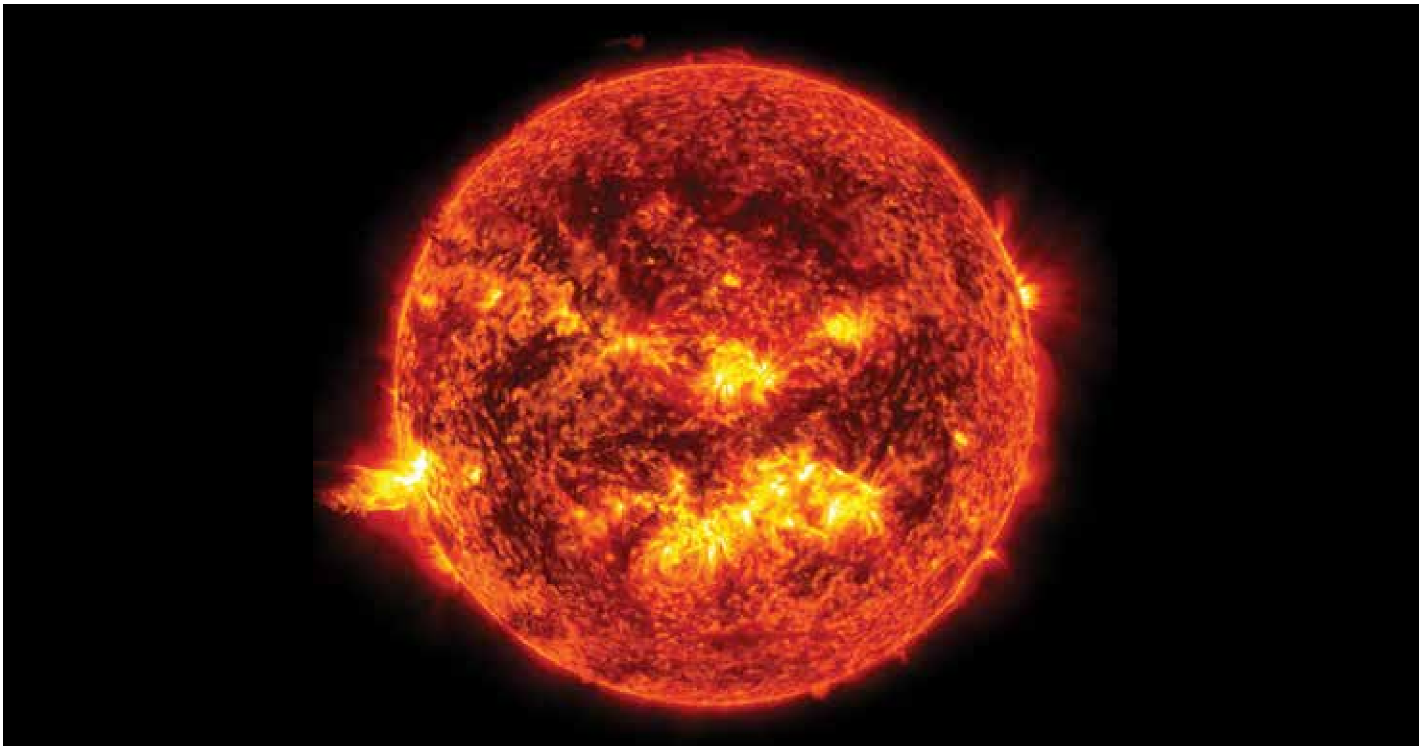
Adrian Marchetti, an associate professor in the University of North Carolina at Chapel Hill's Department of Earth, Marine, and Environmental Sciences, said that "the study provides new insights into how OA will alter the remineralization of silica in the ocean."

"Given how diatoms play critical roles in marine food webs and Earth's carbon cycle," he said, "a decline in diatoms in the world's oceans could have substantial consequences."

Taucher and his coauthors projected that OA will drive a global decline of diatoms by between 13% and 26% by the year 2200.

By **Clarissa Wright** (@ClarissaWrights), Science Writer

Chinese-Led Solar Research Is Looking Bright



On 20 June 2013, the Sun produced a large solar flare—seen in this image at the roughly nine o'clock position—and launched a coronal mass ejection toward Earth. Credit: NASA/Goddard/SDO

Life on our planet is possible because of the Sun, but the relative proximity of our nearest star comes with risks, too. Intense outpourings of radiation and matter from the Sun, for instance, can cripple electronics and even damage human tissue. A cadre of spacecraft is actively monitoring our star, and now several new Chinese-led missions are joining the hunt to better understand the Sun.

A Payload and Then a Satellite

In July of last year, a red and white rocket rumbled off the launchpad at Jiuquan Satellite Launch Center in northern China.

Its payload—the Fengyun-3E meteorology satellite—included China's first space-based instrument designed to study the Sun in the X-ray and ultraviolet regimes: the Solar X-ray and Extreme Ultraviolet Imager. The primary scientific objective of this instrument is to improve forecasts of space weather near Earth, said Bo Chen, the engineer at the Changchun Institute of Optics, Fine Mechanics and Physics, Chinese Academy of Sciences, in charge of the design and development of the instrument. To that end, the Solar X-ray and Extreme Ultraviolet Imager observes events such as solar flares, which can launch electromagnetic waves toward Earth.

In 2021, China also launched its first satellite dedicated entirely to solar observations. The Chinese H-Alpha Solar Explorer (CHASE) satellite is currently in a Sun-synchronous orbit roughly 500 kilometers above Earth. Its scientific payload is an imaging spectrograph that observes Hα, a spectral line produced by hydrogen in the visible part of the electromagnetic spectrum. One of CHASE's key capabilities is that it can scan the entire disk of the Sun in less than a minute. That high scanning cadence allows researchers to trace the rapid evolution of areas of the Sun known as active regions.

These areas of the Sun are of particular interest, said Li Feng, a solar physicist at the Purple Mountain Observatory, Chinese Academy of Sciences, in Nanjing. That's because events like solar flares and coronal mass ejections—which potentially can be dangerous to astronauts and even electronic equipment here on Earth—tend to originate from active regions. "Most solar eruptions are from active regions," said Feng.

"We can get a deeper diagnostic of the eruption process."

And CHASE's spectral observations reveal a lot more about active regions than could be gleaned from imaging alone. The temperature and velocity of these regions can be studied in detail, said Feng. "We can get a deeper diagnostic of the eruption process."

A Multi-instrument Mission

Later this year, another Chinese-led solar mission, the Advanced Space-based Solar

Observatory (ASO-S), is slated to launch. Like CHASE, ASO-S will be in a Sun-synchronous orbit, but it'll be a bit farther from Earth—roughly 700 kilometers in altitude. ASO-S will be the first Chinese solar mission to carry multiple instruments: a magnetograph for measuring the Sun's magnetic field, a hard X-ray imager for recording the Sun's most energetic electrons, and a telescope sensitive to Lyman-alpha, a spectral line of hydrogen in the ultraviolet part of the electromagnetic spectrum.

The scientific goals of ASO-S center around studying solar eruptions and understanding how they relate to the Sun's magnetic field, said Feng, who is one of ASO-S's assistant chief scientists. With the observatory's Lyman-alpha Solar Telescope, for instance, it will be possible to measure the direction and speed at which a coronal mass ejection—an outpouring of high-energy material, including such particles as protons and electrons—is heading toward Earth.

It's important to predict when a coronal mass ejection will arrive in the near-Earth environment, said Jingnan Guo, a space physicist at the University of Science and Technology of China in Hefei. That's because such an event can change the shape of Earth's magnetosphere, potentially rendering satellites vulnerable to a barrage of particles capable of harming delicate electronics. "If the magnetosphere is compressed, those satellites might be exposed," said Guo.

Scientists around the world are looking forward to analyzing the new measurements from ASO-S—all of the mission's data will be made public following the observatory's commissioning phase, several team members reported earlier this year in *Nature Astronomy* (bit.ly/China-ASO-S).

Watch for the Ring

In the coming years, another Chinese-led mission will aim to observe the Sun in an unprecedented way: from all sides simultaneously. The Solar Ring mission, currently in its planning stages, is slated to consist of three identical spacecraft orbiting the Sun, at the Earth-Sun distance, separated by 120°. The first spacecraft will be located 30° upstream of Earth, a configuration that allows for a variety of angles between Earth and the various Solar Ring spacecraft. That's an important design characteristic, said Quanhao Zhang, a solar physicist at the University of Science and Technology of China and a member of the Solar Ring team. "We can use the observations from different angles to reconstruct the three-dimensional configuration of the solar wind."

One of the primary scientific goals of the Solar Ring mission is to determine how the solar wind—a constant outflow of solar plasma—propagates outward into the solar system. Ten instruments are planned for the Solar Ring mission, including payloads to study radiation and particles emitted by the Sun and our nearest star's magnetic field and surface vibrations.

It's an exciting time to be doing solar research, said Feng. The Sun affords us a unique glimpse of a star up close, and new and upcoming technologies will be able to best exploit that vantage point, she said. "It's a natural laboratory."

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

After GRExit: Reducing Bias in Geoscience Graduate Admissions

Graduate admissions committees serve as gatekeepers, deciding who has access to higher education—and to a large extent, to careers—in fields spanning the humanities and science, technology, engineering, and mathematics (STEM). These committees have long relied on Graduate Record Exam (GRE) results as a supposedly objective measure by which to compare and rank applicants. Recently, though, many graduate programs, including geoscience departments, have staged a "GRExit"; that is, they dropped the GRE as an application requirement because of its recognized biases and because of pandemic restrictions on access to the test. Amid this shift, programs are seeking to implement more holistic evaluations; however, there are not many examples within the geosciences to guide their practice.

The geosciences graduate program at the University of Massachusetts Amherst (UMass Amherst) piloted dropping its GRE requirement for graduate applicants in early 2018. In the first few admissions cycles after that decision, the admitted graduate students proved well qualified and capable, but the admissions committee was relying on unstructured assessments that are themselves vulnerable to bias. For example, when two candidates appeared to be similarly strong, we might have distinguished between them on the basis of the reputations of their undergraduate schools (halo bias), their perceived love of the outdoors (affinity bias), slight differences in grade point average (GPA; ambiguity aversion), or the effectiveness of recommendation letter writers in championing their mentees (framing bias). Clearly, this approach was still far from ideal, and we found ourselves wondering how best to move on from dropping the GRE.

Evaluate the Person, Not Just the Numbers

Holistic applicant reviews can reduce biases in graduate admissions by placing greater emphasis on skills and personal attributes—inherent qualities of candidates themselves—than on quantitative metrics, such as GPA, which may be influenced by disparities in applicants' work conditions [*Kent and McCarthy*, 2016; *Wilson et al.*, 2019]. However, many of the holistic admissions best practices applied in STEM were developed within other science disciplines that differ in critical ways from the geosciences [e.g., *Wilson et al.*, 2019].

First, the specific aspects of someone's educational background that tend to make them a strong applicant (e.g., whether they've taken courses in mathematics) vary across the broad range of geoscience subdisciplines. Without consensus on what constitutes a strong applicant, geoscience admissions committees need a structured evaluation process to avoid falling back on criteria that perpetuate inequities, such as privileging students from elite undergraduate programs or those with prior research experience [*Posselt*, 2016].

Second, compared with programs in other science fields, many graduate geoscience programs support a higher proportion of new students with research assistantships (RAs) as opposed to, say, teaching assistantships or fellowships. This reliance on RAs introduces additional sources of possible bias by putting admissions decisions largely into the hands of faculty principal investigators (PIs), who select students for specific projects, rather than with a centralized admissions committee [*Kent and McCarthy*, 2016].

The UMass Amherst Geosciences graduate program recently adopted a holistic review process that excludes the GRE, gathers responses to customized supplemental prompts, and relies on multiple rubric assessments to judge the likelihood that applicants will be successful in our program through more equitable evaluations (Figure 1). The limited capacity of faculty to take on new advisees and the fact that our program does not admit a student without the approval of at least one potential faculty adviser mean, however, that some excellent graduate applicants are not admitted. Our primary goal with our new process, which we detail below and which may serve as a useful model for other programs, is thus not to achieve full equity but to reduce biases in admissions decisions as much as possible.

Fig. 1. Modifications to the University of Massachusetts Amherst (UMass Amherst) Geosciences program graduate admissions process began in 2018 and extended over several admissions cycles.

Holistic applicant reviews can reduce biases in graduate admissions by placing greater emphasis on skills and personal attributes than on quantitative metrics that may be influenced by disparities in applicants' work conditions.

Moving Toward Holistic Admissions

Prior to 2018, the graduate admissions process in the UMass Amherst Geosciences program was similar to that of many other programs. Our admissions committee used a combination of GRE scores, GPA, a personal statement, recommendation letters and accompanying rankings (called "referee letters" and "referee rankings" in Figure 2), and input from potential advisers to evaluate each applicant. Advisers had access to all applicant materials and sometimes interviewed applicants as well.

This committee, which includes individuals representing different research areas in our program, engaged in a discussion process that as described by *Posselt* [2016], is common in nonconsensus disciplines where there isn't consistent agreement on the required training for strong candidates. In our effort to reach agreeable outcomes, our admissions committee was vulnerable to making decisions for the sake of conformity and to implicit biases because we didn't have a structure for making decisions. In addition, our process relied heavily on candidate rankings by potential advisers, but individual approaches to these rankings varied widely across the program.

Because dropping the GRE did not address the biases in our process, the admissions committee took a first step toward holistic admissions in winter 2020 by developing a list of traits that correlate with success in our graduate program. Focusing on applicants' traits rather than experiences can reduce admissions bias [e.g., *Megginson*, 2009] and create a consistent evaluation approach for nonconsensus disciplines like the geosciences [e.g., *Posselt*, 2016].

We initially compiled a list of traits that graduate schools and employers typically ask referees to address in their assessments of candidates. We then narrowed this list to six traits that most closely correlate with student success across all research groups in our program: perseverance, independence, curiosity, ability to work in teams, maturity, and communication skills.

For our admissions process to be effective in helping the committee to select the applicants most likely to thrive in our graduate program, application materials must reveal

The admissions committee took a first step toward holistic admissions in winter 2020 by developing a list of traits that correlate with success in our graduate program.

information about each of the six traits for success. However, when the admissions committee mapped the effectiveness of each application component in informing each trait (Figure 2), they found that these tools were not reliable indicators of potential success in our program. This finding confirmed what some of our graduate students had noted in spring 2019 (Figure 1).

The personal statement offered an opportunity for applicants to demonstrate this potential, but in practice, the degree to which the statements actually demonstrated potential for success varied widely. This observation suggested that applicants had varying access to mentoring about which strengths they should highlight in their personal statements. After discussing this mapping and the apparent ineffectiveness of the existing admissions process, the faculty agreed that we needed a new approach. Having this broad agreement was critical for instituting change in our program because the new approach would require greater effort from each faculty adviser.

A Change of Approach

One effective strategy for gathering information on traits for success in graduate school is to require supplementary application materials that specifically demonstrate the assessed traits. In our case, a four-person committee developed a supplemental form consisting of several open-ended prompts that map to desired traits. The committee included one current graduate student, whose perspective on how the six designated traits related to their own success in graduate school was critical for crafting supplemental prompts that would be both relatable to applicants and revealing to the admissions committee.

We focused on process-based questions rather than on outcome-based questions that would advantage applicants with particular achievements. For example, rather than asking about research experience, which is not available to all undergraduates, we ask candidates to describe their independence, curiosity, and problem-solving skills. Candidates can draw from any previous experience in answering this prompt, including a research project. We also took care to avoid leading questions. For example, our committee recognized that working successfully in teams does

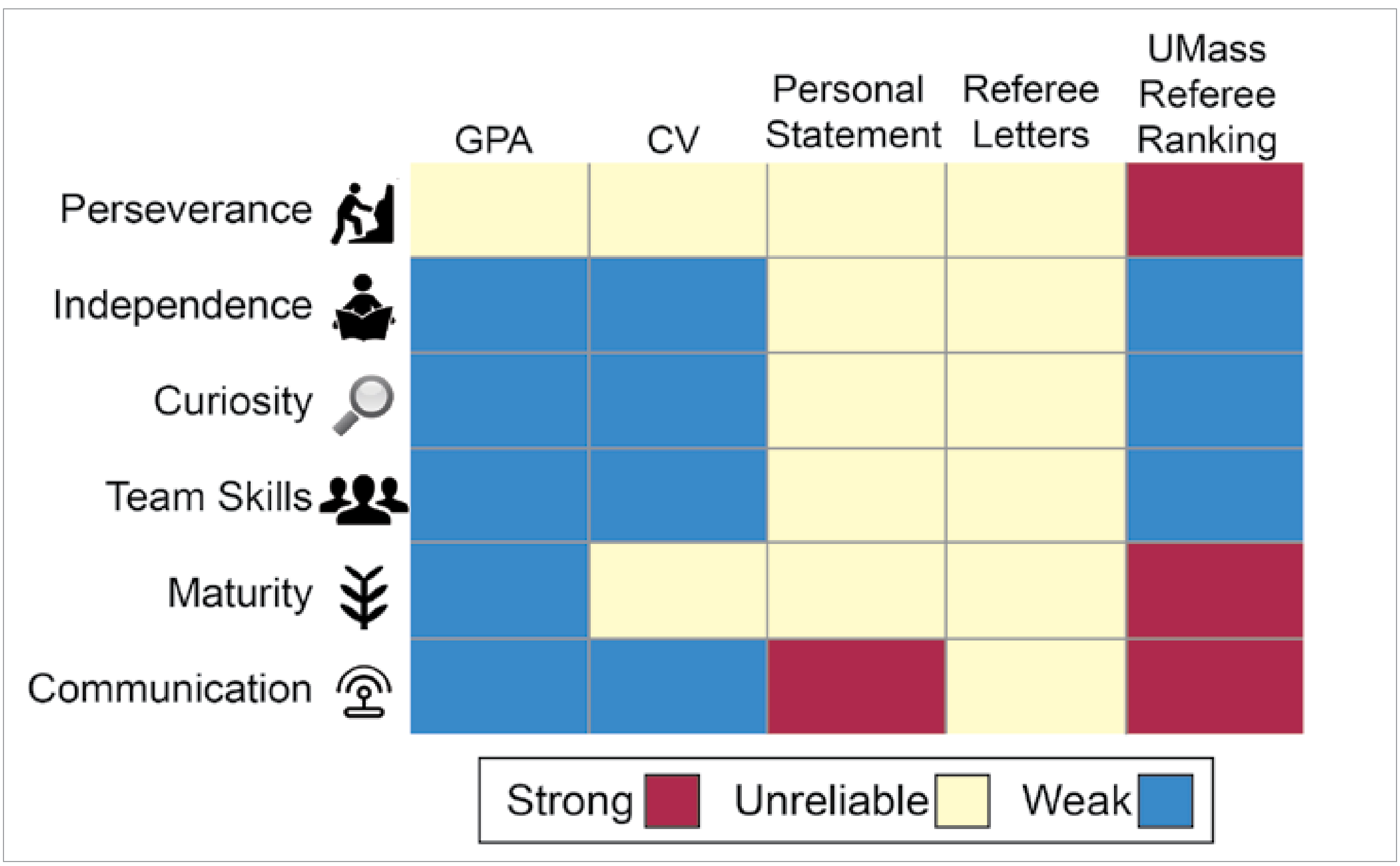


Fig. 2. In winter 2020, after dropping the GRE, the UMass Amherst geosciences graduate admissions committee qualitatively assessed how reliable each application component was for indicating a student's potential success in the program. The review revealed that components were mostly unreliable. For example, the referee ranking questions (in which reference letter writers were asked to rank candidates compared with other students) of the UMass Amherst graduate school did not specifically ask about curiosity, independence, or team skills.

not necessarily mean being a leader. Asking applicants to describe their past success in any of a range of team roles is more inclusive of different personalities and encourages applicants to speak to their strengths.

Each prompt explains how the traits we aim to evaluate contribute to success in graduate school (see Table 1 at bit.ly/Eos-after-GRExit). These explanations add transparency to how applications will be considered and reduces disparities among students with variable access to effective mentors. Applicants can see the prompts in advance of applying on our graduate program's web page, and we suggest they share the prompts with the people writing their letters of recommendation.

Following holistic admissions best practices [*Michel et al.*, 2019], we use standardized rubrics that use evidence-based scoring (on a scale of 1–3) to evaluate applicants and track how specific components of the application reveal each trait (see Table 2 online). Each score must be substantiated with evidence from some part of the application, and we provide examples to guide this process. The faculty in our program requested that in addition to scoring for the six designated traits, the rubric include a score for motivation and alignment to the research program, which is typically assessed through personal interviews.

We focused on process-based questions rather than on outcome-based questions that would advantage applicants with particular achievements.

Most holistic admissions processes depend on a central admissions committee trained in bias vulnerabilities to make equitable admissions decisions [*Michel et al.*, 2019]. Because half of the graduate students in our program are supported by PI-funded RAs for particular research projects, we need a structure for including faculty advisers in the admissions process. Consequently, both our admissions committee and potential advisers complete rubrics for each student, and composite scores from each assessor are considered equally.

Advisers have been encouraged to watch a 15-minute video that provides training on how to recognize bias in admissions, assess applicant traits, and use the rubrics. Advisers are also provided with effective interview questions, which were compiled by the committee that developed the supplemental prompts. In nearly all cases, the variance among composite rubric scores from different assessors was within one point, which speaks to the strength of this approach for guiding admissions decisions. In the very rare cases when scores differ more substantially, the evidence-based structure of the rubric provides valuable insights that help the admissions committee chair understand and resolve the conflicting scores.

A Clearer View of the Candidates

Our new admissions process means that an adviser can no longer appeal to how well they think an applicant would fit into their specific research group as the sole argument for admission, but rather must demonstrate the applicant's broader potential for success. Using this process has required widespread buy-in from our faculty to the notion that it serves the best interests of their research groups.

Having used the rubrics for multiple admissions cycles now, several faculty members have remarked that the process helped them recognize strengths of candidates who might not have been ranked as highly in our former process because of unseen biases. For example, the supplemental prompts have revealed strengths, such as the ability to manage two jobs simultaneously, that likely would not have emerged through a traditional personal statement focused on a student's research interests.

Another advantage of the new process is that all applications are read carefully, not just those of applicants who contact faculty directly. Faculty have reported that although the holistic process takes more effort, it has improved their ability to assess candidates compared with our previous approach. And they have strongly supported continuing this new practice. Going forward, committees of faculty and graduate students will periodically review and update our admissions process with attention to how the demographics and retention of our graduate students evolve.

We encourage geoscience graduate programs who haven't done so already to consider using a structured admissions process that uses supplemental prompts and rubrics, such as those shared here. These tools can and should be adjusted to best suit the goals and constraints of a given program.

In our program, we have seen that a holistic admissions process can open doors for qualified applicants who might otherwise be overlooked. If enough programs pursue a similar path, we can substantially reduce bias in admissions decisions and foster greater diversity in the next generation of geoscientists.

Several faculty members have remarked that the process helped them recognize strengths of candidates who might not have been ranked as highly in our former process because of unseen biases.

Acknowledgments

All UMass Amherst Geosciences program faculty contributed to the transition to holistic admissions. The authors thank Forrest Bowlick, Haiying Gao, Ray Bradley, Stephen Burns, Mike Williams, Isaac Larsen, and Steve Turner for serving on the various committees that instituted these changes.

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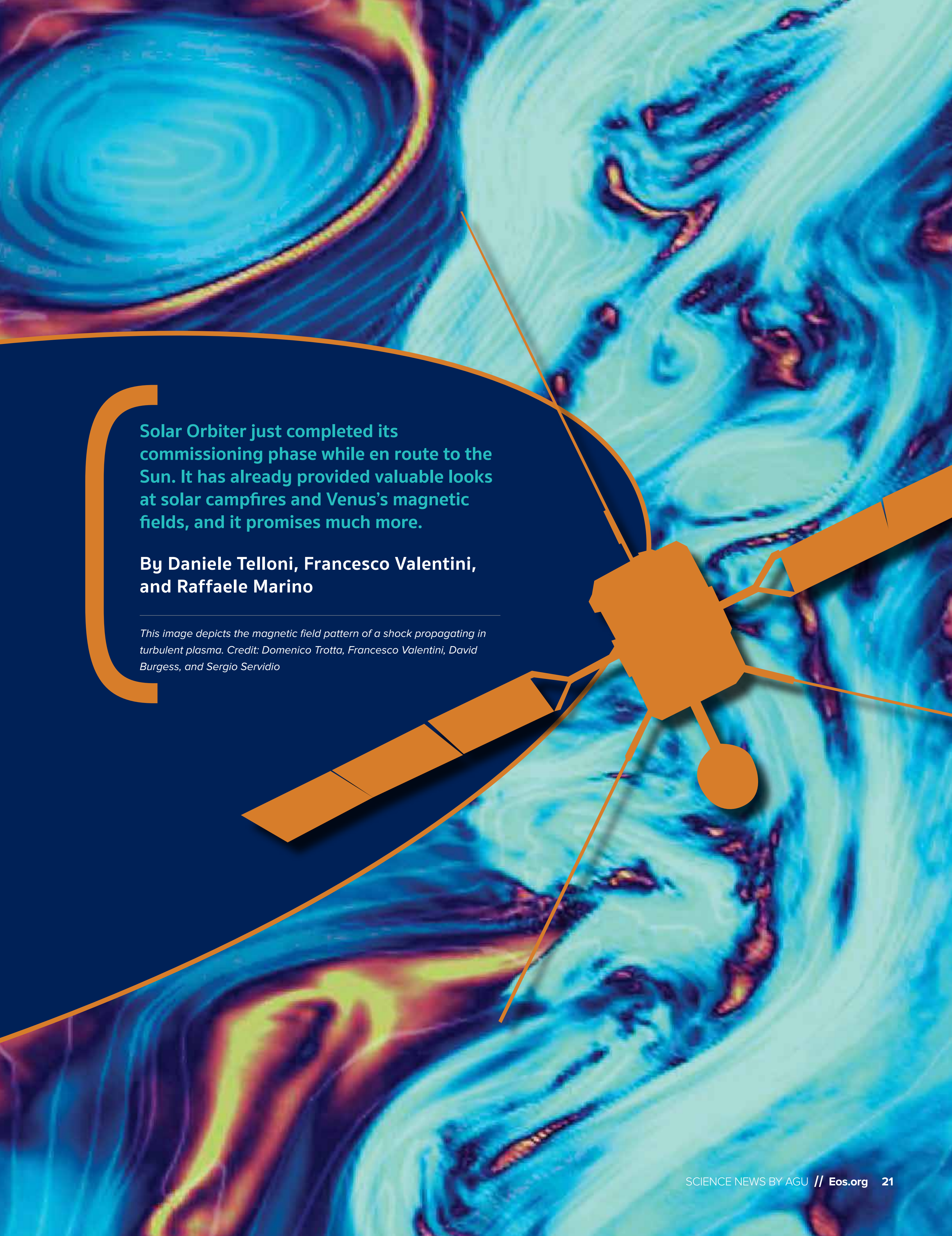
▶ **Read the article at bit.ly/Eos-after-GRExit**

A NEW JOURNEY AROUND (AND AROUND) THE SUN



Solar Orbiter just completed its commissioning phase while en route to the Sun. It has already provided valuable looks at solar campfires and Venus's magnetic fields, and it promises much more.

By Daniele Telloni, Francesco Valentini, and Raffaele Marino

This image depicts the magnetic field pattern of a shock propagating in turbulent plasma. Credit: Domenico Trotta, Francesco Valentini, David Burgess, and Sergio Servidio

The Sun is one of billions of stars forming the Milky Way, which is, in turn, one of the billions of galaxies populating the universe. Yet to us, the Sun is not simply one of many stars. It is the most important celestial body, both sustaining life on Earth and posing persistent hazards in the form of damaging radiation. It is also the only star we have direct access to by means of robotic probes—or by the observations of our own eyes.

> **Among the groundbreaking observations that Solar Orbiter has made already are those of short-lived, small-scale flickering bright spots, nicknamed "campfires," in the solar corona.**

Indeed, generations of scientists, since Galileo Galilei in the 16th and 17th centuries and even before, have used observations of the Sun to investigate a large variety of astrophysical phenomena, from the formation of stars to the origins of stars' self-sustained magnetic fields. These fields are responsible for violent, impulsive events on our star, such as flares and coronal mass ejections (CMEs), which sometimes direct bursts of high-energy ionized particles, or plasmas, toward our planet.

Studying how our Sun interacts with the surrounding region it influences, called the heliosphere, has further allowed us to investigate physical processes that are ubiquitous in the universe. One such process, magnetic reconnection, involves the breaking and rejoining of oppositely directed magnetic field lines that occur during various phenomena, including CMEs, and can release tremendous amounts of energy. Another is turbulence (famously called by Richard Feynman the most important unsolved problem of classical physics), which contributes to the acceleration of particles in space and plays an important role in the dynamic and energetic processes of the solar environment.

It is therefore not surprising that some of the most important missions of the space exploration era have focused on observing the Sun and the solar wind, the plasma flow that continuously expands from the Sun's outer atmosphere, or corona, into the heliosphere. Now a new mission, Solar Orbiter, is set to advance our understanding further—in fact, it is already doing so.

The Closest Look Yet at the Sun

Solar Orbiter, a joint mission of the European Space Agency (ESA) and NASA, was successfully launched from Kennedy Space Center in Florida on 10 February 2020 [*Müller et al.*, 2020]. The mission is one of the most technologically advanced and recent assets in a series of large ground-based and space-based solar observatories, with the latter group including Skylab, Solar Maximum Mission, Solar and Heliospheric Observatory, Parker Solar Probe, and others.

Solar Orbiter's main purpose is to help us achieve a better understanding of how the Sun creates and controls the heliosphere and why solar activity changes with time. The spacecraft is the first to carry both remote sensing and in situ instruments (10 in total) so close to the Sun—about 42 million kilometers away, or one third of the Earth-Sun distance, at its closest. With each orbit of the Sun and with gravitational assists from Venus, it will gradually lift out of the orbital plane (ecliptic) of the planets in our solar system, potentially reaching orbital planes with inclinations of up to about 33° from the ecliptic.

Thanks to its unique payload and the range of tilted orbits it will cover, Solar Orbiter will observe the Sun from different perspectives and take the closest images of the star ever. It will also observe, for the first time, the solar magnetic poles, regions where most of the so-called fast solar wind originates and the polarity of the Sun's magnetic field reverses periodically [*Zouganelis et al.*, 2020]. The synergy of remote sensing and in situ observations collected by Solar Orbiter will enable scientists to connect transient magnetic events and the continuous solar wind to their sources on the Sun.

Campfires on the Sun, Magnetic Fields on Venus

Solar Orbiter's data production routine officially started on 27 November 2021 after more than a year and a half of commissioning as the spacecraft was en route toward its first production orbit. Even before then, however, it had revealed new discoveries about the Sun. Several of these results have been collected in a special issue of *Astronomy and Astrophysics* (bit.ly/solar-orbiter-first).

Among the groundbreaking observations that Solar Orbiter has made already are those of short-lived, small-scale flickering bright spots, nicknamed "campfires," in the solar corona. These tiny flares, which had eluded observation by previous spacecraft, were first imaged in May 2020 by the Extreme Ultraviolet Imager (EUI) on board Solar Orbiter [*Berghmans et al.*, 2021].

From the recent images, scientists found that these fine structures cover the entire solar surface and occur far more frequently than larger flares. And they are now thought to contribute significantly to the extreme heating of the corona, although exactly how is not clear. The corona, where temperatures can rise to upward of 1 million degrees Celsius, is much hotter than the material below it—a seeming paradox that has puzzled solar physicists for many years. Campfires may be the missing piece of the puzzle, explaining how energy is released, transported, and eventually converted into heat in the corona.

Although Solar Orbiter's main objective is to shed new light on unsolved mysteries of the Sun, the mission has also offered insights into our neighboring planet Venus. During its first Venus flyby in December 2020, Solar Orbiter revealed new details of the planet's unusual magnetic configuration [*Allen et al.*, 2021]. In particular, scientists verified that Venus's magnetosphere, which is generated by the interaction of the solar

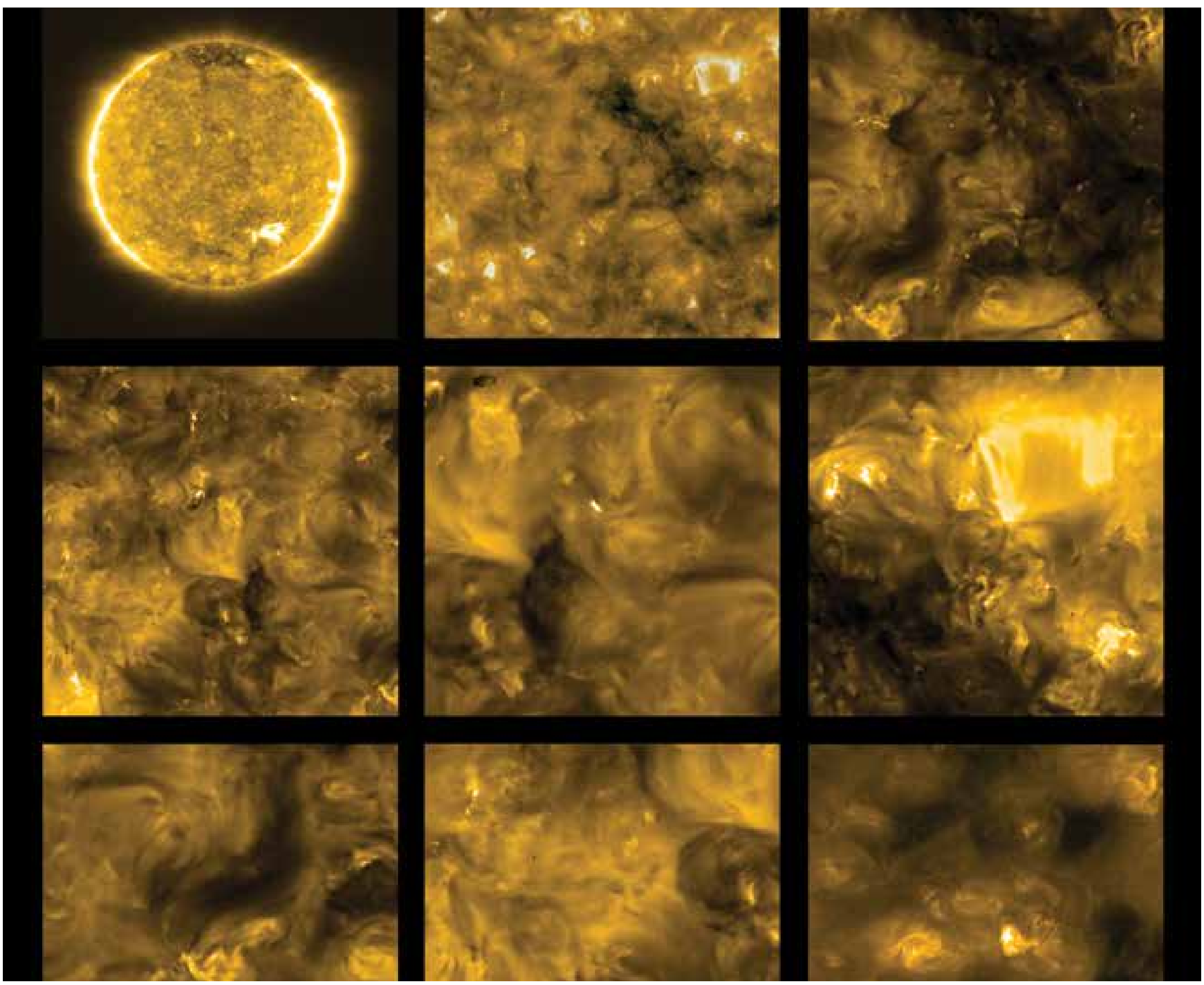
The Solar Orbiter spacecraft approaches the Sun in this artist's illustration. Credit: European Space Agency wind with the planet's ionosphere, protrudes behind the planet to form a magnetotail up to 300,000 kilometers long. Scientists already knew about Venus's unusual magnetosphere from previous missions in the 1960s and 1980s; however, they didn't know until now how far an induced magnetosphere could extend before it falls apart.

Using measurements from the Energetic Particle Detector (EPD) aboard the spacecraft, Solar Orbiter also found that Venus's magnetosphere is able to accelerate plasma particles to millions of kilometers per hour through multiple mechanisms, including wave-particle interactions, turbulence, and current sheet crossings (which involve electrical currents confined to a surface). These findings allowed researchers to speculate about the formation and evolution of exoplanet magnetospheres outside our solar system, which cannot be observed directly with current technologies. To this end, it is crucial to confirm and corroborate measurements made by modern spacecraft with modeling of poorly accessible astrophysical objects and phenomena. State-of-the-art numerical simulations are an indispensable tool in this regard because they can realistically reproduce the dynamics and physical conditions of interplanetary plasmas.

For example, recent numerical experiments explained how the interaction of shocks and plasma turbulence in the magnetosphere of Venus can accelerate particles and play a role in the process of plasma heating [*Trotta et al.*, 2021], thus supporting analyses of observational evidence from Solar Orbiter. The synergistic use of measurements and numerical modeling is central to the exploitation of the unprecedented observations made by Solar Orbiter.

Pairing with Parker

Companion observations made by Solar Orbiter and NASA's Parker Solar Probe [*Fox et al.*, 2016] offer unique opportunities for comprehensive study of our star and its environment [*Velli et al.*, 2020], as well as of how this environment evolves with



In May 2020, the Extreme Ultraviolet Imager (EUI) on board Solar Orbiter spotted tiny flares in the Sun's corona called "campfires." These features are visible as small bright spots in these images acquired at a wavelength of 17 nanometers. Credit: Solar Orbiter/EUI Team/ESA and NASA; CSL, IAS, MPS, PMOD/WRC, ROB, UCL/MSSL distance from the Sun and with solar activity. These opportunities arise because of the complementary trajectories covered by Solar Orbiter and Parker Solar Probe as they orbit around the Sun. Thanks to seven Venus flybys, Parker Solar Probe will gradually shrink its orbit around the Sun, coming as close as 6.16 million kilometers to the Sun, about 7 times closer than any spacecraft has come before.

When the angular separation between the two spacecraft is 90°, with the Sun at the vertex of the angle, the coronal sources of local plasma phenomena—observed in situ by Parker Solar Probe—can be determined using the remote sensing instruments aboard Solar Orbiter. The first such "quadrature" configuration, which occurred in January 2021, allowed scientists to track, for the first time, the same plasma volume as it expands from the extended corona to the very inner heliosphere. It also allowed them to infer crucial quantities in the wind acceleration region along the coronal current sheet, such as the flow-aligned magnetic field, the Alfvén radius (where the speeds of the solar wind and Alfvén waves are equal), and the bulk kinetic energy flux density of the solar wind [*Telloni et al.*, 2021b].

Similarly, radial alignments of the two spacecraft (i.e., when they are simultaneously in line with each other and the Sun) are key for investigating how plasma parcels in the solar wind evolve as they propagate outward. Analysis of the first such radial alignment, which occurred in September 2020, revealed that the solar wind evolves from a less developed turbulent state, dominated by Alfvénic fluctuations near the Sun, to a state of fully developed turbulence dominated by intermittent events in locations closer to Earth [*Telloni et al.*, 2021a].

Along with Parker Solar Probe, Solar Orbiter will also improve our capability to trace and forecast the propagation of the most powerful perturbations produced by solar activity, including coronal mass ejections, throughout the interplanetary medium, as well as to forecast impacts of these perturbations on the geospace environment. Monitoring heliospheric space weather in the short term and predicting how the Sun may affect power grids, as well as space-related technologies for telecommunication, transportation, and other applications, are of paramount importance given our increasing reliance on this infrastructure.

Thanks to seven Venus flybys, Parker Solar Probe will gradually shrink its orbit around the Sun, coming as close as 6.16 million kilometers to the Sun, about 7 times closer than any spacecraft has come before.

Revealing Solar Secrets

People always have looked at the Sun with hope, wonder, and awe. A symbol of rebirth and the cyclical nature of life, an inspiration to poets, and an object of worship in ancient times, the Sun also has guarded secrets of the cosmos dating back to the origin of the universe.

Just as Prometheus stole fire—a symbol of knowledge—and gave it to humans, so Solar Orbiter will provide future generations with new knowledge about our star.

Just as Prometheus stole fire—a symbol of knowledge—and gave it to humans, so Solar Orbiter will provide future generations with new knowledge about our star, offering a deeper understanding of how it operates and how it affects life for better and worse. But even if the mission results in the Sun holding fewer secrets—and even though, amid the vast universe, the Sun is a tiny yellow dot like the zillions of other bright dots sparkling in the sky—it will remain a beautiful source of wonder for us here on Earth.

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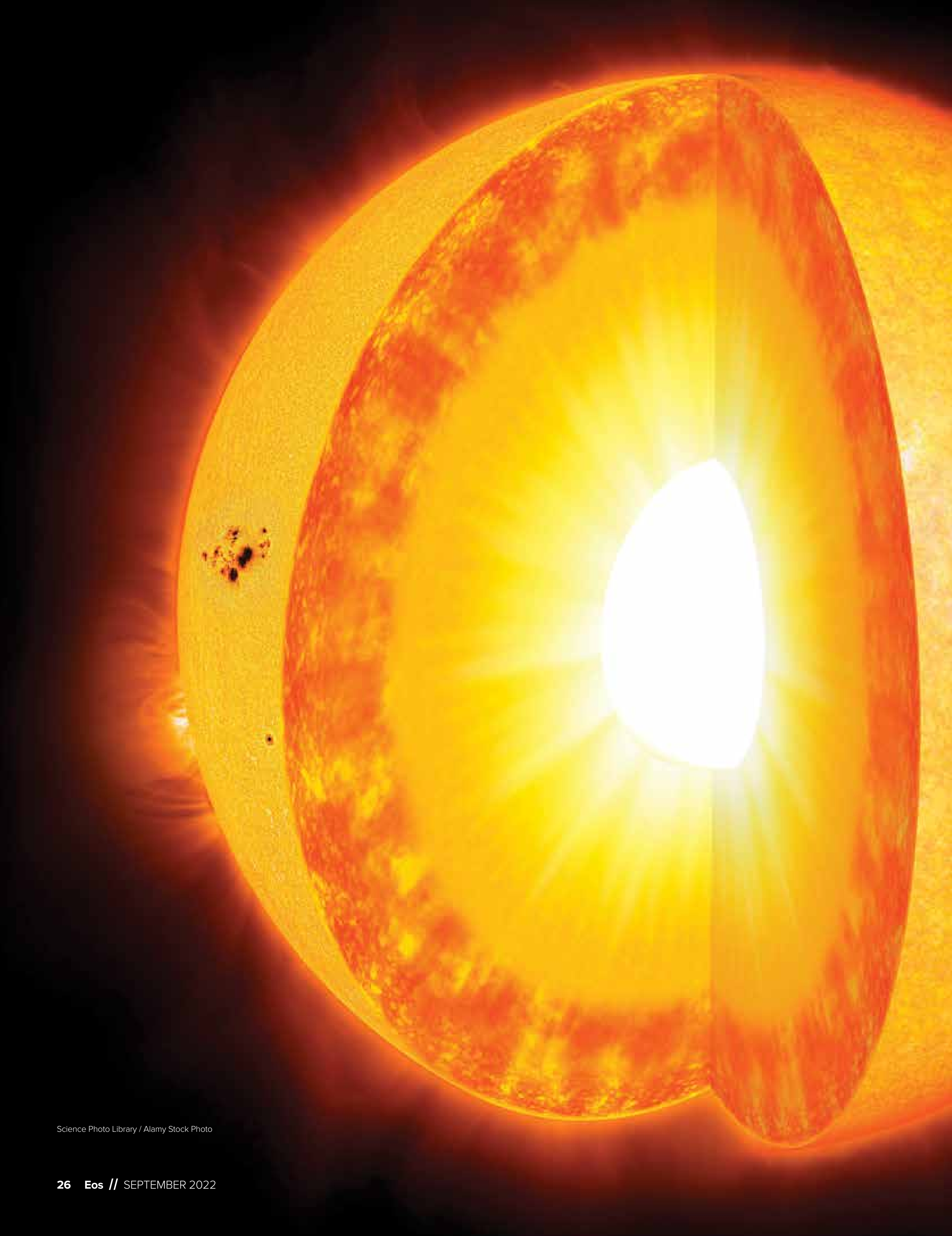
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SHAKE, RATTLE, AND PROBE

Helioseismology allows scientists to study the interior of the Sun, solve some basic physics mysteries, and forecast space weather.

By Damond Benningfield

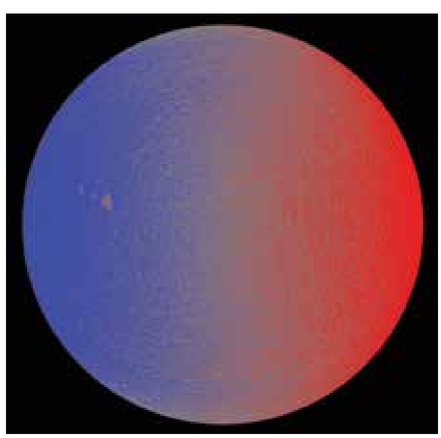
CREATED BY THE MOTIONS OF GIANT BUBBLES OF HOT GAS, THE WAVES CAN TRAVEL AROUND THE ENTIRE SUN, MOVING FROM THE SURFACE TO DEEP INSIDE TO THE SURFACE AGAIN IN A CYCLE THAT CAN REPEAT FOR ANYWHERE FROM HOURS TO MONTHS.

It may not roll, but the surface of the Sun shakes and rattles like—pick your favorite analogy—a giant bell, a pipe organ with millions of pipes, or a concert hall filled with the hum of many orchestras tuning at the same time.

Scientists who study the Sun have used those comparisons and others to describe the star's constant vibrations, caused primarily by sound waves rippling below the surface. Created by the motions of giant bubbles of hot gas, the waves can travel around the entire Sun, moving from the surface to deep inside to the surface again in a cycle that can repeat for anywhere from hours to months.

For solar physicists and others, the waves are powerful tools for studying the Sun, other stars, and even other fields of physics. They have probed the Sun's interior structure and motions, provided insights into the solar dynamo, and raised questions about the Sun's chemical composition. They offer a glimpse of the farside of the Sun, improving space weather forecasts. And they helped solve a problem in particle physics that led to a Nobel Prize.

The study of these waves is known as helioseismology, and it uses instruments on the ground and in space to keep a constant eye on the Sun. This effort has provided 3 decades of nonstop observations that have greatly advanced our knowledge of the Sun. "Helioseismology is the only way to see inside the Sun," said Sushanta Tripathy, an associate scientist at the National Solar Observatory (NSO) in Boulder, Colo.



A Doppler image of the Sun reveals motion on its surface. The motion is dominated by the Sun's rotation, so the eastern side of the disk is blueshifted, whereas the western side is redshifted. Waves at the surface, which are the target of helioseismology, create the "fuzzy" appearance of the disk. Credit: NASA/GSFC Scientific Visualization Studio, SDO Science Team, and Virtual Solar Observatory

"All of our observations of the Sun are based on what we can see at the surface," said Lisa Upton, a research scientist at the Southwest Research Institute, also in Boulder. "We can't dive in to see inside. But helioseismology is a revolutionary technique. It's amazing, the things it can do."

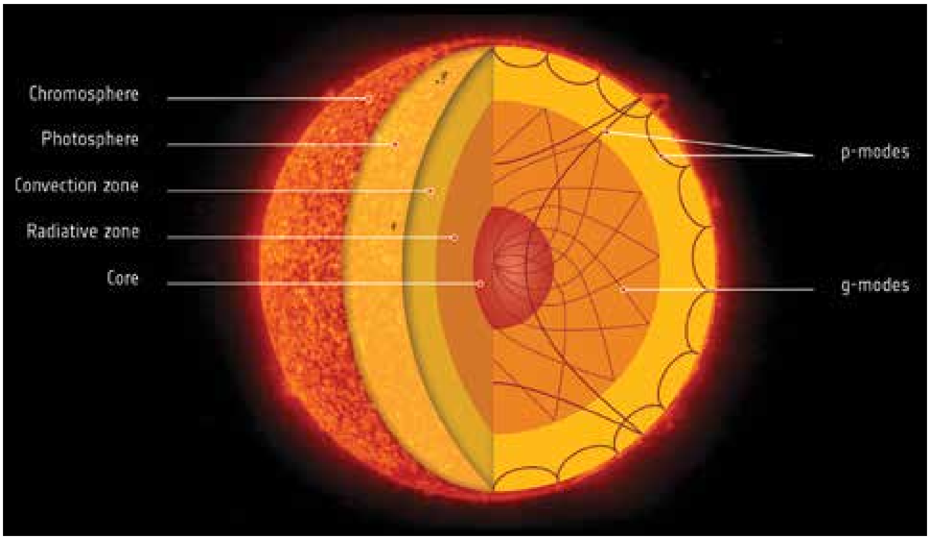
Sound Waves "All Over the Place"

Helioseismology began in the 1960s when Robert Leighton and his colleagues discovered oscillations on the surface of the Sun. "He was looking at solar granulation, and turbulence was a big topic at the time," said John Leibacher, an emeritus astronomer at NSO and a former director. "He was taking images at a specific wavelength, and he expected, as the images got farther apart in time, they'd look less and less coherent. What he found, much to his great surprise, was that after about 5 minutes, they were back in phase.... He discovered a periodicity on the surface of the Sun, which was completely unexpected."

A few years later, Leibacher, who studied the phenomenon for his master's thesis, and others independently devised an explanation: sound waves trapped in a cavity just below the surface, generated by the motions of blobs of hot gas at the top of the Sun's convection zone.

The Sun consists of three main layers. The core, which accounts for roughly 25% of the Sun's radius, is where hydrogen nuclei fuse to make helium, converting some of their mass to energy. The core is wrapped by a radiative zone making up more than half of the Sun's radius, where energy slowly trickles outward. The outer 25% of the solar radius consists of the convection zone, where cells of plasma as big as Texas rise like bubbles in a pot of boiling water. As the cells approach the surface, they cool, lose buoyancy, and sink. That constant churning creates pressure waves (also called sound or acoustic waves) within a few hundred kilometers of the surface.

"As the plasma rises and falls, it creates turbulence," said Jason Jackiewicz, a professor of astronomy at New Mexico State University in Las Cruces. "That's a source of acoustic noise. It creates sound waves all over the place, all the time. Some of them interfere constructively, building up a resonance. They're created at the surface, then go down and back up, down and back up, down and back up. Each oscillation has certain properties, just like the waves in a musical instrument."



This illustration depicts the interior structure of the Sun, showing acoustic pressure waves ("p" modes) and gravity waves ("g" modes). Credit: ESA; Sun's chromosphere based on SOHO image; credit: SOHO (ESA and NASA)

"The region where the waves are created is very noisy," said Leibacher. "Not to be too anthropomorphic, but it's like a lot of people screaming and shouting there. Or a better analogy might be a bunch of people sitting on a piano at once. If you listen to it, it's just white noise. It's only because the waves last a long time that we can isolate them into individual modes."

The waves have a roughly 5-minute period. Astronomers have discovered about 10 million individual modes for the waves, with roughly a million of them shaking and rattling the surface at any given time.

Like the seismic waves that travel through Earth as a result of earthquakes, the Sun's waves have important diagnostic abilities. As they travel into the Sun, they're refracted toward the surface by changes in temperature, density, and composition. Individual waves are redirected differently depending on the circumstances of their creation and their path through the Sun. A careful analysis thus provides a detailed look at conditions deep in the Sun. Some modes are better tuned to provide details about sunspots and other surface phenomena.

Astronomers "see" the waves by measuring the Doppler shift all across the Sun's surface. Each wave causes the surface to jiggle up and down a little. The change isn't dramatic—only a few meters to a few tens of meters per second. To put that in perspective, Usain Bolt runs the 100-meter dash at about 10 meters per second.

Detecting and understanding the waves require long-term monitoring of the Sun. That can't be accomplished by a single ground-based station, so astronomers have built networks of Sun-watching telescopes across the planet. They've also placed instruments in space, where they can stare at the Sun constantly, unobstructed by clouds or the blurring effects of Earth's atmosphere.

One early helioseismology network was GONG (Global Oscillation Network Group), established by NSO in 1995. Still in operation today, it consists of six small, identical stations around the world, one each in California, Hawaii, the Canary Islands, Australia, Chile, and India. "We joke that the Sun never sets on GONG," said Leibacher.

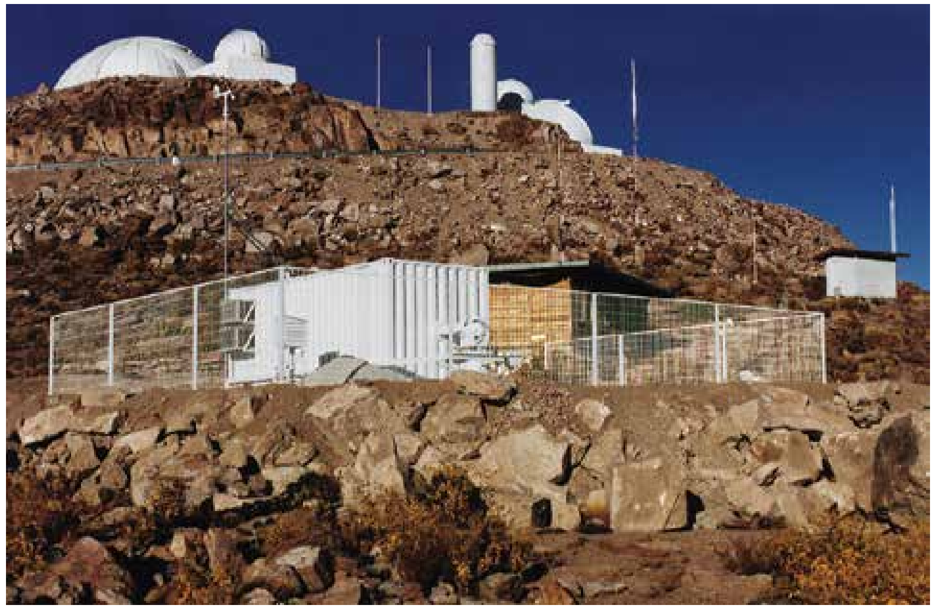
Each station, housed in an industrial cargo container, includes an interferometer to measure the Sun's surface oscillations and an instrument to measure it's magnetic field, allowing scientists to correlate the surface waves with magnetic activity.

The first space-based helioseismology instrument took to the skies shortly after GONG entered service, aboard SOHO (Solar and Heliospheric Observatory). Although SOHO continues to operate, the instrument was retired in 2011 when it was superseded by the Helioseismic and Magnetic Imager (HMI) aboard the Solar Dynamics Observatory (SDO). HMI provides higher resolution and a higher data rate than its predecessor.

"When ground-based telescopes look at the Sun, they see it through this boiling

"IT'S LIKE A LOT OF PEOPLE SCREAMING AND SHOUTING THERE. OR A BETTER ANALOGY MIGHT BE A BUNCH OF PEOPLE SITTING ON A PIANO AT ONCE."

EARLY DISCOVERIES WITH HELIOSEISMOLOGY APPLIED AS MUCH TO GENERAL QUESTIONS IN PHYSICS AS TO THE SUN ITSELF, BEGINNING WITH THE "SOLAR NEUTRINO PROBLEM."



The Global Oscillation Network Group (GONG) includes six international sites, including this station at the Cerro Tololo Inter-American Observatory in Chile. GONG was one of the earliest networks studying helioseismology. Credit: CTIO/NOIRLab/NSF/AURA

cauldron of atmosphere," said SDO project scientist W. Dean Pesnell at NASA's Goddard Space Flight Center in Maryland. "That introduces a lot of noise. We don't have that problem."

Small Particles, Big Science

Early discoveries with helioseismology applied as much to general questions in physics as to the Sun itself, beginning with the "solar neutrino problem."

Neutrinos are created in abundance during nuclear fusion reactions in the cores of the Sun and other stars. Because neutrinos are almost massless, they zip through the Sun and Earth without interfering with other particles. That makes them good probes of what's happening in the Sun's core, but it also makes them difficult to catch.

Early detectors counted only a third as many neutrinos as expected from models of the solar interior. "The nuclear physicists all said, 'Oh, our theories are right, and your observations must be wrong—the temperature of the Sun must be a little cooler than you astronomers think,'" said Leibacher. "We said, 'No, there's nothing wrong with our observations; there must be something wrong with the physics of neutrinos.' For once, we were right."

Helioseismology confirmed that the Sun's interior temperature profile was as expected, leaving nuclear physicists to ponder other solutions. They eventually realized that the neutrinos produced by the Sun were transforming themselves into one of two other "flavors" as they raced through the solar system. The physicists who discovered the solution received the 2015 Nobel Prize in Physics.

Tachocline and Core

In addition to confirming the Sun's internal temperatures, early observations also confirmed its interior structure, with a sharp, well-defined boundary at the base of the convection zone that can be pinpointed to within less than 1% of the Sun's radius.

"There are lovely results on…the existence of the tachocline—a shear layer that marks the transition between the convection zone, which has differential rotation, and the radiative region, which rotates uniformly as far as we can tell," said Yvonne Elsworth, a professor of helioseismology, physics, and astronomy at the University of Birmingham in the United Kingdom. Elsworth is a former director of the first helioseismology network, BiSON (Birmingham Solar Oscillations Network), which has been watching the Sun since 1976.

Details about the energy-generating core, however, have proven harder to obtain.

"The acoustic waves don't spend very much time there to sense the rotation, and not many of them [go that deep], so they're hard to observe," said Jack Harvey, an emeritus astronomer at NSO and one of the creators of GONG. "Our knowledge of the core is very fragmentary."

Another type of wave, known as a gravity wave, could help test those models. These longer-frequency waves are generated by oscillations in the core itself. They produce little or no signal at the surface, making them difficult to detect.

A 2017 study reported seeing the imprint of gravity waves in 16.5 years of data from SOHO, suggesting that the core rotates roughly once per week, compared with roughly once every 4 weeks at the surface (bit.ly/gravity-sun-core). However not all solar physicists accept these results. "We don't really know if [gravity waves] have been observed yet," said Harvey.

Cycling Through the Sunspots

Although helioseismology has not yet answered questions about the core, it's provided many details about the convection zone, in particular its rotation.

Astronomers have known for centuries that the surface of the Sun rotates differentially. By tracking sunspots as they crossed the solar disk, they could see that the polar regions rotate faster than the equator. Helioseismology confirmed that the differential rotation continues through the convection zone all the way to the shear layer.

"Identifying that shear layer is important because solar activity is caused by magnetic fields, and there was a big question about where the magnetic field is generated," said Alexei Pevtsov, associate director of the NSO Integrated Synoptic Program. "That strong shear layer, at the base of the convection zone, is where the dynamo operates."

Yet the dynamo is poorly understood, leaving scientists to ponder how it helps drive the Sun's magnetic cycle.

The cycle lasts roughly 11 years. At its peak, many dark sunspots speckle the Sun's surface. The peak also produces a greater number of solar flares and eruptions of giant clouds of hot gas known as coronal mass ejections. At the cycle's low point, the surface is almost bereft of such activity. At the end of a cycle the Sun's polarity flips, with the north magnetic pole becoming the south magnetic pole and vice versa, making the overall cycle 22 years long.

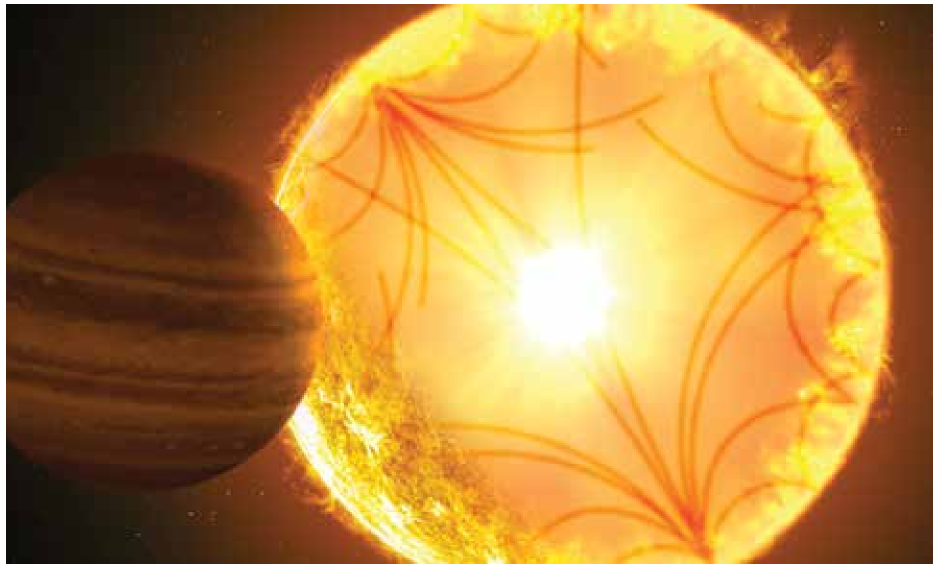
No two cycles are the same. "The cycle is regular, but it's not *perfectly* regular," said Sarah Gibson, a senior scientist at the National Center for Atmospheric Research's High Altitude Observatory in Boulder. Cycles vary in both length and intensity. The most recently completed one, which ended in December 2019, was one of the weakest on record. The current cycle was forecast to be equally meager, and it began that way, but it has exceeded projections in recent months.

One key to the solar cycle is a "conveyor-belt" flow revealed by helioseismology. Known as a meridional flow, it resembles the Hadley cells in Earth's atmosphere. The basic concept says giant cells of plasma move from the equator toward the poles. There, they dive below the surface, then

The Solar Dynamics Observatory takes aim at the Sun in this artist's conception. Credit: NASA/GSFC

"IDENTIFYING THAT SHEAR LAYER IS IMPORTANT BECAUSE SOLAR ACTIVITY IS CAUSED BY MAGNETIC FIELDS, AND THERE WAS A BIG QUESTION ABOUT WHERE THE MAGNETIC FIELD IS GENERATED."

HELIOSEISMOLOGY IS PROVIDING ROUGH VIEWS OF THE SUN'S FARSIDE, OFFERING WARNINGS OF LARGE SUNSPOTS DAYS BEFORE THEY ROTATE INTO VIEW. "THIS IS ONE OF THE BIG ACHIEVEMENTS OF THE WHOLE FIELD OF HELIOSEISMOLOGY."



A Jupiter-sized planet passes in front of a star in this artist's conception, with arrows indicating the flow of sound waves within the star. Astronomers learn about both the star and its planet from studying the waves at the star's surface. Credit: Gabriel Perez Diaz/Instituto de Astrofísica de Canarias

flow back toward the equator, where they return to the surface, completing the cycle.

The flow is "very important to theories of solar activity," said Harvey. "Our best theories of the solar cycle depend on that kind of flow, so we'd like to know what it's like. But the measurements are very subtle because the flows move at a few meters per second. You can run that fast."

The measurements are further complicated by the fact that neither ground-based nor current space-based telescopes can see the poles.

"A polar view is the linchpin in all of this," said Gibson, who served as project scientist for SOLARIS, a proposed solar polar mission that was rejected by NASA earlier this year. "If we can observe the poles, see the flows, we could rule out some mechanisms."

Improving Weather Forecasts

Understanding the Sun's magnetic cycle better is important for a practical application: forecasting space weather. As heavy outbursts of solar radiation and charged particles interact with Earth's own magnetic field, they can damage orbiting satellites, knock out power grids on Earth's surface, weaken oil pipelines, and cause other problems. NOAA, the U.S. Air Force, and several international organizations provide space weather forecasts to help operators protect potentially vulnerable assets.

Helioseismology is providing rough views of the Sun's farside, offering warnings of large sunspots days before they rotate into view. "This is one of the big achievements of the whole field of helioseismology," said Tripathy.

As waves travel through the Sun, they interact differently with sunspots than with the unblemished surface. And because the waves can travel around the entire star, some of them reveal the presence of farside sunspots as the waves ripple to the nearside. "We can predict that an active region that we've never actually seen before will appear on the east limb of the Sun on this date and at this location," said Leibacher. "It's an interesting party trick, if you will. It's also interesting solar physics."

As the databases of observations grow larger, scientists are testing other interesting bits of solar physics as well. As one example, the observations aren't necessarily agreeing with profiles of the Sun's composition obtained through other techniques.

The Sun consists almost entirely of hydrogen and helium, with a smattering of heavier elements—about 2% of its total mass—that were forged inside other stars. The heavier elements, known as metals, were expelled into space when the stars died and were then incorporated into the Sun as it formed from a cloud of interstellar gas and dust. Slight variations in the proportions of these elements cause differences in a star's internal temperatures and other characteristics, so fully understanding what's going on inside a star today—and how the star will evolve—requires precise knowledge of its composition.

It seems like there are fewer metals in the Sun than researchers thought, said Jackiewicz. "That has major implications for stellar astrophysics in general. We compare every star to the Sun—'That star has 10% of the metallicity of the Sun, or that star has twice the metallicity.' That's great, but it assumes we know the metallicity of the Sun. I don't know that anyone's willing to say we know that for sure anymore."

From One Star to Many

Although astronomers use helioseismology in part to learn about how other stars operate, they use a similar technique—asteroseismology—to study other stars in part to learn about the Sun.

Asteroseismology observations have come from the databases of Kepler, TESS (Transiting Exoplanet Survey Satellite), and other satellites designed to hunt for exoplanets. The craft keep a steady gaze on large numbers of star systems for weeks or longer, so their observations can be used to glean information about the stars as well as their planets.

Because the stars are so far away, they appear as just pinpoints of light, so astronomers can't detect the shaking and rattling with the same level of detail as on the Sun. Instead of millions of different modes, they see perhaps a few dozen, observed as minor changes in brightness rather than changes in surface motion, which are integrated across the star's entire disk. Still, that provides enough information to characterize a star's interior temperature and structure.

"We've measured the pulsations of about 30,000 stars," said Jackiewicz. The vast majority are red giants—old, bloated stars that have converted the hydrogen in their cores to helium and now are beginning to fuse the helium to produce heavier elements. "That's the boon of the last 10 years of asteroseismology, which is great, because the Sun will become a red giant in a few billion years."

A red giant's core is smaller, denser, and hotter than the Sun's, so it produces stronger gravity waves, which are more easily detected at the star's surface. "So we know more about the rotation of the cores of red giants than the Sun," Jackiewicz said.

With asteroseismology, "we can look at 10,000 different realizations of the Sun," said Leibacher. "We can observe the Sun only today, not in a million or a billion or 5 billion years. But we…can do asteroseismology of what the Sun will become, which is pretty amazing."

Asteroseismology is also helping astronomers study exoplanets. "The properties of the stars are tied to the properties of the planets," said Jackiewicz. "With seismology, we have access to parameters and things that traditional observations don't. So we can tell if it's a Jupiter-type planet or an Earth-type planet. It's a really active area of research."

Helioseismology remains an active area as well, although its tools are aging. SDO, for example, has been operating for more than 12 years. Although it's in good shape and could go for several more years if it receives funding, according to Pesnell, its instruments can't be upgraded, and the spacecraft can't be serviced if something goes wrong.

And GONG "is getting a little long in the tooth," according to both Harvey and Leibacher. "It was designed for 3 years, not 30," said Harvey.

GONG scientists have proposed a next-generation version of the network that would incorporate improved instruments, better enclosures than the current cargo containers, and perhaps sites at higher altitudes to enable observations of the Sun's hot outer atmosphere, the corona. Last year, however, the National Science Foundation rejected a proposal for the new network.

"We've refurbished GONG's cameras and computers, so we can probably extend it for another 5, 7, maybe 10 years, but not more than that," said Pevtsov. "It won't last forever."

"I think a next-generation GONG is more or less inevitable; it's only a matter of how and when," said Leibacher. "But we can't just skip a [solar] cycle. You can't rewind and see what happened 10 years ago. You have to be observing day by day to try to make sense of the Sun's dynamo"—and understand how the surface keeps shaking and rattling with a million vibrations.

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▶ **Read the article at bit.ly/Eos-shake-rattle-probe**

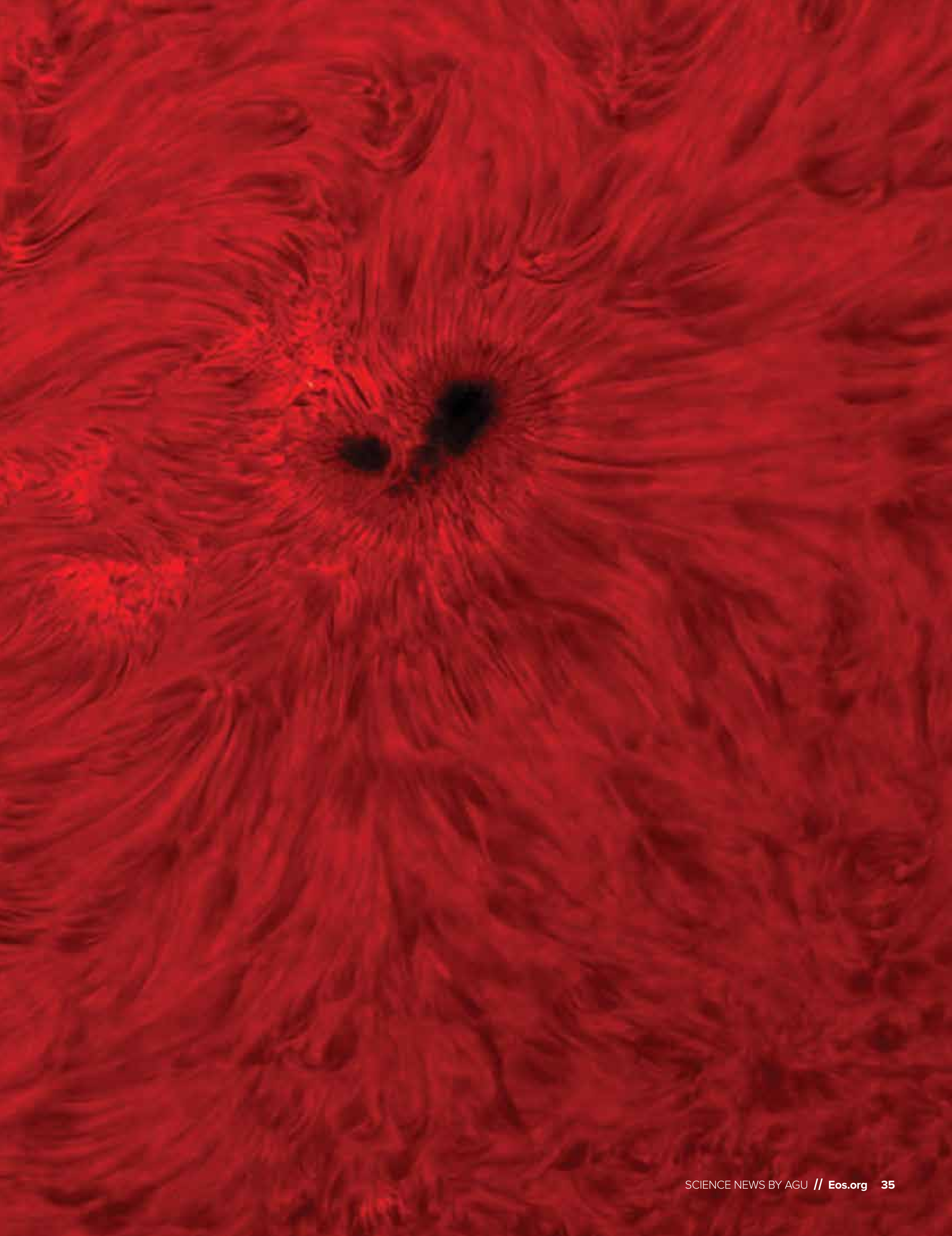
"WE COMPARE EVERY STAR TO THE SUN—'THAT STAR HAS 10% OF THE METALLICITY OF THE SUN, OR THAT STAR HAS TWICE THE METALLICITY.' THAT'S GREAT, BUT IT ASSUMES WE KNOW THE METALLICITY OF THE SUN. I DON'T KNOW THAT ANYONE'S WILLING TO SAY WE KNOW THAT FOR SURE ANYMORE."

11 DISCOVERIES AWAITING US AT SOLAR MAX

By Kimberly M. S. Cartier

Each solar cycle might seem like the same old story, but one thing has changed significantly since the previous solar maximum—our technology.

We are in the middle of solar cycle 25, which means that the Sun has been slowly ramping up its sunspot and flare activity for the past few years. Credit: Stocktrek Images, Inc./Alamy Stock Photo

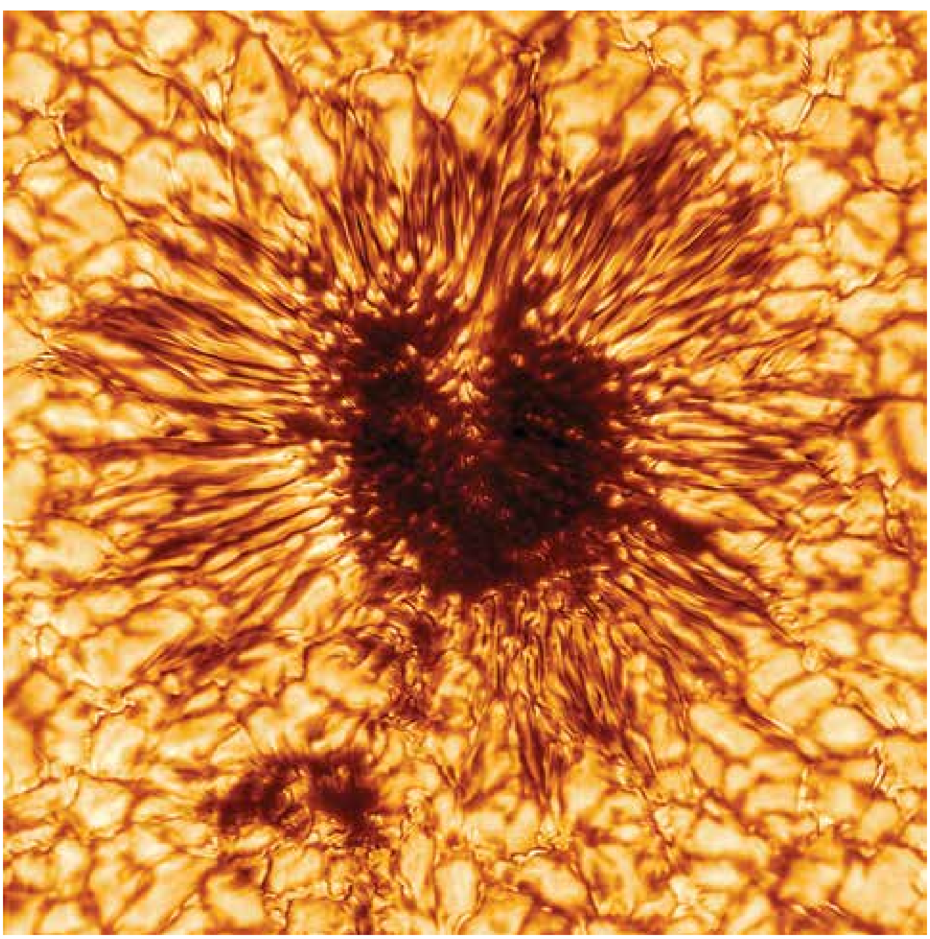


We are in the middle of a solar cycle, and we've been here before. That's not to say a solar cycle is exactly the same every time—some cycles are far more active than others, and sometimes the Sun skips a cycle completely. But the overall pattern remains the same and repeats every 11 years, even if the details vary slightly each time.

The current solar cycle, number 25, started in 2019, which means that the Sun has been slowly ramping up its sunspot and flare activity for the past few years. Solar maximum, when the Sun's magnetic polarity flips and it's expected to be the most active, is anticipated to happen sometime between 2023 and 2026.

"As we are heading towards the solar maximum, we expect many more active regions to appear," said Kiran Jain, a solar physicist at the National Solar Observatory in Boulder, Colo. Initial forecasts of cycle 25 predicted that it would produce activity levels similar to those of the previous cycle, which were slightly below average, but "the current cycle has been more active so far" than during the same phase of cycle 24.

Scientists hope that cycle 25 will continue to provide more excitement than did cycle 24—they want to see spots and flares of all sizes and intensities and many coronal mass ejections (CMEs) that traverse interplanetary space to interact with planets' magnetic fields. But whether that trend persists or the maximum of cycle 25 is the same as any other, solar scientists will assuredly learn far more than they did 11 years ago. Since the previous solar maximum, there have been major advances in solar-observing technology, solar and planetary magnetic theory, and computational power.



The Daniel K. Inouye Solar Telescope in Hawaii took this image of a sunspot on 28 January 2020 as part of its science verification phase. The field of view is 19,312 kilometers (12,000 miles) across. Credit: NSO/NSF/AURA, CC BY 4.0 (bit.ly/ccby4-0)

Here are 11 discoveries scientists hope to make during the upcoming solar maximum that weren't possible during the previous one.

1 Sunspots, Eruptions, and Flares

The 11-year solar cycle is also known as the sunspot cycle because active regions on the Sun's surface often manifest sunspots. Astronomers have been tracking sunspots for centuries. "As crude a measurement as it is for quantifying solar activity, sunspot number is nevertheless the thing I most readily keep an eye on," said Mathew Owens, a space physicist at the University of Reading in the United Kingdom. "We have more than 400 years of nearly continual sunspot observations, so it's invaluable for putting the current conditions on the Sun in a long-term context." Given the decidedly average forecast for cycle 25, "we aren't necessarily expecting extreme space weather. But the Sun can always surprise us."

In fact, University of California, Berkeley space scientist Janet Luhmann noted that despite cycle 24's lackluster sunspot performance, "one of the most extreme events ever observed with modern instruments occurred in July of 2012. The truth is that the really extreme storms do not care if the sunspot number maximum is weak."

What solar maximum ideally will do is produce flares at a wide range of intensities, especially those at the highest intensities, to help scientists develop more accurate models of flare generation. "We want to understand how flaring activity depends on solar cycle," said Monica Bobra, a solar scientist at Stanford University in California. "In the last decade, we've only observed about 40 large, or X-class, flares." Low-intensity flares are far more common even in weak solar cycles and at solar minimum, "so even though we're taking so much data, in some ways we're data starved because we have a really imbalanced data set," she said.

2 The Sun's Structural Secrets

Unlike the 400-year history of sunspot monitoring, this will be only the third solar maximum for which we have continuous helioseismic coverage, said Sarbani Basu, an astronomer at Yale University in New Haven, Conn. The study of helioseismology looks at the propagation of pressure waves as they travel through the Sun, much like the study of seismology considers seismic waves as they travel through

Earth. Helioseismology can measure details of the internal structure of the Sun, which has a core, a radiation-dominated middle layer, and a convection-dominated outer later.

"There are very tentative indications of changes in the structure in the deep solar interior associated with the solar cycle," explained Jørgen Christensen-Dalsgaard, who studies solar structure and evolution at Aarhus University in Denmark. "The understanding of the physical reasons for these relations is still very incomplete, and the new data [collected during maximum] will undoubtedly be very useful in this regard."

"We barely have a 40-year history of good helioseismic data," Basu said. "Good coverage of the entire solar cycle is essential. Having said that, the maximum does act as the demarcation of the two parts of the solar cycle and hence a change in behavior. That is what excites me most about the upcoming maximum." Helioseismic data could track those changes.

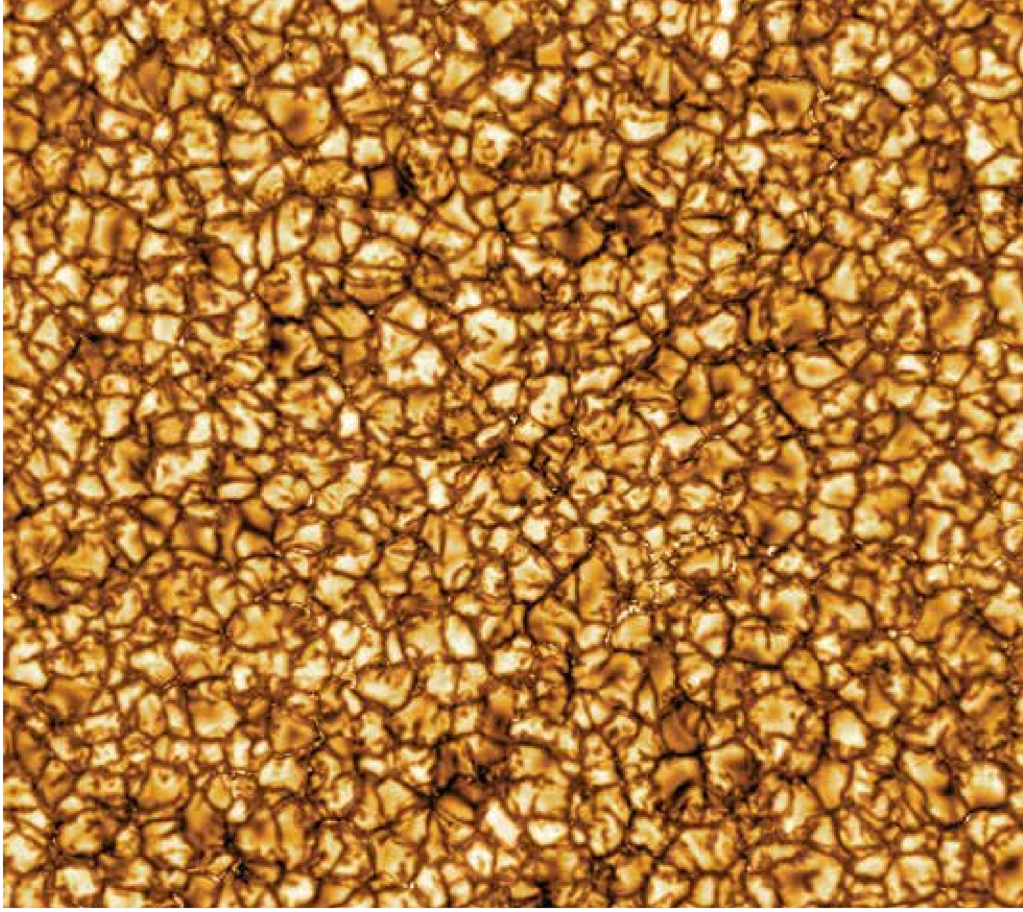
Solar physicists can also use helioseismology to investigate how the Sun's magnetic field affects the seismology of sunspots and active regions during solar maximum, Jain said. She is particularly interested in "the subsurface properties that can reliably predict the emergence of active regions in the farside hemisphere as well as the nearside hemisphere." Can helioseismology detect the rise of magnetic structures on the Sun's farside before they manifest on the solar surface? Jain wants to find out.

3 Movement Beneath the Surface

Helioseismology can also reveal how the different layers of the Sun rotate. "With helioseismology we have found bands of slightly slower and faster rotation in the outer parts of the Sun—the so-called convection zone—that are clearly related observationally to the solar surface activity," said Christensen-Dalsgaard. "In fact, the first signs of a new solar cycle typically appear in this rotation pattern, overlapping with the end of the previous cycle."

Deeper within the Sun, a region known as the tachocline separates the radiative zone from the convective zone, which rotate at different speeds.

"I will be monitoring the internal dynamics, particularly the changes in the so-called tachocline where solar internal rotation changes from being differential in latitude (i.e., each latitude rotating at a different rate) to a solid body–like rotation," Basu explained. "Unlike some other solar features, the changes in the tachocline do not follow the [11-year] sunspot cycle. The question: Do the changes follow the 22-year magnetic cycle instead? Helioseismic data collected from now until the next solar maximum will be able to answer that question."



This first-light image from the Daniel K. Inouye Solar Telescope is the highest-resolution image of the solar surface ever taken. The image covers a patch of the Sun 36,500 × 36,500 kilometers (22,600 × 22,600 miles) in area, and the smallest features are only 30 kilometers (18 miles) in size. Each granule represents a small convection cell on the solar surface, bringing hot material up to the surface and bringing cooler material back down. Credit: NSO/NSF/AURA, CC BY 4.0 (bit.ly/ccby4-0)

4 Many "Eyes" Staring at the Sun

Solar scientists now have a fleet of spacecraft flying around the inner solar system. NASA's Advanced Composition Explorer (ACE), Solar Dynamics Observatory (SDO), Solar Terrestrial Relations Observatory (STEREO), and Deep Space Climate Observatory (DSCOVR) have been the workhorses of space-based solar observing for more than a decade and have built an extensive catalog of solar observations. Two newer solar spacecraft, NASA's Parker Solar Probe (PSP) and the European Space Agency's Solar Orbiter (SO), are designed to explore two never-before-seen regions of the Sun.

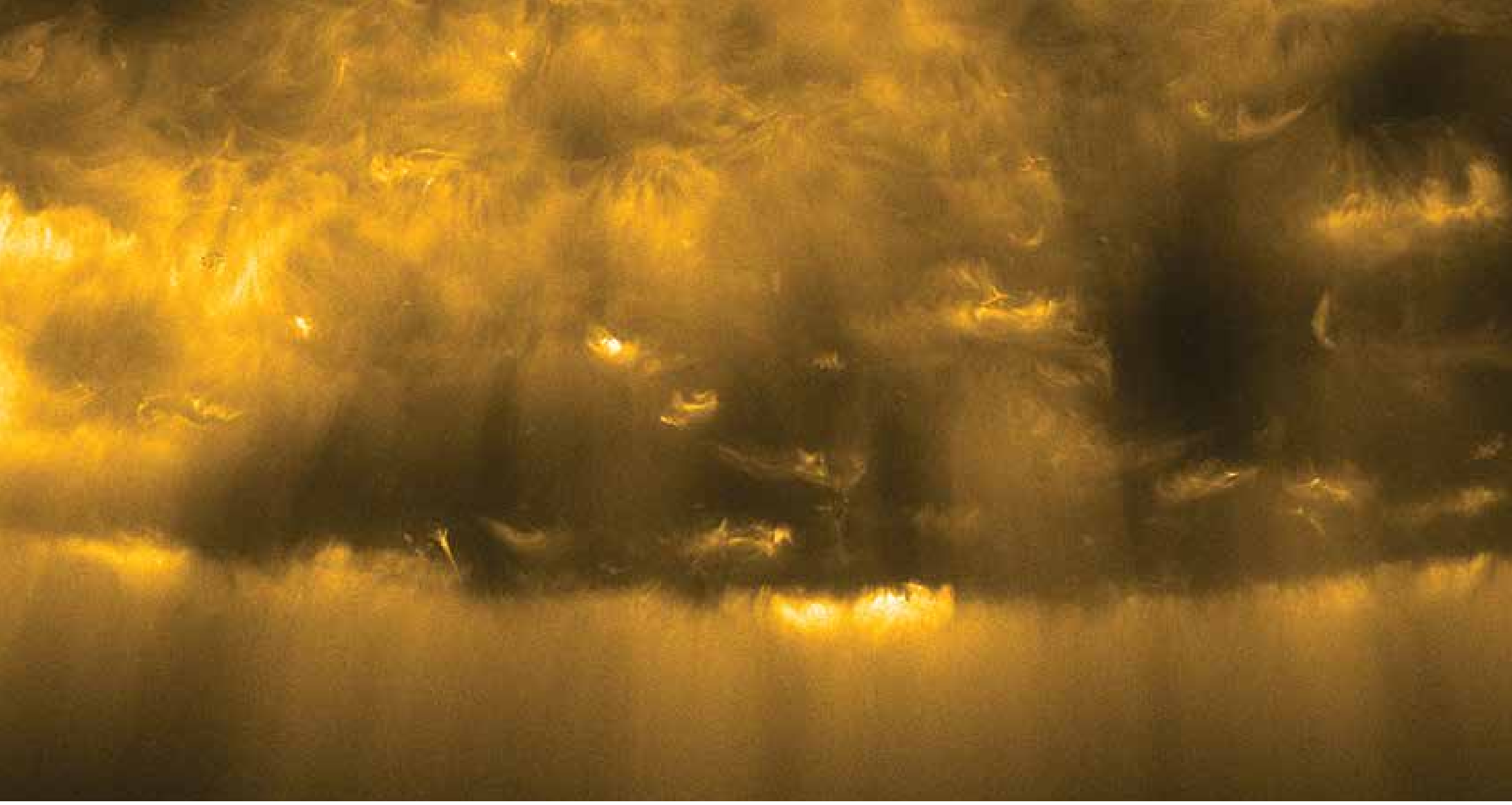
"Solar Orbiter is still at an early stage but will provide first direct views of the solar poles," Jain said. "As we have learnt from the polar observations of other planets, we may discover something unusual at the solar poles which has not been observed yet."

"With every new addition to our robotic and ground-based 'observers' of solar and space environment conditions—including those sited in regions not previously visited like Parker Solar Probe—we improve our knowledge of the connections between the Sun's behavior and its surrounding space environments," said Luhmann. PSP is exploring the mysterious solar corona.

Other spacecraft, like BepiColombo, a joint mission between Europe and Japan, are on their way elsewhere but have advanced magnetometers that can make critical solar measurements.

Xiaojun Xu, a solar physicist at Macau University of Science and Technology in China, said, "More and more satellites placed or to be placed to many locations with different heliocentric distances, especially the PSP and Solar Orbiter, in the past and the future are the biggest innovation for studying the Sun and the solar wind as well as planets."

"While the quiet phase of the solar cycle provides the opportunity to establish the physics of baseline conditions," Luhmann



ESA's Solar Orbiter obtained this first look at the Sun's south pole in March 2022. The observations were taken in extreme ultraviolet wavelengths. Credit: ESA and NASA/ Solar Orbiter/EUI Team

said, "the active Sun produces the space weather 'storms' that greatly enhance the types and amounts of energy transferred to the planets and their atmospheres. Thus, each new solar maximum is in effect experienced with 'new eyes.'"

5 Peering Inside a CME

Active regions on the Sun's surface "are the major driver of space weather," Jain said. "Eruptive phenomena, such as flares and coronal mass ejections, may create conditions that can affect humans and technology in many ways, and some may lead to catastrophic effects. Thus, it is important to understand their origin, the complex physical processes lying below and above the Sun's surface, and the interactions between the Sun and Earth." Active regions, and therefore CMEs, will be more common during the upcoming solar maximum.

Christian Möstl, a solar scientist at Graz University of Technology in Austria, and his team are trying to "better understand and model the magnetic structure of CMEs, which should then give us a better chance to forecast their Earth impacts." The combination of solar maximum and new missions is "an absolutely glorious setup for making new discoveries and increasing the accuracy and lead time of space weather forecasts."

Möstl said that seeing a CME event first in solar images and then in a spacecraft's magnetic field and plasma detectors will help scientists better connect the physical shape of a CME to its magnetic structure, which in turn will help space weather forecasters down on Earth. "We wait and hope that a CME travels towards these radially aligned spacecraft at those times, which is just pure chance, of course." Solar maximum increases the chance that a well-equipped spacecraft will pass through a CME. "The new goal is to say, 'This CME has this type of morphology, so the magnetic structure is going to be like this.'"

6 CMEs on the Move

With more CMEs on the way and more spacecraft flying around to detect them, it's possible that a single CME event will intersect multiple spacecraft in multiple locations in the solar system.

This type of multipoint observation of a CME has happened a few times since the launch of Solar Orbiter, Möstl said. Two CMEs impacted Solar Orbiter, BepiColombo, and Earth, and [since then] there have been a few more. There should be a lot more events like this as we go into solar maximum, all helping us to understand how the CME magnetic field evolves from Sun to Earth."

A chance alignment between a CME and multiple spacecraft would be rare, but it's also possible that a single spacecraft might cross the same CME twice. For example, as Parker Solar Probe continues its slow spiral inward toward the Sun, it might cross the magnetic core of a CME in two locations on its journey. Traveling in and out of a CME twice could help scientists understand how a CME's magnetic field evolves as it travels through the solar system.

How about multiple CMEs crossing each other? Far from impossible. "During solar maximum, CMEs interact with other CMEs much more often, just because there are more eruptions," explained Möstl. "This can lead to slipstream effects, so that a following CME is actually traveling faster than if it would propagate on its own, leading to different Earth arrival times, like sports cars when overtaking one another. When CMEs run into each other, they can coalesce and merge, which again alters their magnetic structure, affecting the magnetic storm level when they impact Earth."

7 From Space Weather to Space Climate

When solar storms and CMEs arrive at Earth, they can precipitate space weather and other geomagnetic activity. "Severe space weather will occur more frequently, and we'll get to investigate it with a new fleet of spacecraft and instruments," said Owens. Moreover, "the coming solar cycle adds to only five previous that we've measured directly with spacecraft. Thus, there's a great deal of opportunity for learning how long-term changes in solar activity—space climate—varies and controls more rapid space weather."

"Our capabilities in terms of spaceborne observations have increased rapidly within the last 10 years," said Erdal Yiit, a planetary scientist at George Mason University in Fairfax, Va. "Besides many others, NASA's GOLD and ICON satellites can be mentioned as promising tools that will aid our understanding of space weather effects on Earth." GOLD, or Global-scale Observations of the Limb and Disk, and ICON, or Ionospheric Connection Explorer, investigate Earth's thermosphere and ionosphere response to Earth-Sun interactions.

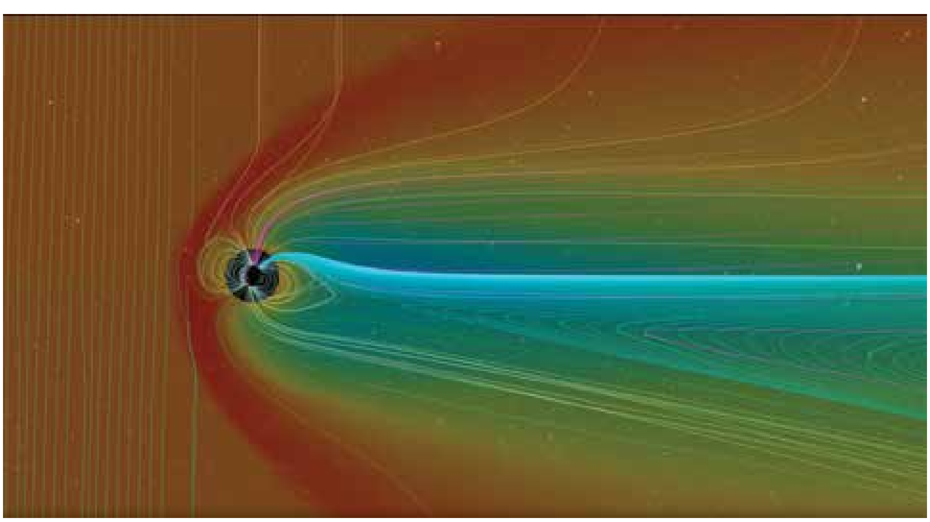
In her work, Bobra seeks to predict space weather "by analyzing millions of images of the Sun with machine learning algorithms. And I'm excited to continue doing that!" she said. She's interested in collecting space weather observations that span a solar cycle or more to help train those algorithms. "At some point you reach a threshold with the data you already have. But augmenting our current data sets with new, consistent, continuous measurements from a constellation of satellites, all taking data over a long period of time, will greatly increase our capacity to predict space weather."

8 Mapping Our Magnetosphere

Earth's magnetic field, which is generated by our spinning iron-nickel core, can be roughly described as a dipole magnet. But in reality, the shape and structure of the magnetic field are more complex. Upstream, or facing the solar wind head-on, the magnetic field lines are compressed as they battle the magnetically charged solar wind plasma. The field downstream is elongated and trails behind the planet like a tadpole's tail.

During the upcoming increase in solar storms and CMEs, "we will have several upstream spacecraft with both solar imaging and in situ solar wind plasma and magnetic field detection capability," said Luhmann. "The latter will provide a better idea than ever before of how uniform (or not) the local space environment conditions are in the vicinity of Earth."

Solar maximum brings not just an influx of high-intensity solar storms but also a reversal of the Sun's large-scale magnetic polarity—magnetic north flips to magnetic south. "We are investigating the performance of the interplanetary magnetic fields near Earth during the reversal of the Sun's magnetic field, which only takes place near solar maximum," said Xu. "We believe some clues can be found near Earth. If there are many CMEs or flares in the next years, we can conduct more studies about the response of planets to such solar storms."



A screenshot from a video that simulates how Earth's magnetic field responds to a strong CME event (find the video at bit.ly/Eos-solar-max). The particle density of the solar wind is visualized in color; cooler colors represent lower particle density, and warmer colors represent higher particle density. When a CME event reaches Earth and increases the particle density by up to 5 orders of magnitude, Earth's dipole magnetic field (shown by lines of constant magnetic strength) is compressed upwind of the solar wind flow and elongates downwind. Credit: Tom Bridgman/NASA Scientific Visualization Studio

9 Push for "Sun to Mud" Predictions

Solar storms and their resultant space weather can have significant impacts on our technology, from GPS satellites in orbit to power grids on the ground. There is a big scientific and political push to develop faster and more accurate predictions of inclement space weather so that these negative impacts can be anticipated and mitigated. Because the previous solar cycle was not very active and didn't provide a lot of new data on extreme events to work with, there has been more focus recently on developing machine learning- and artificial intelligence (AI)-based models to improve our forecasting capabilities.

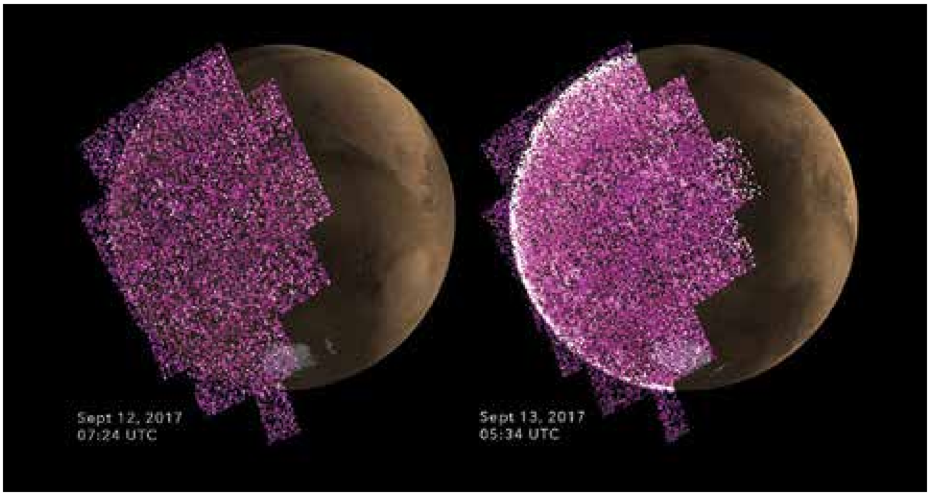
"But even with all of the physics-based model developments over the last decade," Luhmann said, "we are still not making routine 'Sun-to-mud' space weather models—either in retrospective or forecast mode—of even more moderate events," let alone the extreme events that will be more common during solar maximum. "However, we are getting closer."

"I personally think that a combination of very fast physical models with machine learning methods is the best avenue to make progress in space weather forecasting," said Möstl. "This is because it's hard to make progress for an AI alone when it does not know the physics of a system." During this solar maximum, scientists are anticipating a trove of data on solar activity at a wide range of intensities to help train those models and improve their speed and accuracy.

At the British Geological Survey (BGS), "we monitor the Sun closely for coronal mass ejections and the solar wind using SDO," said Ciaran Beggan, a geophysicist at BGS in Edinburgh who works to improve their real-time space weather forecasting. SDO orbits "at the L1 Lagrange point, where DSCOVR and ACE provide real-time values of the solar wind speed, density, magnetic strength, and orientation." BGS supplements those data with measurements from their ground-based magnetic observatory network to make real-time predictions of geomagnetically induced currents that can knock out power grids.

10 Much Ado About Planets

CMEs that miss Earth entirely continue to travel through the solar system and can affect planets farther away from the Sun. In the past, scientists have observed how solar storms can trigger iono-



On 13 September 2017, an intense solar storm struck Mars and triggered a planetwide aurora, imaged here by NASA's MAVEN orbiter. Because Mars's weak magnetic field is embedded in the planet's crust, its aurorae aren't concentrated at the planet's poles like they are on Earth. The violet glow represents Mars's nightside ultraviolet emission before (left) and during (right) the aurora, superimposed over a simulated image of Mars's dayside crescent. Credit: NASA/University of Colorado, Public Domain

spheric activity like aurorae on Jupiter and Saturn. "Heliophysics has been moving into an era in which space weather is of interest throughout the solar system," Luhmann said. Planetary scientists are excited to see how the more regular and regularly more intense solar activity will influence Mars's magnetic field and atmosphere.

"The occurrence of any CME would attract our attention" said Xu, whose research group studies how the solar wind interacts with planets and moons. "We want to study the interplanetary coronal mass ejections continuously using multiple spacecraft from near the Sun to Earth and to Jupiter."

Although Mars and Earth are both rocky planets with liquid metallic cores, Mars no longer actively generates its magnetic field. A weak remnant of it remains embedded in Mars's crust, but if Earth's magnetic field is like a protective blanket shielding us from harmful radiation, Mars's magnetic field is more like a wet tissue. "Especially for Mars, using the measurements jointly from MAVEN and Tianwen-1, better understandings about Mars' climate change are expected," Xu said. MAVEN, or Mars Atmosphere and Volatile Evolution, is a NASA mission that has been monitoring Mars for 8 years, and Tianwen-1 is China's first Mars mission, which arrived at the Red Planet in February 2021.

"On Mars, the MAVEN mission has already been performing measurements in the ascending phase of the solar cycle," Yiğit said, which can now be compared with its past observations during solar minimum and provide data across a full solar cycle. "There are a number of space weather models that have been continuously developed over [that] time, which are powerful tools to study how the atmosphere and ionosphere change on Earth and Mars due to space weather effects."

Christensen-Dalsgaard's research group "is also active in exoplanet research and hence very interested in how stellar magnetic activity may affect the habitability of exoplanets," he said, for example, how it affects planetary atmospheres. How the magnetospheres of Earth and Mars respond to solar events of different intensities might also help astronomers understand how extrasolar planets might survive the stellar winds of their own host stars, many of which are far more active than our Sun.

11 The Sun's Impacts on the Ground

Technologies that observe the Sun aren't the only tools that have evolved since the last solar maximum. "For example, how reliant are some systems like self-driving vehicles or trains on GPS, and what happens if its accuracy is affected?" asked Beggan. The upcoming increase in intense solar-induced geomagnetic activity might put these new technologies to the test. "These types of issues can be engineered out, of course, but knowing they are there in the first place is important and is often revealed when they are assumed to be reliable but then fail unexpectedly."

Beggan also raised the issue of how power grids, both old and new, will respond to the increase in intense storms. At the British Geological Survey, "we have built a number of new models of the U.K.'s high-voltage power grid and the high-pressure pipeline network to understand the impact of geomagnetically induced currents on transformers and pipeline corrosion during large geomagnetic storms," he said. "These can really only be tested and further refined during big geomagnetic storms.... During solar minimum there were only a few big storms to play with. A few [more] large storms would be a good test of the models to see how well our simulations match what happens in reality."

Pushing Past the Solar Peak

This solar maximum will also highlight what tools we don't have yet and need to develop before the next solar maximum. For example, Bobra said, eventually we will want to launch a constellation of satellites that gives us continuous 360° monitoring of the Sun's surface. "Large solar flares are rare already, and we're missing half of them because we can't see the farside of the Sun," she said. This will also help scientists test their models of solar activity on the Sun's farside.

Over the past decade, machine learning and artificial intelligence have been moving us toward real-time predictions of space weather and geomagnetic activity. "New tools coming from machine learning research may allow us to push that a step further," Beggan said, "and to use the data...to make predictions on the ground 30–45 minutes ahead of time, which would be a great step forward."

But to truly test and train those predictive models, scientists need data, and those data come from solar storms. "Tying all these new models and tools together," Beggan continued, "particularly if they can be trained and tested on some big events with modern instrumentation and measurements, would bring the goal of an accurate, automated, real-time forecasting and prediction system into reach."

Author Information

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▶ **Read the article at bit.ly/Eos-solar-max**

How Land Deformation Occurs When Fault Sections Creep

Strike-slip faults can be fickle about their movement—they can move slow and steady or remain stationary until their built-up stress is let loose in one go. But how do these faults' movements change from a locked and sudden release to a steady creep? And how does this change affect the rock around the fault? Understanding where these deformation styles occur and the variables that contribute to the kind of movement is important in determining earthquake hazards.

To uncover what happens near a change in slip, *Ross et al.* created a physical model to isolate slip behavior along a strike-slip structure. They used deforming silicone as an analogue for Earth's crust, which allowed them to disregard other variables that can influence slip types, including lithology differences, deformation history, and fault geometry.

One side of the experiment remained stationary while the other side moved, and along that boundary between the two sides, one portion was stuck to itself, or locked, while another was cut to simulate creep. Colored sand grains were sprinkled on the surface to track motions. Top-down time-lapse photography captured 2D deformation, whereas 3D deformation was tracked with photogrammetry.

The researchers found that contraction develops where the creeping portion of the fault runs into the locked section of the fault. Simultaneously, at the opposite end of the locked section as the creeping section pulls away from it. This pattern repeats in secondary locations, creating an alternating pattern of extension and contraction. These zones have opposite vertical motions, creating topographic highs and lows.

When the researchers compared their model to field data on the San Andreas Fault in central California, they found that both model and field data showed a pattern of alternating extension and contraction across the creeping fault sections. According to the authors, this work shows that a change in slip behavior can lead to off-fault deformation and could explain some of the patterns seen along the San Andreas Fault. (*Geophysical Research Letters*, https://doi.org/10.1029/2021GL096784, 2022) —**Sarah Derouin**, *Science Writer*

Strike-slip faults like the San Andreas have sections of locked movement and sections of slow and steady creep. Credit: John Wiley/Wikimedia, CC BY 3.0 (bit.ly/ccby3-0)

Understanding Earthquakes Triggered by Wastewater Injection

Since 2009, many central U.S. residents have faced increasing earthquake activity. Research has suggested that these tremors are linked to wastewater injection into deep wells by oil and gas companies. However, the precise dynamics of these earthquakes are still being revealed.

To shed new light, *Pennington et al.* investigate the characteristics of a M_W 4.0 earthquake that shook Guthrie, Okla., in 2015. This quake was the largest in a series of earthquakes near Guthrie that were triggered by wastewater injection in the region.

The researchers used seismic data to computationally invert for the precise locations of slip along the fault during the earthquake. In addition, they compared slip dynamics of the Guthrie quake with those of several other earthquakes of similar size that occurred along active or reactivated faults in North America and East Asia.

They found that the M_W 4.0 Guthrie earthquake had a complex rupture pattern featuring four distinct patches along the fault where slip took place, similar to patterns seen for earthquakes along other reactivated faults. In contrast, earthquakes along active faults showed more diffuse slip patterns.

The findings suggest that the slip dynamics of the M_W 4.0 Guthrie earthquake resulted from nonuniform stress and strength conditions that were present prior to the quake. Changes in pore pressure caused by wastewater injection likely enhanced these initial conditions. However, the fault's structure likely drove the distinctive slip pattern, with pore pressure playing a secondary role.

These results could help guide further research into the dynamics of reactivated faults, and they could help inform earthquake hazard modeling. (*Journal of Geophysical Research: Solid Earth*, https://doi.org/10.1029/2021JB023564, 2022) —**Sarah Stanley**, *Science Writer*

Despite Improvements, China's Air Remains Unsafe

Fine particulate matter ($PM_{2.5}$) and ozone exposure are major public health problems in China. Although useful, atmospheric models used to analyze these and other air quality concerns over the years are expensive to run, limiting how often researchers can use them.

New results from *Conibear et al.* worked around this limitation by training machine learning algorithms to find associations between the inputs and outputs of atmospheric models. The researchers then used the algorithms to analyze emissions levels and the origins of those emissions from 2010 to 2020.

They found that efforts to reduce $PM_{2.5}$ emissions in China are working. Average $PM_{2.5}$ levels across the country have dropped from their peak of 52.8 micrograms per cubic meter in 2012 to 33.5 in 2020. The change brings $PM_{2.5}$ levels from about 10 times above the World Health Organization's (WHO) guideline to about 7 times the guideline. The authors discovered that the biggest drops in $PM_{2.5}$ generation occurred in the industrial and residential sectors. Improvements in transportation, agriculture, and power generation also played small roles.

Although $PM_{2.5}$ levels appear to have peaked in 2012 and then declined—a trend supported by on-the-ground observations—the situation with ozone is more complicated. The researchers' models suggest that ozone levels have dropped since 2015, but on-the-ground measurements show a sharp increase. This discrepancy may be the result of imperfections in simulations, according to the authors.

Overall, the researchers estimate that the drop in $PM_{2.5}$ prevented 187,800 premature deaths in 2020, or 9% of the deaths attributable to $PM_{2.5}$ exposure. Reducing $PM_{2.5}$ levels to 25 micrograms per cubic meter, which WHO recommends as an interim goal for countries trying to reach the recommended annual mean of 5 micrograms per cubic meter, would require a further 80% drop in industrial and residential emissions below 2020 levels. The authors predict that such a drop would prevent another 440,800 premature deaths per year. (*GeoHealth*, https://doi.org/10.1029/2021GH000567, 2022) **—Saima Sidik,** *Science Writer*

Air pollution obcsures a jade pagoda in Beijing, China. Credit: Daniel Case/Wikimedia, CC BY-SA 3.0 (bit.ly/ccbysa3-0)

Algorithm Detects Thousands of Levees Missing from U.S. Database

Over the past 300 years, humans have dramatically altered rivers through mining, draining, dredging, levee construction, and other activities. Artificial levees, for instance, provide a barrier between rivers and their floodplains to prevent flooding, but can they stand in the way of important natural processes.

To better understand how artificial levees affect modern rivers in the United States, it is important to have a reliable, updated database of levee locations. However, the existing National Levee Database developed in 2006 by the U.S. Army Corps of Engineers fails to capture many of the nation's smaller structures. In a new study, *Knox et al.* use machine learning to detect the artificial levees that are missing from the database.

To create their algorithm, the researchers tried out several different machine learning models and variables taken from the National Elevation Dataset, National Land Cover database, and National Hydrography Dataset. After several trials, they developed an algorithm that was 97% accurate at detecting artificial levees.

They found that 113,222 miles (182,213 kilometers) of potential levees, or areas that may be artificial levees but are not identified by the database, across the 100-year floodplains of the United States are not included in the current database. This finding suggests that the existing database contains just one fifth of the country's actual total levee count, and most of those areas were located in the upper and lower Mississippi and Missouri basins.

The researchers conclude that with the addition of the levees found by the new model, 2% of the country's rivers are modified by levees, though larger streams are modified along up to 35% of their length. Such extensive modifications could have implications for the health of these river ecosystems. (*Water Resources Research*, https://doi.org/10.1029/2021WR031308, 2022) **—Rachel Fritts,** *Science Writer*

Levees, such as those in New Orleans, are constructed to protect riverside towns from flooding, but they can also prevent natural processes important to river health. Credit: Infrogmation of New Orleans/Wikimedia, CC BY-SA 2.0 (bit.ly/ccbysa2-0)

Side Benefits of Climate Action May Save Millions of Lives in Africa

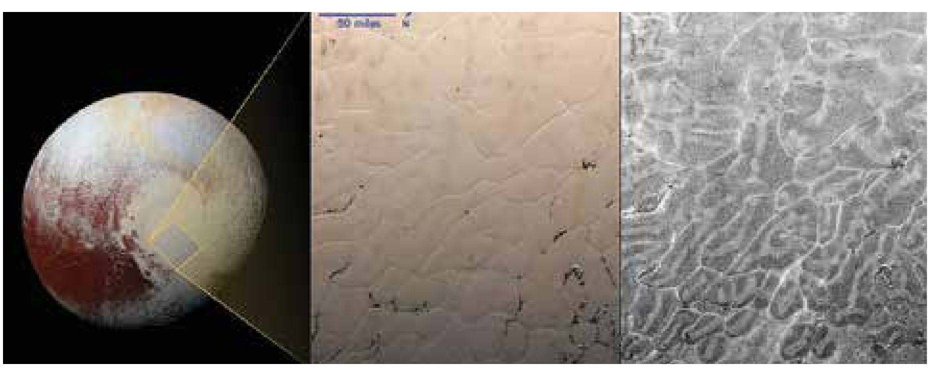
Moving from fossil fuels to clean energy sources comes with many side benefits, including a reduction in air pollution, which is responsible for premature deaths of 8–10 million people annually around the world.

In a new study, *Shindell et al.* model the impacts that cleaner air and sustainable growth would have on Africa under a scenario in which Earth warms by about 2°C by 2100. The researchers predict that levels of many pollutants in Africa, including carbonaceous aerosols, sulfur dioxide, and ammonia, would drop substantially, but the magnitudes of the drops would vary across different regions. East and West Africa, for example, would be expected to see large drops in carbonaceous aerosols, whereas northern, central, and southern Africa would see levels largely unchanged.

Despite these differences, the researchers predict that all regions of Africa will experience massive benefits if climate action results in cleaner air. By around 2050, the number of premature deaths annually could drop by around 45,000 in southern Africa and 175,000 in West Africa, with other regions of the continent experiencing intermediate declines. Cumulatively, cleaner air could prevent about 3 million premature deaths on the continent by 2050 and more than 10 million by the end of the century, according to the authors. (*GeoHealth*, https://doi.org/10.1029/2022GH000601, 2022) **—Saima Sidik,** *Science Writer*

A truck emits a cloud of pollution while driving in Cameroon. Credit: Photokadaffi/Wikimedia, CC-BY-SA-4.0 (bit.ly/ccbysa4-0)

Clues to Pluto's History Lie in Its Faults



Scientists studied the faults and cracks in Pluto's "heart" to better understand the planet's lithosphere. Credit: NASA/JHUAPL/SwRI

The world first glimpsed Pluto up close when NASA's New Horizons spacecraft whizzed by it in July 2015. One of the most exciting discoveries scientists made based on New Horizons data was that Pluto, despite orbiting at more than 5 billion kilometers from the Sun, may contain a liquid water ocean under its water ice surface.

This liquid water ocean offers intriguing clues about how Pluto formed and retained enough heat to melt all that ice. In the years since the flyby, two general formation hypotheses have emerged.

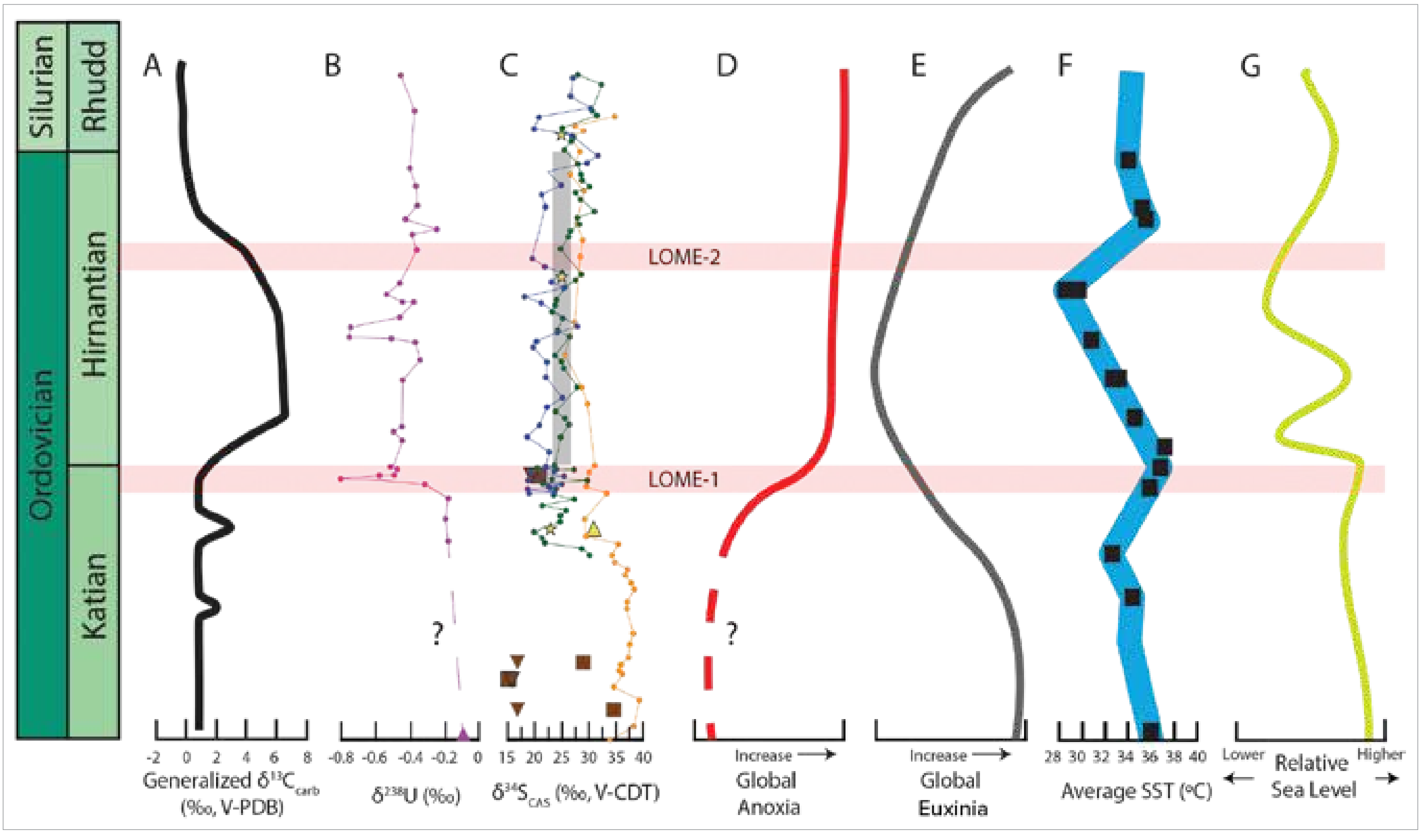
Clue's that can help scientists understand Pluto's formation include the thickness of its outer icy crust as well as the geological features that make up its surface. In a new study, *McGovern et al.* focus on Sputnik Planitia, a vast basin that makes up the western portion of Pluto's bright "heart." Sputnik Planitia formed after an impact and eventually filled with nitrogen ice. The basin measures 1,500 × 900 kilometers and features a ridge that rises 1 kilometer above the surrounding landscape. Fractures and cracks radiate from the basin like spokes on a bicycle wheel, the authors write.

These fractures and cracks are key to understanding how the nitrogen ice load affects Pluto's surface and lithosphere.

The researchers ran computer models testing various starting conditions for Sputnik Planitia to find the lithosphere thickness that best fits today's geological features. They found that the lithosphere is probably 45–70 kilometers thick and that the initial depth of the impact crater that forms Sputnik Planitia was probably shallow, no more than 3 kilometers deep.

McGovern and colleagues note that their finding is consistent with the "hot" theory of Pluto formation that posits Pluto formed via violent impacts and started out with more liquid, much of which froze over the following millennia. They also note that the stress on the outer shell is probably facilitating some cryovolcanism at several sites surrounding Sputnik Planitia. (*Journal of Geophysical Research: Planets*, https://doi.org/10.1029/2021JE006964, 2021) **—JoAnna Wendel,** *Science Writer*

What Conditions Accompanied the Late Ordovician Mass Extinction?



Trends in geochemical and climate proxies seen in carbonates in this and previous studies—including (curve A) carbon isotopic ratios (δ13C) used with biostratigraphic markers to correlate records in time, (curve B) uranium isotopic ratios (δ238U) recording nonsulfidic anoxia, and (curve C) sulfur isotopic ratios (δ34S)—indicate Late Ordovician–early Silurian conditions and their relationship to two Late Ordovician mass extinction (LOME) pulses (horizontal bars). Generalized changes in the extent of (curve D) global marine anoxia and (curve E) euxinia are inferred from these proxies. The two rightmost curves show (F) inferred average sea surface temperatures (SST) and (G) eustatic sea level over this period. Credit: Kozik et al., with data from various sources

The second most severe mass extinction in Earth's history occurred in the Late Ordovician, specifically during the Hirnantian Age about 445 million years ago. At that time, 85% of marine species were eliminated in two pulses, comprising the only major mass extinction associated with icehouse conditions. However, the exact causes of the extinction, especially the potential role of marine oxygenation, remain uncertain. *Kozik et al.* present paired iodine concentrations and sulfur isotope data from three sites hosting Late Ordovician carbonate rocks to constrain both local and global marine oxygenation surrounding the extinction. Their results indicate that during the two extinction pulses, anoxia in local shelf environments (indicated by iodine-to-calcium ratios) persisted against a backdrop of waning and then waxing global euxinia—anoxia plus sulfidic water columns—as shown by variations in sulfur isotopic ratios ($\delta^{34}S$) in the carbonates. Using geochemical models, the researchers found that the mass extinction was strongly associated with expansions of nonsulfidic anoxia on shelves combined with glacioeustatic sea level change and climatic cooling. This study provides new details about paleoredox conditions in Late Ordovician oceans and places them into the context of coincident changes in climate, eustatic sea level, and the biosphere. (https://doi.org/10.1029/2021AV000563) **—Susan Trumbore**

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PRINCETON UNIVERSITY

POSTDOCTORAL RESEARCH ASSOCIATE

The Atmospheric and Oceanic Sciences Program at Princeton University in cooperation with NOAA's Geophysical Fluid Dynamics Laboratory (GFDL) seeks **a postdoctoral or more senior research scientist** to conduct studies on the seasonal predictability of atmospheric rivers. The project aims (1) to improve our understanding of the processes that contribute to the seasonal predictability of atmospheric rivers and their associated precipitation extremes, particularly over North America, and (2) to identify pathways to improve the simulation of atmospheric river activity in state-of-the-art subseasonal-to-seasonal dynamical forecast models.

Under the supervision of Dr. Nat Johnson, the selected candidate is expected to leverage available observational and global climate model data to develop diagnostics for seasonal atmospheric river and extreme precipitation predictability. A primary outcome will be an assessment of seasonal atmospheric river activity predictability (out to 12 months) in two NOAA seasonal prediction systems, GFDL's Seamless System for Prediction and EArth System Research (SPEAR) and NCEP's Unified Forecast System (UFS). Additional outcomes include one or more peer-reviewed publications led by the candidate and the development of process-oriented diagnostics for the simulation of atmospheric river statistics in dynamical forecast models, which may include diagnosing the roles of atmospheric resolution, model biases, and small-scale ocean-atmosphere interaction and boundary layer processes in coastal regions.

The selected candidate will have a Ph.D. in atmospheric science, hydrology, or a related field. Candidates with strong backgrounds in climate variability and the analysis of large datasets and with strong written and oral communication skills are preferred. Initial appointment is for one year with the possibility of renewal subject to satisfactory performance and available funding. This position is subject to the University's background check policy.

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Review of applications will begin **September 20, 2022**, but applications received after that date may still be considered.

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Dear AGU:

On 10 June 2022, after the spring melt, our research team paddled to the middle of Laguna de la Caldera, a glacial crater lake 3,050 meters above mean sea level in the Sierra Nevada in southern Spain. (Guille Garrido-Cañete is seen here keeping us on our way.) Our task was to redeploy a submersible sonde measuring water quality that had overwintered under the ice. We knew from the water clarity (turbidity measurements from light transmission) data we'd collected, that the lake had been crystal clear during winter.

That day, however, we felt like we were rowing in a cauldron of chocolate! In mid-March, a massive Saharan dust fall had occurred over the Sierra Nevada (see bit.ly/postcard-Saharan-dust-plume).

Intense episodic as well as constant low-level Saharan dust transport contributes to the short- and long-term Mediterranean ecosystem productivity by replenishing nutrients such as iron and phosphorus. Just as mountains intercept rain clouds from moving air masses, they disproportionately intercept dust relative to flatlands. Dust lowers the albedo of snow and lakes, adding to the warming effect on mountain ecosystems. Indeed, we have observed strong decadal trends of increasing warming in the region based on time series measurements from the Sierra Nevada Global Change observatory (https://obsnev.es/).

The redeployed sonde will now track changes in turbidity and productivity through chlorophyll measurements during the growing season to assess the effect of Saharan dust deposition on high-mountain lake ecology.

—**Mani Villar-Argaiz, Guille Garrido-Cañete,** and **Bopi Biddanda,** Instituto del Agua, Universidad de Granada, Andalucía, Spain; also at Robert B. Annis Water Resources Institute, Grand Valley State University, Muskegon, Mich.

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