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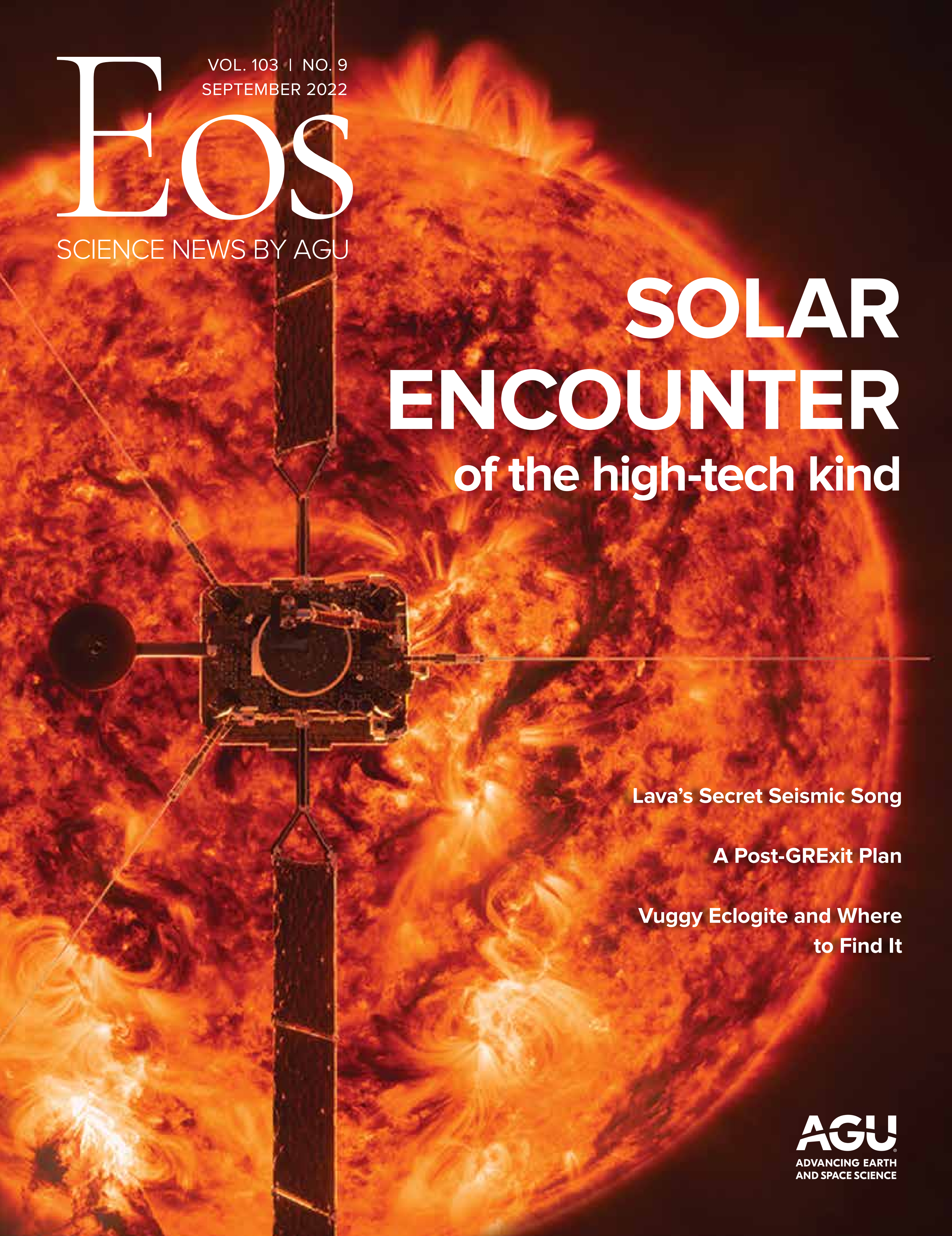

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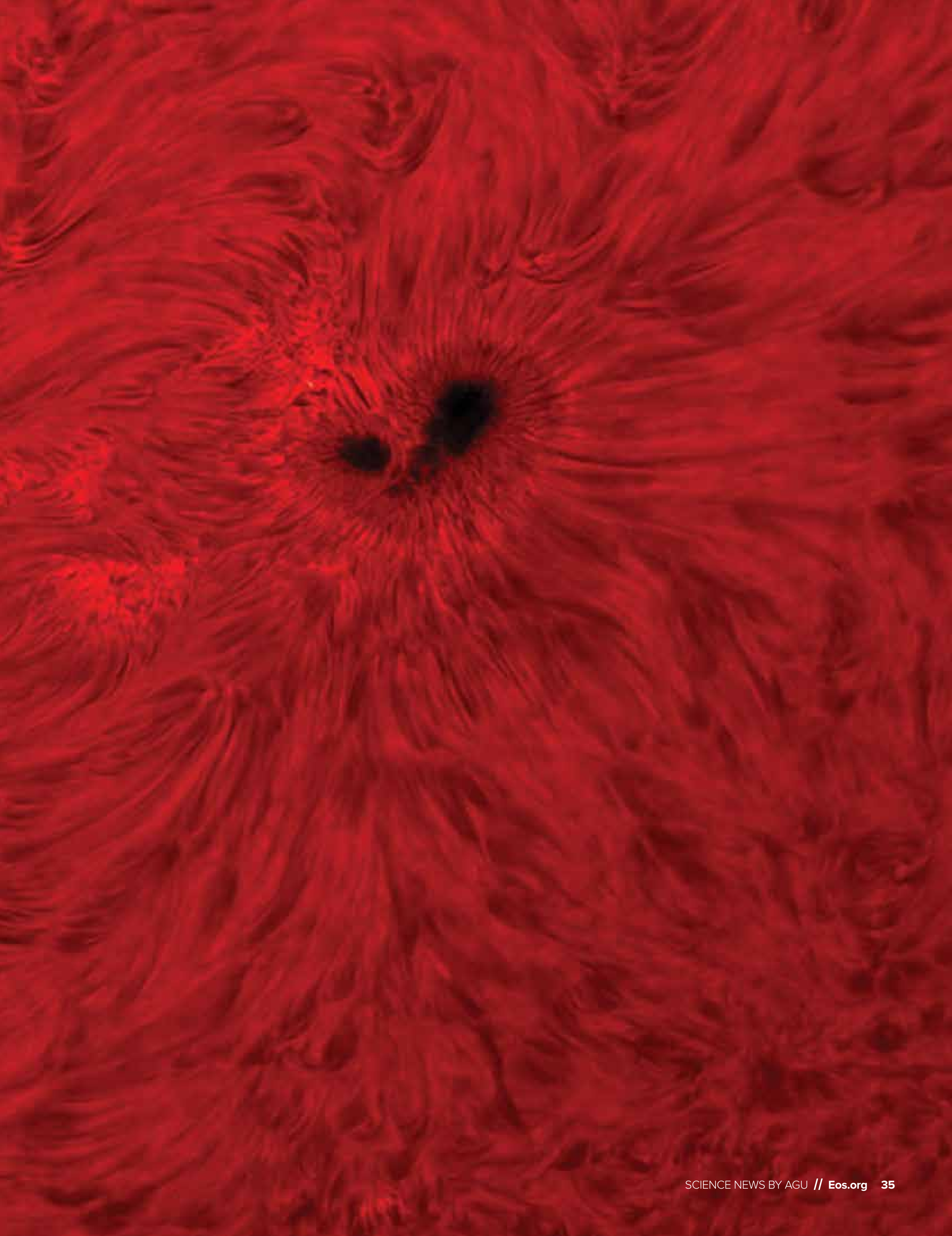
11 DISCOVERIES AWAITING US AT SOLAR MAX

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

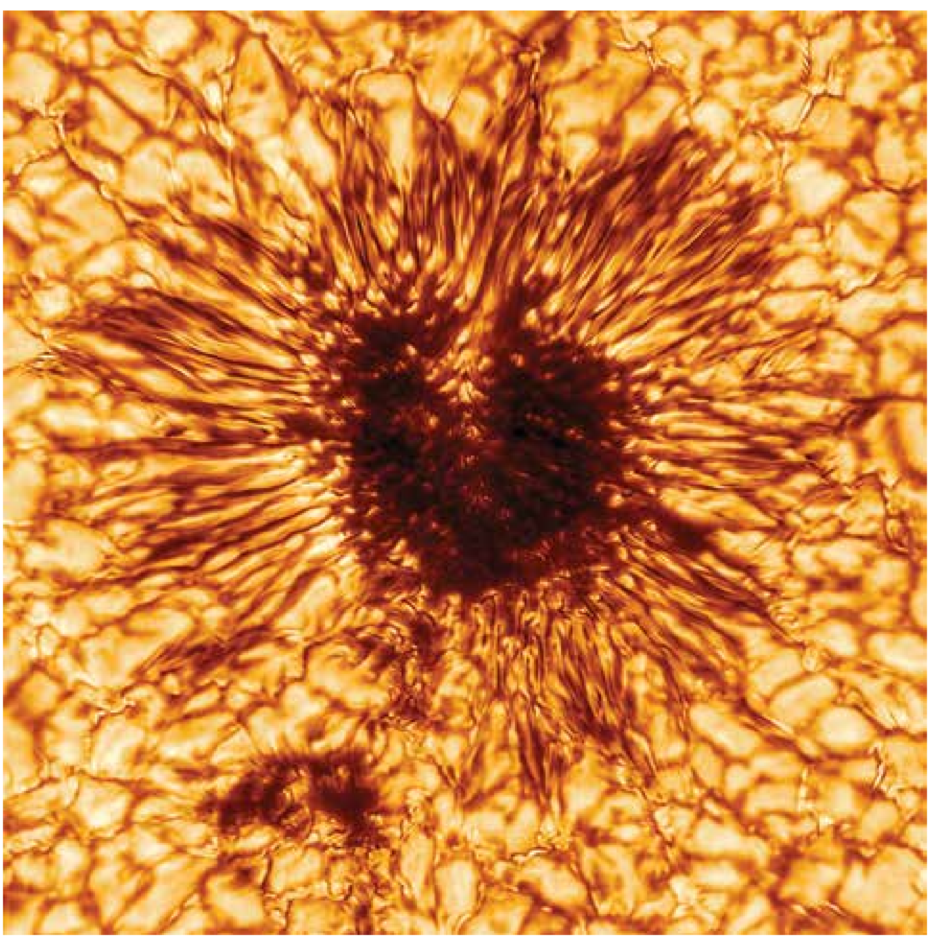


We are in the middle of a solar cycle, and we've been here before. That's not to say a solar cycle is exactly the same every time—some cycles are far more active than others, and sometimes the Sun skips a cycle completely. But the overall pattern remains the same and repeats every 11 years, even if the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

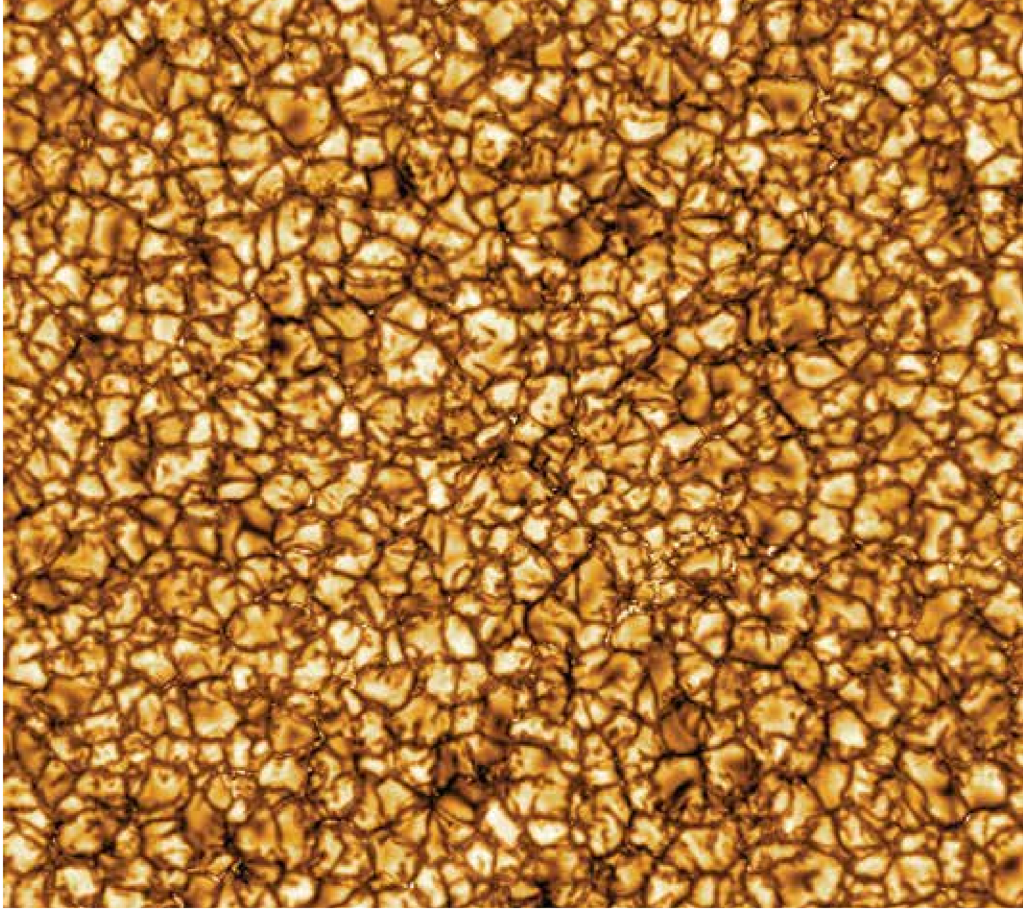
Unlike the 400-year history of sunspot monitoring, this will be only the third solar maximum for which we have continuous helioseismic coverage, said Sarbani Basu, an astronomer at Yale University in New Haven, Conn. The study of helioseismology looks at the propagation of pressure waves as they travel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



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)

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."

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.

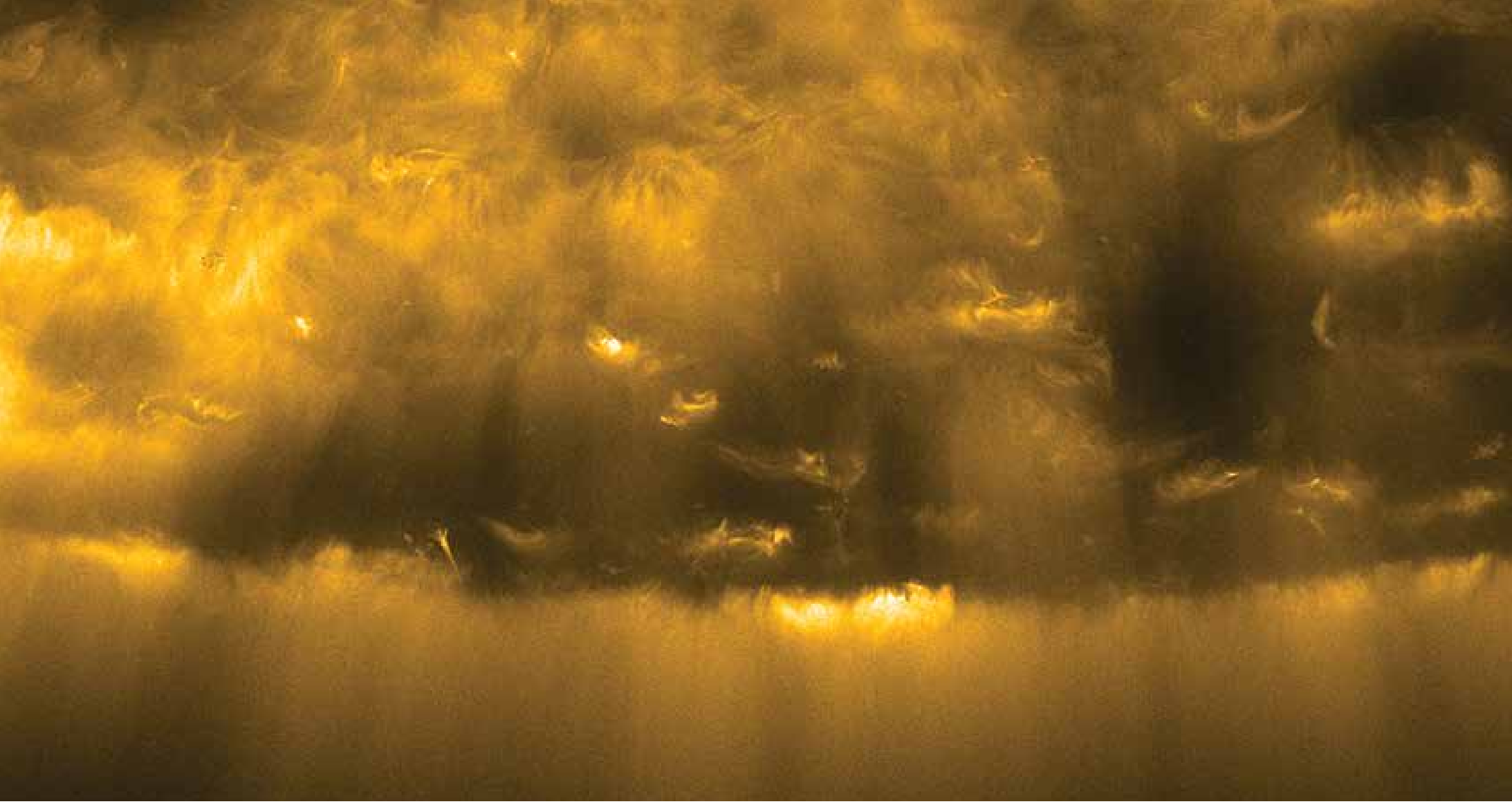
"Solar Orbiter is still at an early stage but will provide first direct views of the solar poles," Jain said. "As we have learnt from the polar observations of other planets, we may discover something unusual at the solar poles which has not been observed yet."

"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.

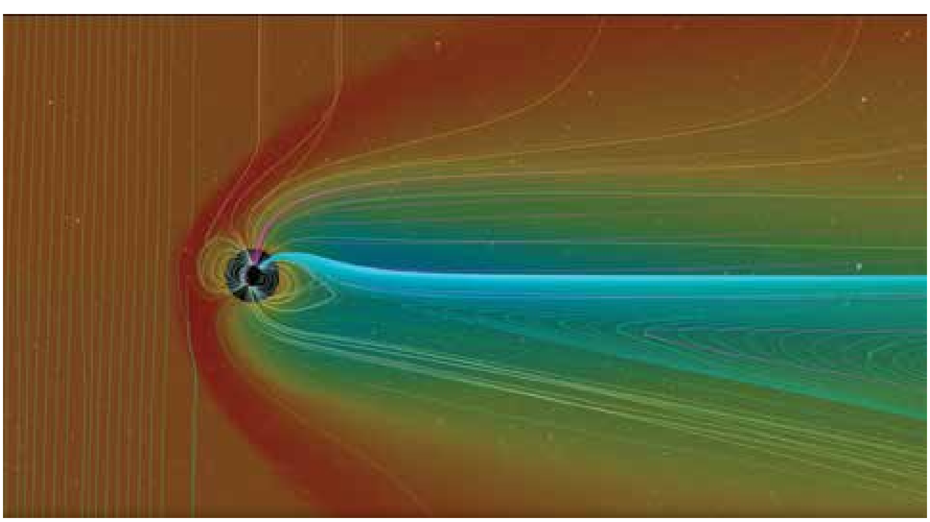
In her work, Bobra seeks to predict space weather "by analyzing millions of images of the Sun with machine learning algorithms. And I'm excited to continue doing that!" she said. She's interested in collecting space weather observations that span a solar cycle or more to help train those algorithms. "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.

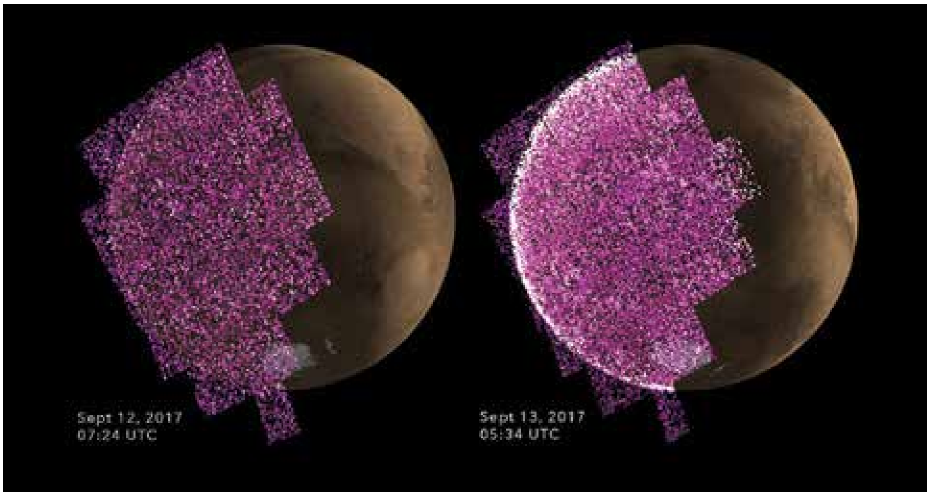
"But even with all of the physics-based model developments over the last decade," Luhmann said, "we are still not making routine 'Sun-to-mud' space weather models—either in retrospective or forecast mode—of even more moderate events," let alone the extreme events that will be more common during solar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

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