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STARBIRTH
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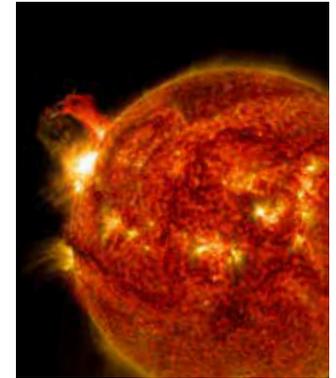


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Artwork: Infinite Wonders by Greg Mort



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ON THE COVER

The center of the solar system, the Sun provides the energy that makes life on our planet possible.

NASA/SDO



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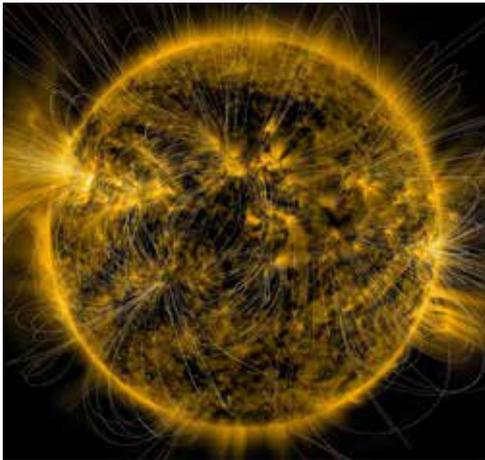


Ask Astro Archives

Answers to all your cosmic questions.

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Getting to know our star



The Sun powers the solar system. Research on our most important star is growing in leaps and bounds. NASA/SDO/AIA/LMSAL



As someone who has just moved to Arizona during the summertime, I'm getting to know the Sun pretty well these days. Although storms bubble up during this so-called monsoon season, the usual day is starkly blue with a blazing star in the sky. Sunscreen has reemerged as a primary household item.

In our hectic lives, many of us too easily forget that we live in a solar system of planets that orbit our star, and that our very existence is due to this nuclear reactor in the sky, a mere 93 million miles away. Our main-sequence star fuses 620 million tons of hydrogen in its core

every second, releasing 400 trillion trillion watts of energy as heat and light with every tick of the clock. That's an enormous amount of power, and makes life on Earth possible.

This month, physicist Sten Odenwald takes us on a behind-the-scenes tour of the Sun and what we know about the most important (well, from our point of view, at least) star in the cosmos. The energy transformation of hydrogen into the heavier elements that characterize stars is fascinating, and the observational aspects of the Sun give us astronomers something to do during the daytime. (But always be exceptionally careful and use proper solar filters to observe our star!)

This month's tour also extends into Earth's atmosphere with our featured story by Contributing Editor Ray Shubinski, who explores how to view rainbows and moonbows. Sunlight and its properties give us much to observe atmospherically, and these phenomena can be fascinating.

And there's more. I deliver a report on the amazing Starmus Festival that occurred last spring in Bratislava, Slovakia, a celebration of astronomy and all the sciences, coupled with music. I hope you'll join me at a future Starmus — perhaps it will allow you to see the world, and maybe even the Sun, in a slightly different way.

Yours truly,

David J. Eicher
Editor



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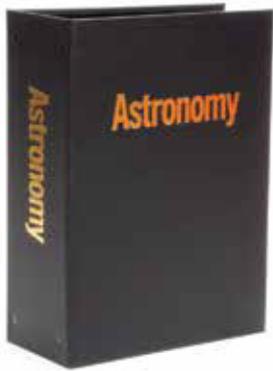


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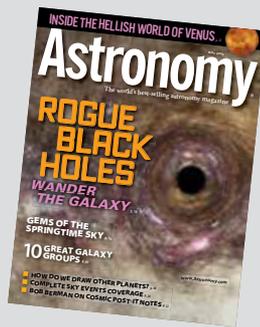
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Los Angeles skyglow is seen from 200 miles (322 km) away atop Mount Whitney in California. NPS/BEN BANET

→ We welcome your comments via email to letters@astronomy.com. Please include your name, city, state, and country. Letters may be edited for space and clarity.

Lighting everywhere

Regarding “Fighting the light” (July 2024), about 10 years ago my wife and I were on a cruise that went up the Amazon River to Manaus, Brazil. I was very surprised to see from the river many light domes. With over 2 million residents, I would not have been surprised at a light dome over Manaus, but the many other domes were unexpected.

— **Bill Murrell**, Oklahoma City, OK

What’s in a name?

While I can appreciate Christopher Cokinos’ article “Fighting the light” tackling the problem of fighting light pollution, I was a bit dismayed to see my first name in large capital letters being used to convey something which is the bane of all astronomers, both amateur and professional. I always thought of my first name as being a rather friendly, not fiendish, name. And one must consider that there are other astronomy/space-related individuals named Alan, such as Alan Shepard, Alan Bean, Alan Guth, Alan Dyer, Alan MacRobert, as

well as Alan Stern! May I suggest instead ELAN, for Excessive Lighting At Night? Or perhaps something more sinister, like DArksky Reduction Through High Illumination: DARTHI. Other suggestions are welcome, of course, but if we are to effectively engage the general public, in my opinion, the more sinister the acronym, the better. — **Alan Pasicznyk**, Doylestown, PA

Lunar nicknames

I enjoyed Robert Reeves’ article “Postcards from the Moon” (July 2024). As a Boy Scout volunteer, I would help scouts earn their astronomy merit badge. Viewing the planets through the telescope was always a hit. The stars were more of a challenge; I would use asterisms (Beehive, Coathanger, etc.) to keep them interested. The Moon would initially get “oohs” and “ahs,” but would quickly go to “seen one crater, seen them all.” Reeves’ nicknames for lunar features would certainly help keep them interested. Having them make up their own nicknames for features would also keep them engaged. So thanks for helping readers see the Moon from a fresh perspective.

— **Kelly Havey**, Redding, CA

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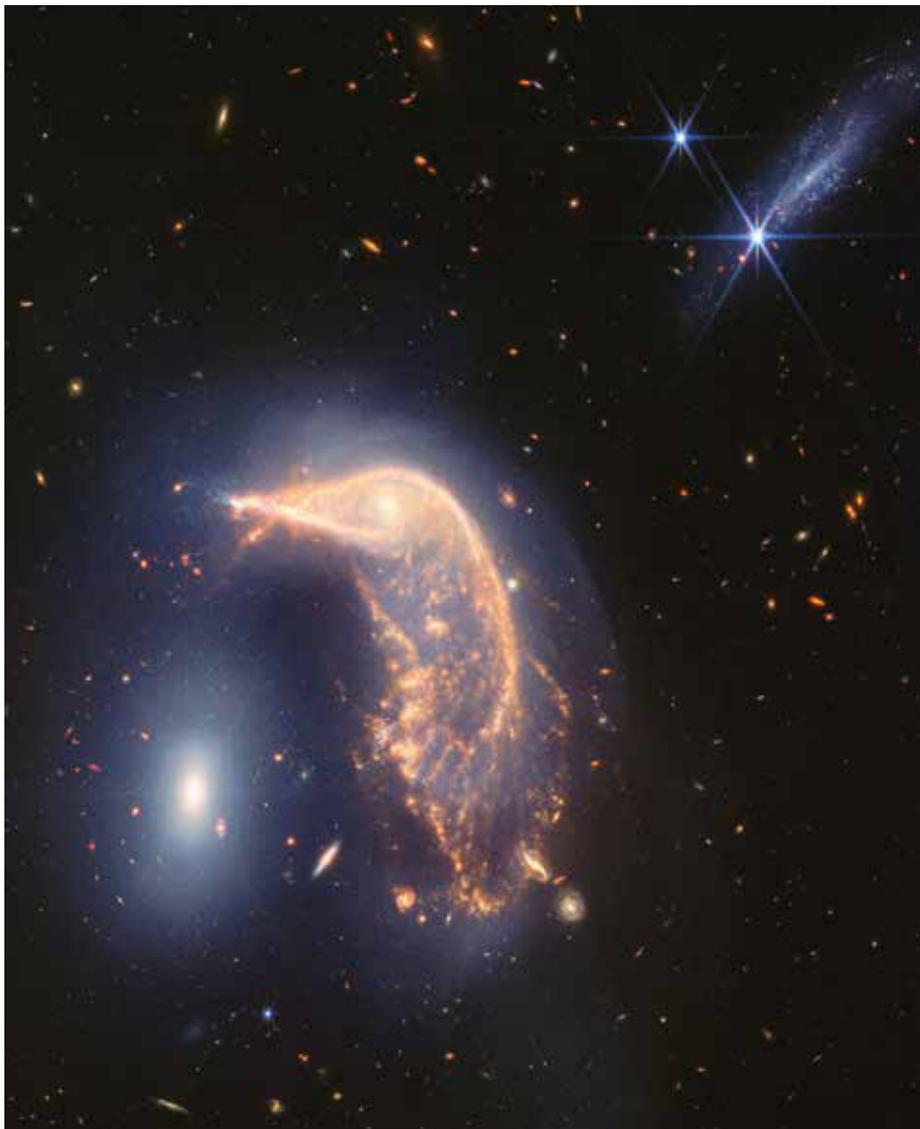
SNAPSHOT

JWST IMAGES A PENGUIN AND EGG

The shot celebrates two years of science with the space telescope.

Time flies when you're having fun — and making cosmic discoveries. On the two-year anniversary of the start of its science operations, the James Webb Space Telescope (JWST) revealed this infrared portrait of Arp 142, a pair of interacting galaxies also known as the Penguin (NGC 2936, at center) and the Egg (NGC 2937, at left). The shot combines near- and mid-infrared views from NIRCam and MIRI, respectively.

The galaxies are currently just 100,000 light-years apart. Astronomers estimate the pair made an initial close pass some 25 million to 75 million years ago and will undergo several more before merging into a single galaxy. The interaction has distorted the Penguin — initially a spiral galaxy — into the shape we see today. Its bright nucleus forms the bird's eye and head, while the galaxy's arms — filled with waves of bright star formation — form its feathered body. By contrast, the compact, elliptical Egg doesn't contain much gas and dust, so it has largely retained its shape. Both are surrounded by a soft blue glow given off by stars scattered from their homes by the merger. — ALISON KLESMAN

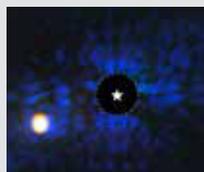


HOT BYTES



DUCK AND COVER

Astronauts aboard the International Space Station briefly sought shelter in return vehicles on June 26 when a defunct Russian satellite broke up, creating more than 100 pieces of trackable space debris.



SIBLING SWAP

JWST directly imaged the cold, massive exoplanet Epsilon (ϵ) Ind Ab while searching for a different planet around its star. The planet's mass and orbit eliminate the possibility another large world is waiting to be found.

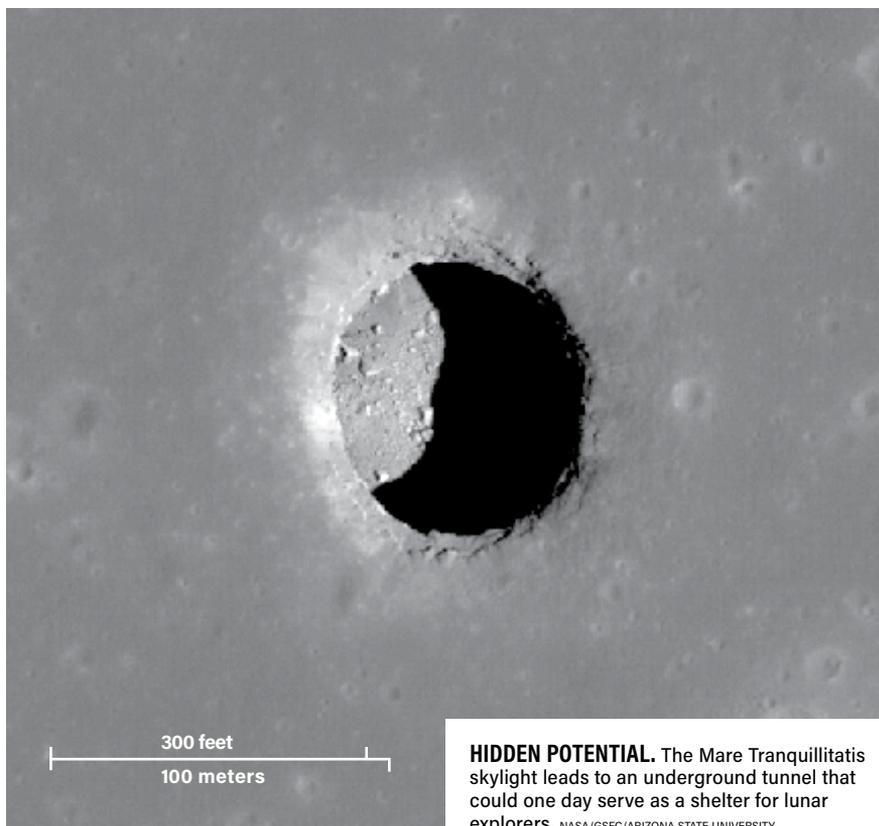


OPEN QUESTION

NASA's Curiosity rover recently drove over and broke open a rock in its path, revealing pure elemental sulfur crystals — a first-of-its-kind find on the Red Planet. Scientists aren't sure yet how they formed.

LUNAR LAVA TUBE COULD SHELTER A FUTURE MOON BASE

A volcanic eruption formed an underground tunnel on the Moon, uncovered by a recent analysis of radar data.



HIDDEN POTENTIAL. The Mare Tranquillitatis skylight leads to an underground tunnel that could one day serve as a shelter for lunar explorers. NASA/GSFC/ARIZONA STATE UNIVERSITY

» The Moon's surface presents an unforgivingly harsh environment. Without an atmosphere or magnetic field, it is vulnerable to deadly coronal mass ejections from the Sun, levels of hazardous radiation 150 times greater than on Earth, and a perpetual rain of impacting meteorites. Its temperature ranges from 260 degrees Fahrenheit (127 degrees Celsius) in the daytime to -280 F (-173 C) during lunar night.

For all these reasons, prospective lunar explorers are increasingly considering an alternative to living on the Moon's surface: living beneath it, in subsurface caves. Over the past

15 years, satellite images have revealed hundreds of large pits lined with ledges that appear to overhang their floors. Researchers have hoped these could be openings to more cavernous underground spaces, like lava tubes — subsurface channels through which molten lava once flowed — left over from volcanic eruptions billions of years ago. But evidence has been lacking.

A new analysis of radar observations, published July 15 in *Nature*, indicates that at least one such pit, located in Mare Tranquillitatis (Sea of Tranquillity), leads to an underground tunnel that extends for tens of meters — and possibly much longer.

A NEW TRANQUILLITY BASE?

Scientists first recognized lunar pits 15 years ago in images from Japan's Kaguya and NASA's Lunar Reconnaissance Orbiter (LRO). Since then, more than 200 skylightlike pits ranging from 16 to 1,000 feet wide (5 to 300 meters) have been found with the additional help of India's Chandrayaan and China's Chang'e orbiters. Around a dozen pits have shown promise of leading to underground chambers.

A 2017 study of one example in the Marius Hills, a former volcanic hot spot on Oceanus Procellarum, combined Kaguya radar data with gravity data taken by NASA's Gravity Recovery and Interior Laboratory (GRAIL) mission. It revealed that areas around the Marius Hills pit with a deficit of gravity also tended to have a distinct double radar echo — a strong indication of subsurface voids, with a cave floor producing a second echo bounce.

The skylight discussed in the new work was discovered in LRO imagery in 2011. It spans 210 feet (65 m) and features a boulder-strewn floor 120 feet (36 m) below the surface.

The study analyzes the radio signal reflected from Mare Tranquillitatis using LRO's Miniature Radio Frequency instrument in 2010. The radio return signal is consistent with an initial bounce off the Moon's surface and a second bounce from the floor of a subsurface chamber.

3D modeling of the radar signal, accounting for the viewing angle of the satellite, indicates that an underground conduit extends west of the pit and the collapsed rock pile at its center. Further observations could determine whether the conduit continues in the opposite direction, to the east, the team says.



BLOWING UP THE MARKET. Future habitats placed in the shelter of lunar lava tubes could be based on the inflatable BEAM module currently being tested on the International Space Station. NASA

This result is “the first direct evidence of an accessible lava tube under the surface of the Moon,” Lorenzo Bruzzone, a remote-sensing expert at the University of Trento and study co-author, said in a press release. It “suggests that the [Mare Tranquillitatis pit] is a promising site for a lunar base, as it offers shelter from the harsh surface environment and could support long-term human exploration of the Moon,” the authors write.

HOW TO SETTLE A MOON CAVE

In the near term, NASA’s plans for the Artemis program call for landing and establishing a base near the lunar south pole, where astronauts can access water ice within permanently shadowed craters. But underground caves and lava tubes are a natural next step for a permanent, sheltered lunar base.

If a stable, suitable lava tube can be identified, a habitat solution may already be at hand. An inflatable module dubbed the Bigelow Expandable Activity Module (BEAM) has been attached to the International Space Station since 2016 for long-term testing. Instead of sealing off and pressurizing the entire lava tube, it may be more practical to deploy a similar inflatable habitat within the lava tube’s shelter. Additional data returned by LRO’s Diviner Lunar Radiometer Experiment show the temperature within the Tranquillitatis skylight is a benign 63 F (17 C), which would simplify the design of an inflatable habitat.

It would be ironic if, after 30 millennia of evolution, humankind were to revert off-world to being cave-dwellers once again — but lunar lava tubes show real promise to shelter future astronauts.

— ROBERT REEVES

Vera C. Rubin Observatory’s secondary mirror now in place

On July 24, 2024, the 3.4-meter secondary mirror of the Vera C. Rubin Observatory’s Simonyi Survey Telescope in Chile was installed — the first permanent piece of the telescope’s optical system to be put in place. The secondary had been shipped to Chile in 2018 from Rochester, New York, and stored there while the telescope’s mount was completed over the last few years. To install the mirror, a team used a cart to rotate it vertically and then lifted it onto the mount, taking care to not stress the glass.

Following the telescope’s primary mirror installation, slated for August, will come the integration of the Legacy Survey of Space and Time (LSST) camera. Once the system is complete, the decade-long LSST is set to start in 2025.

— ELIZABETH GAMILLO



RUBIN OBSERVATORY/NSF/AURA/E. MUNOZ ARANCIBIA



MARTIAN MOSS

The desert moss *Syntrichia caninervis* — found in the Mojave Desert, Antarctica, and elsewhere — is so hardy it could help terraform Mars, a Chinese team has found. Tests show the plant can survive extreme desiccation, gamma radiation, and five years at a temperature of -112 F (-80 C).

SPACEPLANE MASTER

X-15 pilot and astronaut Joe Engle died July 10 at 91. Due to fly on Apollo 17, he was passed over by NASA in favor of geologist Harrison Schmitt. He later commanded two space shuttle missions, becoming the only person to fly both the X-15 and the shuttle to space.

LOOKING UP

On June 19, Kosovo opened its first national observatory and planetarium, an effort spearheaded by Pranvera Hyseni, a Kosovo native and a Ph.D. candidate at the University of California, Santa Cruz. The primary telescope is a C14 donated by Celestron.

LUNAR ARK

Scientists have proposed building a repository on the Moon to safely store genetic samples of most of Earth’s species. Crater floors near the poles that lie permanently in shadow are cold enough to serve as natural cryogenic freezers, says a July 31 paper in *BioScience*.

FIRST FLIGHT

Europe’s new heavy-lift Ariane 6 rocket made its first demonstration flight July 9, launching to low Earth orbit from French Guiana. The launch system replaces the Ariane 5, which was retired in 2017.

CLOUDY ORIGINS

Our solar system may have passed through a dense molecular cloud 2 million to 3 million years ago, shrinking the Sun’s magnetic field and leaving Earth exposed to the cloud, a *Nature Astronomy* study suggests. This could have resulted in climate change that led to the rise of humans. — MARK ZASTROW

Dwarf galaxies' black holes behave differently

» All massive galaxies like the Milky Way host supermassive black holes (SMBHs) millions to billions of times the mass of the Sun in their centers. But astronomers aren't yet sure whether all dwarf galaxies are similarly structured, with massive black holes (MBHs) thousands to millions of solar masses.

Though faint and difficult to study, dwarf galaxies offer clues about the early universe. Modern-day dwarfs help astronomers better understand what early galaxies and black holes looked like, and how they evolved.

While at the Max Planck Institute for Extraterrestrial Physics in Germany, Riccardo Arcodia (now at MIT) set out to study whether MBHs accrete matter in the same way as their supermassive counterparts.

When a black hole pulls in material, it forms an accretion disk that emits a range of radiation. X-rays emanate from the black hole's immediate vicinity,

while regions farther out give off infrared and visible light, which varies in brightness over time. Arcodia and his team identified dwarf galaxies whose centers showed infrared and optical signs of MBHs. They then looked for these galaxies in the eROSITA X-ray all-sky survey.

What they found was surprising: Of more than 200 galaxies with visible or infrared indicators of an MBH, only 17 were emitting X-rays. But accreting black holes *should* give off X-rays, and the survey should have been able to pick them up. "We could have detected an X-ray MBH if it were there ... but we didn't," Arcodia said at the 244th meeting of the American Astronomical Society in Madison, Wisconsin. So, most of these low-mass galaxies contain *underluminous* black holes that are not feeding as expected.

Arcodia pointed to many reasons this might be. Unlike larger galaxies, he said, dwarf galaxies are clumpy, with stars and gas distributed unevenly — thus not as readily available to a black hole as in a massive galaxy, where material is concentrated in the center. Additionally, MBHs in dwarf galaxies tend to be offset from the center, also affecting the amount of nearby available food. And there is evidence that lower-mass galaxies experience shorter, more transient accretion — such as the black hole interacting with or swallowing a single star — unlike longer-lived accretion in larger galaxies, again with more material available to a black hole.

Ultimately, he said, "dwarf galaxies and low-mass galaxies are way more complicated than massive ones." — A.K.



LOCATION, LOCATION. The conditions in dwarf galaxies such as NGC 5264 are different enough that it may affect how their central black holes eat, when compared with the supermassive black holes in more massive galaxies. ESA/HUBBLE & NASA

A DISTANT BLACK HOLE AWAKENS



LET THERE BE LIGHT. A disk of gas and dust forms around the massive black hole at the center of the galaxy SDSS1335+0728 in this artist's impression. ESA/M. KORNMESSEUR

A seemingly ordinary galaxy has put on an extraordinary spectacle. About 300 million light-years away, the supermassive black hole in the galaxy SDSS1335+0728 suddenly came to life. A June 18 paper in *Astronomy and Astrophysics* offers key insights as to how it roared awake.

An average-sized galaxy contains a supermassive black hole of about 10 million solar masses. The black hole can sometimes suddenly brighten when a star approaches too closely and the black hole tears it apart and swallows it. This process, known as a tidal disruption event (TDE), creates an accretion disk around the black hole that normally requires weeks or months to dim and die out. But SDSS1335+0728's black hole is different: It has persisted for more than four years — and has only grown brighter.

If the present observation represented a TDE, "this would be the longest tidal disruption event ever seen," says co-author Lorena Hernandez-Garcia, a postdoctoral researcher at the Institute of Physics and Astronomy at Valparaiso University. Instead, she proposes it could represent a different process, albeit one astronomers don't understand yet. Supermassive black holes are known to go dormant and later reactivate, but exactly what triggers these changes remains unclear.

Thanks to the duration of this particular event, it has been observed in multiple wavelengths, including optical, ultraviolet, and X-rays. The latter is ideal for monitoring energetic events. After just after four years, changes have already been seen in the X-ray part of the spectrum; their cause is a tantalizing mystery. Radio observations are now under analysis, says Hernandez-Garcia. "So, we will have more interesting news soon!" — JOHN WENZ

MARS ROCK COULD HAVE SIGNS OF LIFE

NASA'S PERSEVERANCE ROVER, which has operated on Mars since February 2021, has found a large rock containing organic compounds that may have been formed by microscopic life in the distant past.

The evidence is far from definitive, so scientists are not ready to proclaim that life once existed on the Red Planet. But the rock, named Cheyava Falls, "is the most puzzling, complex, and potentially important rock yet investigated by Perseverance," said Ken Farley, Perseverance project scientist at Caltech in Pasadena, in a press release.

Perseverance encountered the rock, which measures 3.2 feet by 2 feet (1 meter by 0.6 meter), at the northern edge of Neretva Vallis, an ancient river valley that emptied into Jezero Crater billions of years ago.

The inside of Cheyava Falls features large white calcium sulfate veins. Perseverance also found dozens of tiny off-white splotches, each ringed in black, reminiscent of leopard spots. The rover's onboard X-ray fluorescence spectrometer found that the black material contains iron and phosphate.

"These spots are a big surprise," said David Flannery, an astrobiologist and member of the Perseverance science team from the Queensland University of Technology in Australia. "On Earth, these types of features in rocks are



SPOTTY VISION. Perseverance found potential evidence for microscopic life in Mars' distant past within this rock, named Cheyava Falls. NASA/JPL-CALTECH/MSSS

often associated with the fossilized record of microbes living in the subsurface."

The Perseverance science team thinks Cheyava Falls may have been mud, with organic compounds mixed in, that eventually turned into rock. Later, fluid penetrated the rock, creating the calcium sulfate veins seen today and resulting in the spots.

Further investigation will require samples to be returned to Earth, Farley said. The rover took a core sample from the rock July 21, which could one day be retrieved by the joint NASA/ESA Mars Sample Return mission. However, that mission's development is currently stalled as NASA seeks commercial partners to do it more cheaply. —MICHAEL E. BAKICH

Titan's seas have tiny waves, tidal currents

Planetary scientists studying data from the Cassini spacecraft have uncovered new clues to three hydrocarbon oceans on Saturn's largest moon, Titan.

The research, published July 16 in *Nature Communications*, used data taken between March 2006 and November 2016, at times when the spacecraft was farthest from Saturn. They show not only evidence for tidal activity in Titan's oceans, but hints that their compositions differ as well.

The team used data from Cassini's Radio Science Subsystem to create a bistatic radar system, where the receiver and the transmitter are far apart. In this case, the receiver was NASA's Deep Space Network on Earth, some 930 million miles (1.5 billion kilometers) away. This configuration gives richer data than conventional radar, but it is not easy to set up. Nonetheless, the experiment worked.

Titan is too cold to sustain surface liquid water; instead, it hosts bodies

of liquid ethane and methane. And the results showed that, at least on the surface, Titan's three largest oceans have different proportions of methane and ethane, depending on their latitude.

"We also have indications that the rivers feeding the seas are pure methane until they flow into the open liquid seas, which are more ethane-rich," said lead author Valerio Poggiali of Cornell University in a press release. "It's like on Earth, when fresh-water rivers flow into and mix with the salty water of the oceans."

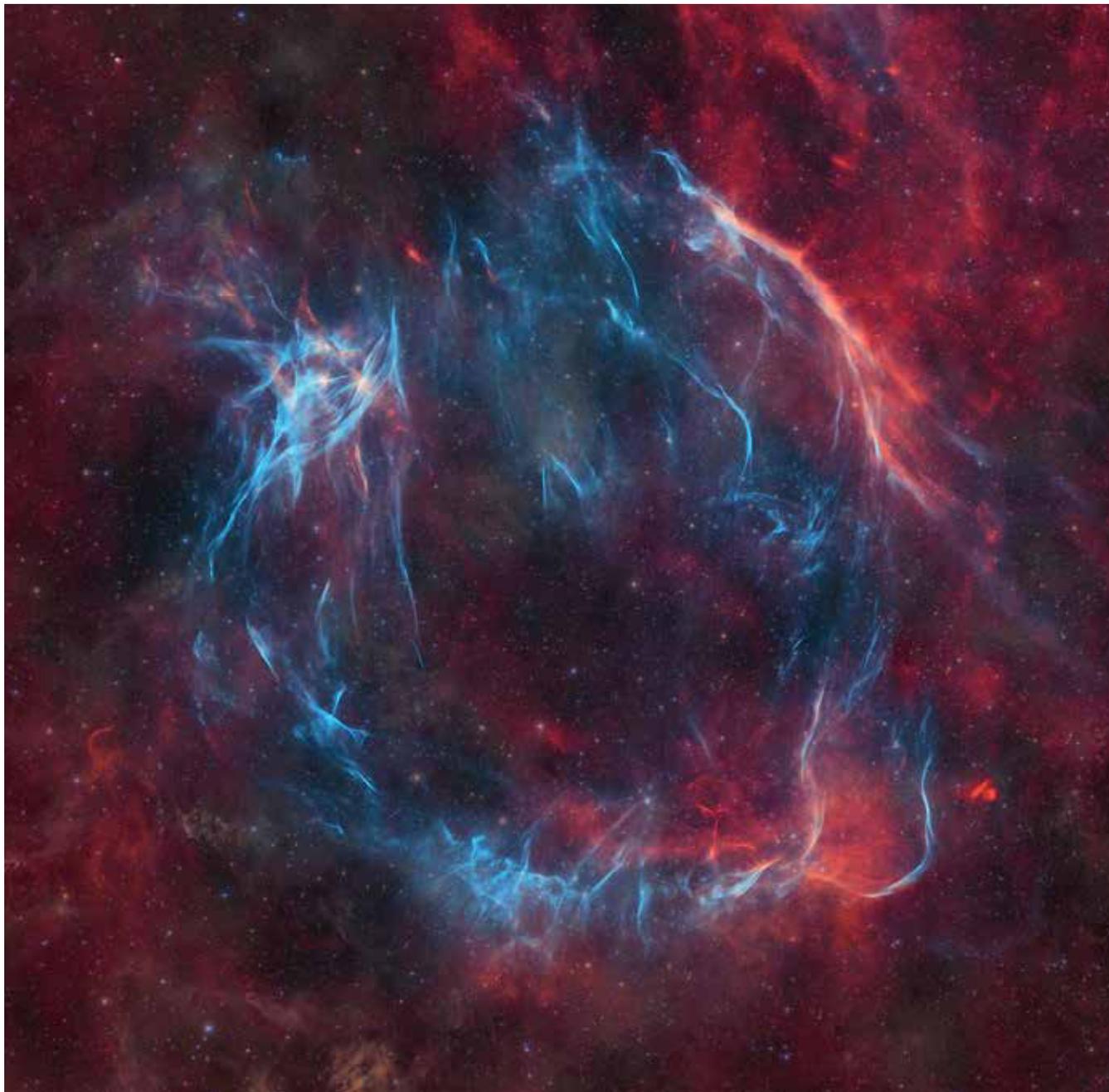
The team was also able to determine that the seas had surface waves only 0.1 inch (3 millimeters) high. Larger waves appeared where rivers meet the

oceans, though there the waves reached only about 0.2 inch (0.5 centimeter) high. Though small, the changes in wave height could point to tidal currents near these areas.

The study offers a wealth of data for future missions, as NASA has funded studies to explore the use of a submersible to study Titan's seas. Understanding conditions there will pave the way toward designing such a mission. —J.W.

QUIET SEA. Sunlight glints off Titan's largest sea, Kraken Mare, in a near-infrared composite from the Cassini spacecraft. Kraken Mare was one of three polar seas researchers studied to examine composition and wave activity. NASA/JPL-CALTECH/UNIVERSITY OF ARIZONA/UNIVERSITY OF IDAHO





FESSEN ET AL. [HTTPS://DOI.ORG/10.3847/1538-4365/AD41DA](https://doi.org/10.3847/1538-4365/AD41DA) (CC BY 4.0)

AMATEURS NAB DEEP-SKY NEBULOUS NYMPHS

In just the past couple of years, wide-field astrophotographers with narrowband filters have revealed nebulae so faint that they have gone undetected by professional observatories for decades. One recent example is a supernova remnant in Cassiopeia dubbed the Nereides Nebula, after the sea nymphs of Greek mythology. This enormous emission shell measures 2.4° by 2.7° — an area six times larger than the Full Moon, and similar in apparent size to the Veil Nebula in Cygnus. The fine blue filaments are ionized oxygen, while the red clouds are glowing hydrogen gas. This image represents almost 260 hours of exposure taken across three continents by a team of four astrophotographers: Bray Falls, Yann Sainty, Nicolas Martino, and Richard Galli. The data were processed by Marcel Drechsler. The Nereides Nebula is one of three new supernova remnants reported June 4 in *The Astrophysical Journal Supplement* in a paper led by astronomer Robert Fesen of Dartmouth College. — M.Z.

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BRINGING THE SUN TO LIGHT

The closest star to Earth is also the best studied, but only recently have we truly begun to uncover its secrets. **BY STEN ODENWALD**

FOR THOUSANDS OF YEARS, humans have worshipped the Sun. Our ancestors built monuments and temples to it, and used it to mark the annual cycle of seasons. For ancient Egyptians, their most important god, Re, was the personification of the Sun itself.

Today, we are no less in thrall to the wonders and mysteries of our nearest star. We've made strides in understanding its major systems and answered many questions about how it produces energy. But the Sun is far from an open book, concealing countless conundrums: its hidden deep core, its roiling layers of gas, its ethereal outer atmosphere, its writhing magnetic field. Solar physicists still cannot fully explain phenomena like the eruption of solar storms or how the corona reaches temperatures of millions of degrees.

Understanding these mysteries is not just an academic matter. In truth, we are just as dependent on the Sun as the ancients were — and in some ways, our modern civilization is even more vulnerable to its heated wrath.

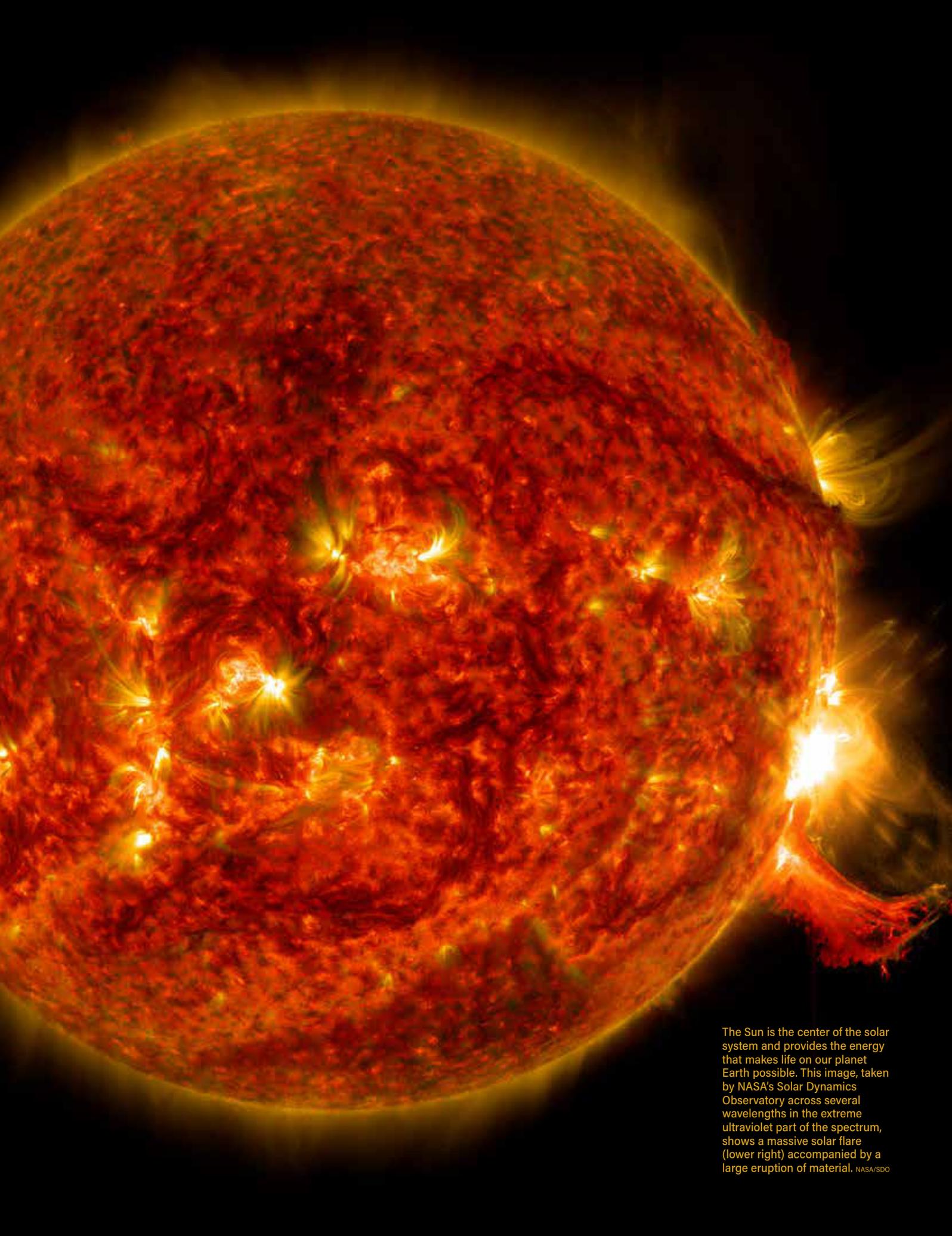
The core of the matter

For millennia, our studies of the Sun were limited to what could be gleaned from observations of its exterior. The earliest records of sunspots are found in China around 700 B.C.E. In the 17th century C.E., telescopic observations of sunspots revealed that the Sun's poles rotate slower than its equator, a phenomenon called differential rotation. By the 19th century, observers had also deduced a cycle in the appearance of sunspots and noted that their appearance was correlated with

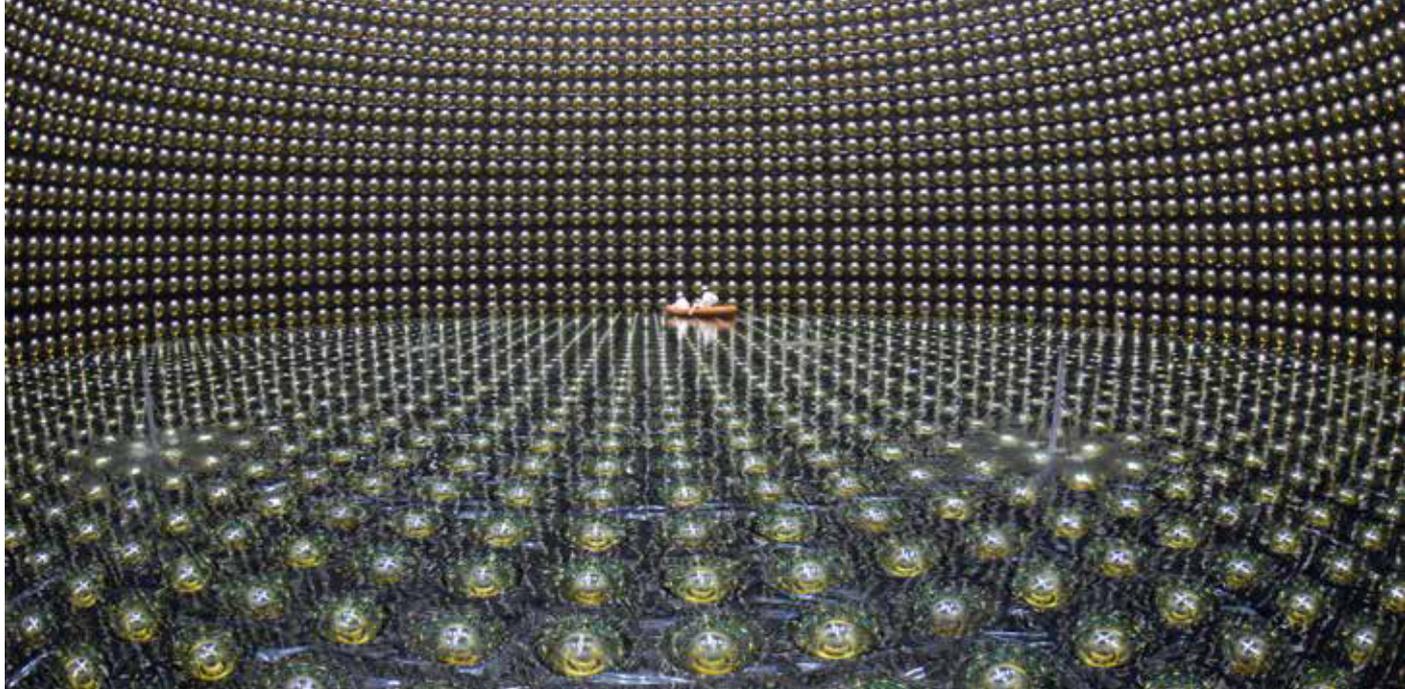
geomagnetic storms on Earth and displays of the aurora.

By the early 20th century, researchers understood that the source of the Sun's energy had to be something truly remarkable. Advances in geology told them that the lifespan of Earth — and therefore the Sun — was measured in billions of years. But all known chemical and gravitational sources of energy were too short-lived.

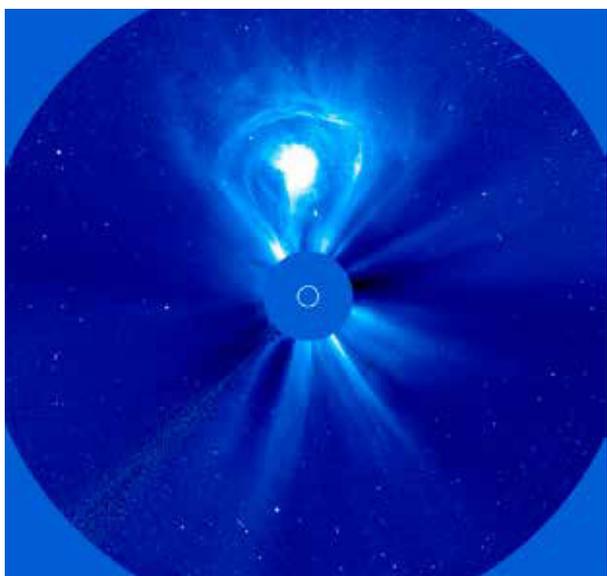
A revolution came in the 1930s, when nuclear fission and fusion were discovered with help from Einstein's iconic $E = mc^2$. Combining principles of nuclear physics with the observed abundance of hydrogen in the Sun, physicists Hans Bethe and Charles Critchfield proposed in 1938 that the Sun's energy was the result of fusion — predominantly, a proton-proton chain reaction.



The Sun is the center of the solar system and provides the energy that makes life on our planet Earth possible. This image, taken by NASA's Solar Dynamics Observatory across several wavelengths in the extreme ultraviolet part of the spectrum, shows a massive solar flare (lower right) accompanied by a large eruption of material. NASA/SDO



Japan's Super-Kamiokande Observatory consists of some 13,000 photodetectors in a water-filled tank 129 feet (39.3 m) wide by 136 feet (41.4 m) tall located nearly 3,300 feet (1,000 m) underground. When a neutrino interacts with the atoms in the water, it creates a brief flash of light, called Cherenkov radiation, that is picked up by the detectors. Here, the tank is being refilled with water in April 2006. KAMIOKA OBSERVATORY, ICRR (INSTITUTE FOR COSMIC RAY RESEARCH), THE UNIVERSITY OF TOKYO



The Large Angle and Spectrometric Coronagraph experiment aboard the SOHO spacecraft is designed to block out the bright Sun to focus on events that occur in the corona. On Feb. 27, 2000, it captured a lightbulb-shaped coronal mass ejection blasting away from the Sun and into space.

NSO/AURA/NSF

Hotter and more massive stars, the physics held, use either a second cycle called the carbon-nitrogen-oxygen (CNO) cycle, or a third, called the triple-alpha process.

According to nuclear theory, these processes produce neutrinos — ghostlike particles that can zip through light-years' worth of matter without being absorbed. Solar neutrinos fly through Earth at nearly the speed of light about 8.5 minutes after they are created in the Sun's core. And in fact, the only direct proof that these fusion cycles were occurring relied on the detection of these neutrinos.

A race began to build detectors

capable of seeing these particles. Physicists Raymond Davis Jr. and John Bahcall began monitoring the Sun for neutrinos in the late 1960s. Solar neutrinos *were* detected, but at only a fraction of the numbers per day that were expected — a situation that became known as the solar neutrino problem.

It turns out neutrinos come in three flavors: electron, muon, and tauon. A single neutrino can be any of these flavors as well as change between them, so a detector must be able to capture all three types to get an accurate tally. The “missing” neutrinos were found once more sensitive detectors like the Sudbury Neutrino Observatory in Ontario and the Super-Kamiokande Observatory in Japan came online in the 1990s, leading to the discovery of this interchange, called neutrino oscillation. And with a full picture of the Sun in neutrinos came confirmation that thermonuclear hydrogen fusion was going on in its core.

Recently other discoveries about the Sun's core have come to light. In 2017, a team led by Eric Fossat at the Côte d'Azur

Observatory in France used 16 years of data from the Solar and Heliospheric Observatory (SOHO) to detect waves traveling through the Sun's interior. These gravity-mode (or g-mode) oscillations are caused by blobs of plasma rising quickly through the Sun, then sinking again once they reach a region with lower density, still far beneath the surface.

Fossat's team deduced that the core of the Sun is rotating faster than the surface, taking one week to complete a rotation, compared with the surface's 30 days. This is probably a remnant of the formation of the Sun itself as it accreted gas from its surroundings, absorbing its angular momentum.

And in 2020, researchers using the Borexino Neutrino Detector in Italy detected neutrinos from the CNO cycle within the Sun. This was the first confirmation that this energy source is indeed operating in the cores of stars and also occurs at all in lower-mass stars like our Sun.

The surface of the Sun

The photosphere, or visible surface of the Sun, is incredibly complex and dynamic, a

seething surface of convection cells, tangled magnetic fields, and explosive flares and prominences. At virtually every scale, from feet to thousands of miles and from seconds to years, there are phenomena demanding explanation.

Among these are sunspots, observed since the first millennium B.C.E. By the 20th century, sunspots were identified as locations where the internal magnetic field of the Sun punches through the surface, causing the local plasma to shine at a lower temperature and appear dark against the brilliant surroundings. Their numbers rise and fall in a roughly 11-year cycle first discovered in 1843 by amateur astronomer

Heinrich Schwabe. Since then, astronomers have tried to decipher this cyclical behavior. A clear explanation leading to reliable forecasts still eludes us, but pieces of the problem have been resolved.

Despite their surface-level appearance, sunspots originate in the Sun's interior. Just below the photosphere is a convection zone, which reaches roughly one-third of the way to the center of the Sun. Within this region, plasma flows like a fluid, carrying heat and energy upward and sinking again once it has cooled. Beneath this sits the tachocline, a transition zone that separates the convective and radiative zones of the Sun. The deeper radiative zone reaches

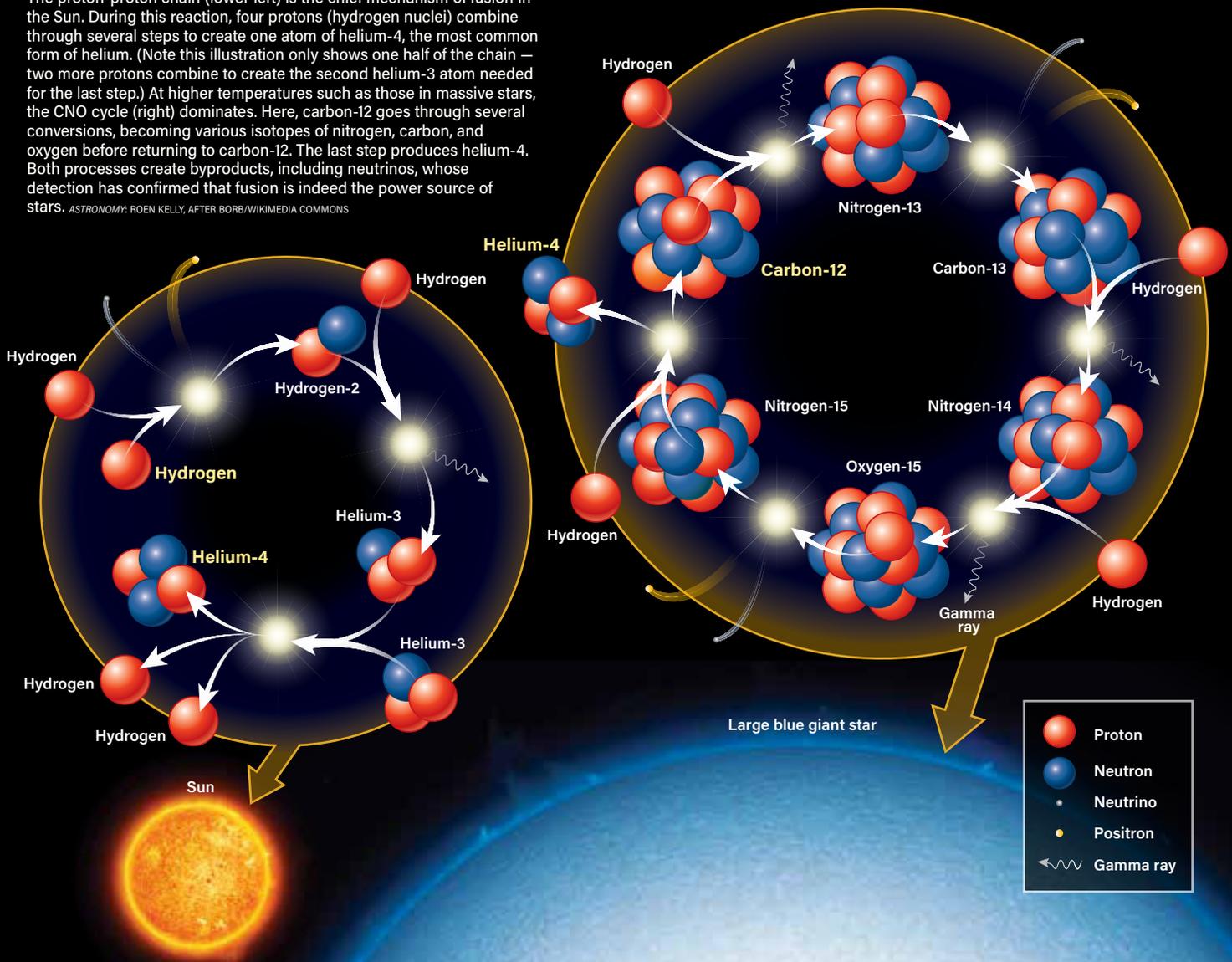
down to the core; within the radiative zone, the solar plasma rotates as if it were a solid body.

Within the tachocline, the differential rotation of the convection zone shears against the uniform rotation of the radiative zone, amplifying the embedded magnetic field. When portions of the magnetic field achieve buoyancy and rise to the surface, they form the sunspot groups we see.

Just as studying seismic waves on Earth allows geologists to probe its inner structure, SOHO's observations of the oscillatory motions of the solar surface allow us to probe how the convection zone and tachocline have changed during the last three sunspot

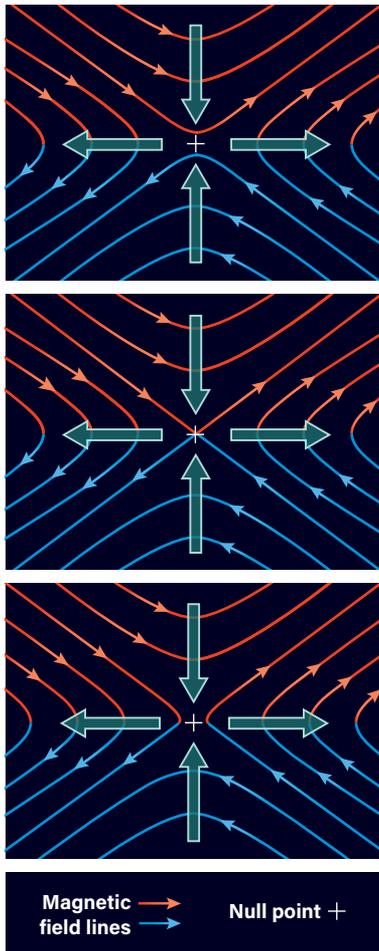
FUSION IN THE SUN

The proton-proton chain (lower left) is the chief mechanism of fusion in the Sun. During this reaction, four protons (hydrogen nuclei) combine through several steps to create one atom of helium-4, the most common form of helium. (Note this illustration only shows one half of the chain — two more protons combine to create the second helium-3 atom needed for the last step.) At higher temperatures such as those in massive stars, the CNO cycle (right) dominates. Here, carbon-12 goes through several conversions, becoming various isotopes of nitrogen, carbon, and oxygen before returning to carbon-12. The last step produces helium-4. Both processes create byproducts, including neutrinos, whose detection has confirmed that fusion is indeed the power source of stars. ASTRONOMY: ROEN KELLY, AFTER BORR/WIKIMEDIA COMMONS

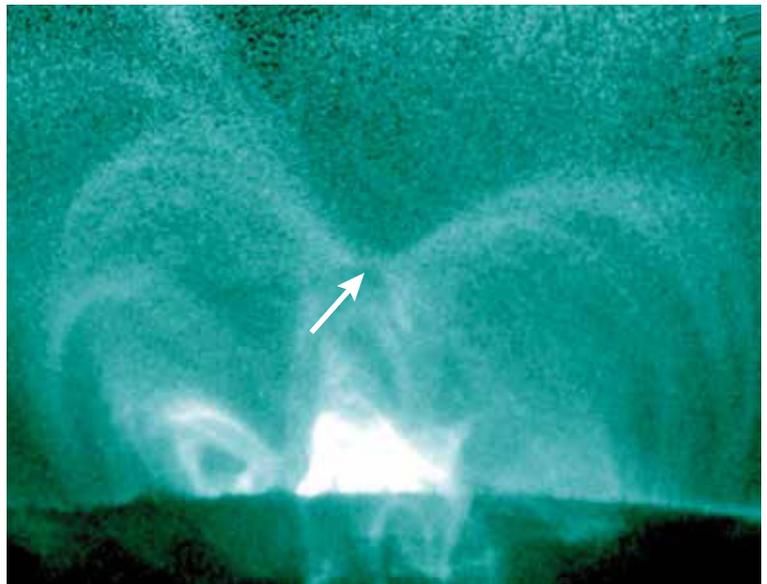


MAGNETIC RECONNECTION

NEAR RIGHT: During magnetic reconnection, magnetic energy is converted to other forms of energy. This simplified schematic shows the steps of a magnetic reconnection event: From top to bottom, magnetic field lines oriented in different directions flow inward (from the top and bottom of the image), reconnect at a null point where the magnetic field strength is zero (plus sign in the center), and move outward again (to the left and right). ASTRONOMY: ROEN KELLY, AFTER CHAMOJACON/WIKIMEDIA COMMONS



FAR RIGHT: This close-up from SDO shows a coronal loop on the Sun just prior to a magnetic reconnection event in April 2014. Visible is the null point, which looks like the cross of an X, where the magnetic field strength drops to zero and reconnection can occur. CHEN ET AL. 2016/COURTESY OF NASA/SDO AND THE AIA, EVE, AND HMI SCIENCE TEAMS



cycles. It seems that just as Earth has equatorial trade winds, the solar interior above the radiative zone has what is called meridional circulation. Plasma at the equator flows to the polar regions at about 45 mph (72 km/h), dives back to the tachocline, and then flows

equatorward, completing one loop every 11 years. Changes in this flow speed seem to be correlated with the strength of the subsequent sunspot cycle — the faster the drift velocity, the stronger the sunspot cycle, as measured by the total area of the sunspots.

Seeking reconnection

On Sept. 1, 1859, English astronomer Richard Carrington was observing a group of sunspots when “two patches of intensely bright light broke out” from them, he later wrote. He had become the first observer to see a solar flare in real time. That night, the aurora borealis was seen as far south as

Cuba and Colombia. Earth had been engulfed by the strongest geomagnetic storm ever recorded — one that, if it occurred today, could have catastrophic impacts on power grids and communications infrastructure.

Carrington’s serendipitous observation showed that the Sun is capable of unleashing tremendous amounts of magnetic energy from sunspots — and that energy can also have enormous impacts on Earth. But understanding the physics of how that actually happens has remained one of the Sun’s most elusive mysteries.

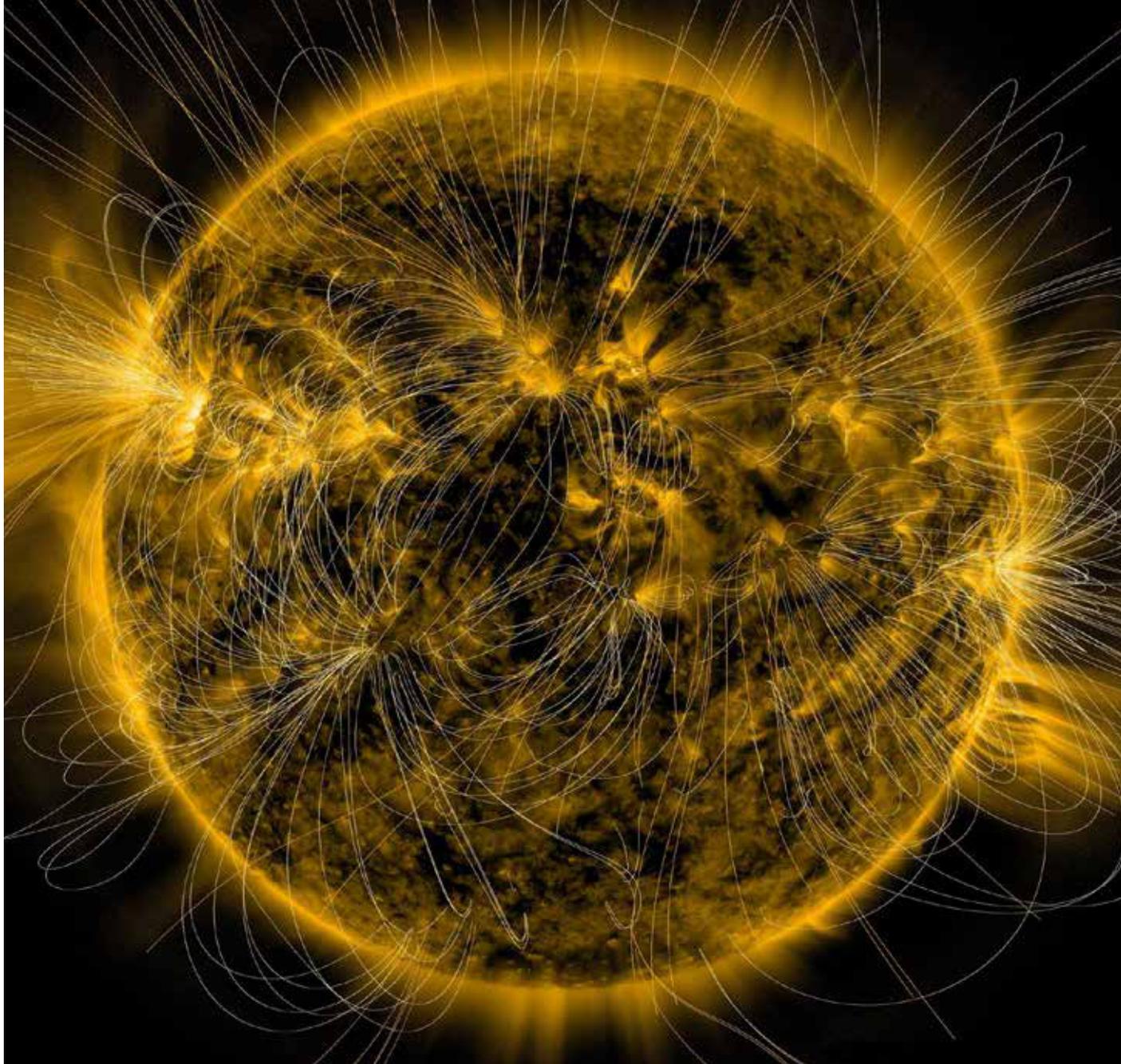
A breakthrough came in 1950, when British space scientist James

THE SUN UNDER A SPECTROSCOPE

THE DEVELOPMENT OF THE SPECTROSCOPE in the mid-19th century allowed researchers to identify the elements present in the solar photosphere — the layer of the Sun that appears to us as its visible surface. This led to the discoveries of mysterious new extraterrestrial elements called helium and coronium, while the exploration of the Sun’s luminosity across wavelengths — its so-called blackbody spectrum — enabled German astronomer Julius Scheiner to make the first estimate of the photospheric temperature.

Quantum mechanics allowed solar physicists to finally understand the relationship between what they were seeing through the spectroscopy and what was physically going on in the photosphere. In her 1925 Ph.D. thesis, Harvard University astronomer Cecilia Payne showed that the spectral features we see in stars do not simply correspond to how much of an element is present, as had been previously thought; rather, they also depend on the energetic states of the atoms within. Hydrogen turned out to be the most abundant element in the Sun and in all other stars.

As for coronium, German astronomer Walter Grotrian and Swedish spectroscopist Bengt Edlén independently came to the provocative conclusion that this was not a new element, but rather emission from the iron atoms that had lost 13 of their 26 electrons — a consequence of the extremely high temperatures in the Sun’s corona. —S.O.



Dungey first described in his Ph.D. thesis at the University of Cambridge a phenomenon called magnetic reconnection: When magnetic field lines in plasma are coiled and twisted, they store magnetic energy, like a wound-up rubber band. When the field lines break and then reconnect, they release this energy by converting the magnetic energy into other forms. This process goes a long way toward explaining how the solar plasma is heated and ejected in explosive flares. The theoretical details were explored by astronomer Peter Sweet and solar physicist Eugene Parker in 1956.

Magnetic reconnection became the canonical explanation for flares and other magnetic phenomena. However, it remained observationally unverified for decades, until space missions in 2008 and 2015 detected magnetic reconnection events in Earth's magnetosphere and the subsequent aurorae they caused.

The Large Plasma Device at UCLA and the Magnetic Reconnection experiment at Princeton University can create magnetic reconnection events in the lab to study their detailed behavior. All of this research has abundantly confirmed the basic

mechanism detailed by Sweet and Parker. Today, scientists use the concept of magnetic reconnection to investigate many systems in the universe, from bipolar outflows in star formation to the disks and jets of supermassive black holes.

The corona

Magnetic reconnection has also emerged as a key to another of the Sun's enduring mysteries: why the corona heats up even as it extends farther away from the Sun.

Our awareness of this conundrum dates to the mid-19th century, when spectra of the corona taken during total solar eclipses

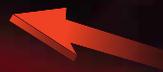
This image combines an ultraviolet image of the Sun taken by SDO in March 2016 with measurements of the solar magnetic field at the surface at the same time. The lines of the Sun's magnetic field, overlaid as arching white lines, cluster most thickly around bright, highly magnetic regions of our star's surface. NASA/SDO/AIA/LMSAL

revealed emission at wavelengths never before seen, unassociated with any known element. It took the development of quantum mechanics in the 1920s to show that some of these lines were not emitted by new elements — they were produced by known elements that had been stripped of several of their electrons, a state only possible if the temperature of the corona was millions of degrees.

Yet the photosphere was an estimated 9,570 to 11,730 degrees Fahrenheit (5,300 to 6,500 degrees Celsius). So, a corona that was so much hotter seemed an impossible state that defied the laws of thermodynamics, much like an ice cube surviving in an oven. How can a hot, million-degree corona sit on top of a much cooler, thousand-degree photosphere?

In 1987, Parker proposed that the corona could reach such temperatures if it were heated by multiple, repeated small flares. This is just one of many theories for how events on the solar surface can heat coronal plasma, and perhaps all of them contribute. But in the last few decades satellite observations have detected explosive flares caused by magnetic reconnection in the inner corona and the transition region separating it from the chromosphere. These flares come in a variety of sizes, down to nanoflares first detected by JAXA's Hinode in 2011, which can see features as small as 470 miles (760 km) across.

The Sun's corona is only visible from Earth during a total solar eclipse. This composite telescopic image of the April 8, 2024, eclipse was processed to accentuate details in the corona beyond what the eye could see; also visible at lower right are the pink prominences many observers reported. The shape and structure of the coronal loops and streamers are a direct result of the solar magnetic field. ALAN DYER



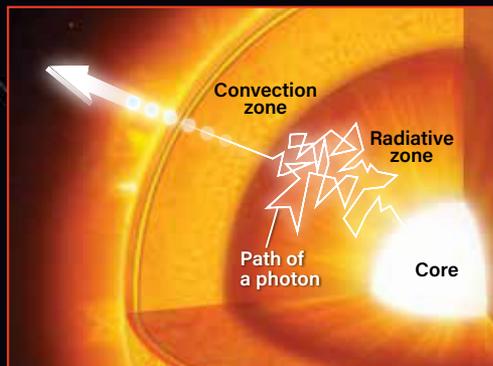
Solar wind
This thin, ionized gas speeds away from the Sun.

Coronal mass ejection
Billion-ton clouds of charged particles leave the Sun moving at millions of miles per hour.

Flare
Flares are sudden releases of energy stored in sunspot magnetic fields.

Convection zone
In the upper layers of the Sun, energy is moved via convection: Hot material rises and radiates heat away, then sinks as it cools.

Radiative zone
Deep inside the Sun, energy generated through nuclear fusion travels outward as radiation, or photons.



The core and radiative zone are so dense that photons cannot travel far before colliding with a particle and being knocked off course. This "random walk" means a photon takes thousands of years to reach the convection zone from the core. After that, it rises more straightforwardly with the material there, reaching the surface in months. ASTRONOMY: ROEN KELLY

ANATOMY OF THE SUN

A massive flare erupts from the Sun on May 10, 2024, as seen by SDO (right). A few days later, as the solar material impacted Earth and its magnetic field, observers around the globe were treated to stunning aurorae, like the display at left in southwestern British Columbia.

LEFT: NASA/MARA JOHNSON-GROH, RIGHT: NASA/SDO

Tachocline

The Sun spins like a solid body below the tachocline, and like a fluid above. Intense shear here helps create the Sun's magnetic field.

Meridional flow

A current of plasma acts as a conveyor belt in the convection zone.

Transition region

A thin region within the Sun's atmosphere separates the cooler chromosphere from the superheated corona.

Corona

This is the Sun's outer atmosphere and source of the solar wind.

Chromosphere

This is the middle layer of the Sun's atmosphere.

Photosphere

This is the Sun's visible surface.

Core

This is the innermost part of the Sun, where hydrogen fuses into helium and releases energy.

Magnetic field lines

Magnetic field lines are pulled into an east-west rotation and become twisted as the lines rotate faster at the equator and slower at the poles.

Prominence

Magnetic fields suspend arches of gas far above the Sun's surface.

Sunspots

These dark spots mark where amplified magnetic fields anchored far within the Sun break through the surface. Carried by the deep meridional flow, sunspot fields emerge closer to the equator as the solar cycle progresses.

Global magnetic field lines

The Sun's global magnetic field is about 10 times more powerful than Earth's. Field lines exit the Sun at the positive pole and enter at the negative pole.

The Daniel K. Inouye Solar Telescope at Haleakala Observatory on Maui captured this striking close-up image of dark sunspots on May 11, 2021. Also visible are individual solar granules: convection cells where hot plasma is rising (yellow centers) and cool plasma is sinking (orange borders).

NASO/AURA/NSF

By combining data from two NASA satellites — the Interface Region Imaging Spectrograph (IRIS), which can image solar structures as small as 155 miles (250 km) every second, and the Solar Dynamics Observatory (SDO) — researchers have discovered that nanoflares undergo magnetic reconnection, leading to the rapid heating of the local solar plasma to millions of degrees. These events are so numerous they can easily explain why the corona reaches millions of degrees.

Coronal mass ejections (CMEs) are another feature of the corona, hurling billions of tons of plasma into interplanetary space. These wreak havoc with planetary magnetic fields upon impact and cause aurorae, magnetic storms, bursts of high-energy protons, and other effects that are harmful to astronauts and satellite technology. These explosions are also

caused by magnetic reconnection in the corona (often accompanying flares in the photosphere). The entrained plasma is then hurled out into space at millions of miles per hour.

Extensive studies of CMEs by satellites both in situ and remotely observing from different angles (such as NASA's STEREO A and B) have allowed us to understand how they are produced and propagate in space. When a CME is first ejected, a shock wave forms as it plows through the denser lower corona. This compresses the local magnetic field, creating a natural particle accelerator that amplifies the energies of plasma particles — mostly protons — by thousands of times. Traveling at nearly the speed of light, these protons arrive at Earth within a few hours and present a severe radiation hazard to astronauts and satellites. They can even be detected on the

ground by instruments that normally monitor the flux of cosmic rays produced by distant black holes and supernovae.

Fortunately, CMEs can now be physically and mathematically modeled so that increasingly accurate forecasts can be made for what to expect near Earth.

The solar wind

The corona may be the outermost visible layer of the Sun, but our star's physical presence reaches far beyond that. In 1951, German astronomer Ludwig Biermann proposed that the shapes of comet tails were affected by a global stream of what he called “corpuscular radiation” from the Sun, and that the comet tails acted like windsocks. In 1958, Parker published the defining paper on what is now called the solar wind. Solar wind particles were subsequently detected by Mariner 2, launched in 1962.

There are two solar wind streams: a slow wind traveling at about 124 miles (200 km) per second and a fast stream at about 250 miles (400 km) per second. The slower wind is more persistent and correlates nicely with Parker's model, while 1973 X-ray studies conducted on the Skylab space station found that the high-speed wind is associated with features called coronal holes. These holes occur where the magnetic lines of force from the corona open out into interplanetary space and act like pipes through which the hot coronal plasma can flow quickly outward.

But where does the solar wind originate? For decades, researchers had lacked direct observations of any proposed mechanism, including magnetic reconnection. But in recent years, this has changed dramatically.

Since 2018, NASA's Parker Solar Probe has been detecting magnetic “switchbacks” in the outer regions of the corona, in which the local magnetic field rapidly changes direction. Scientists

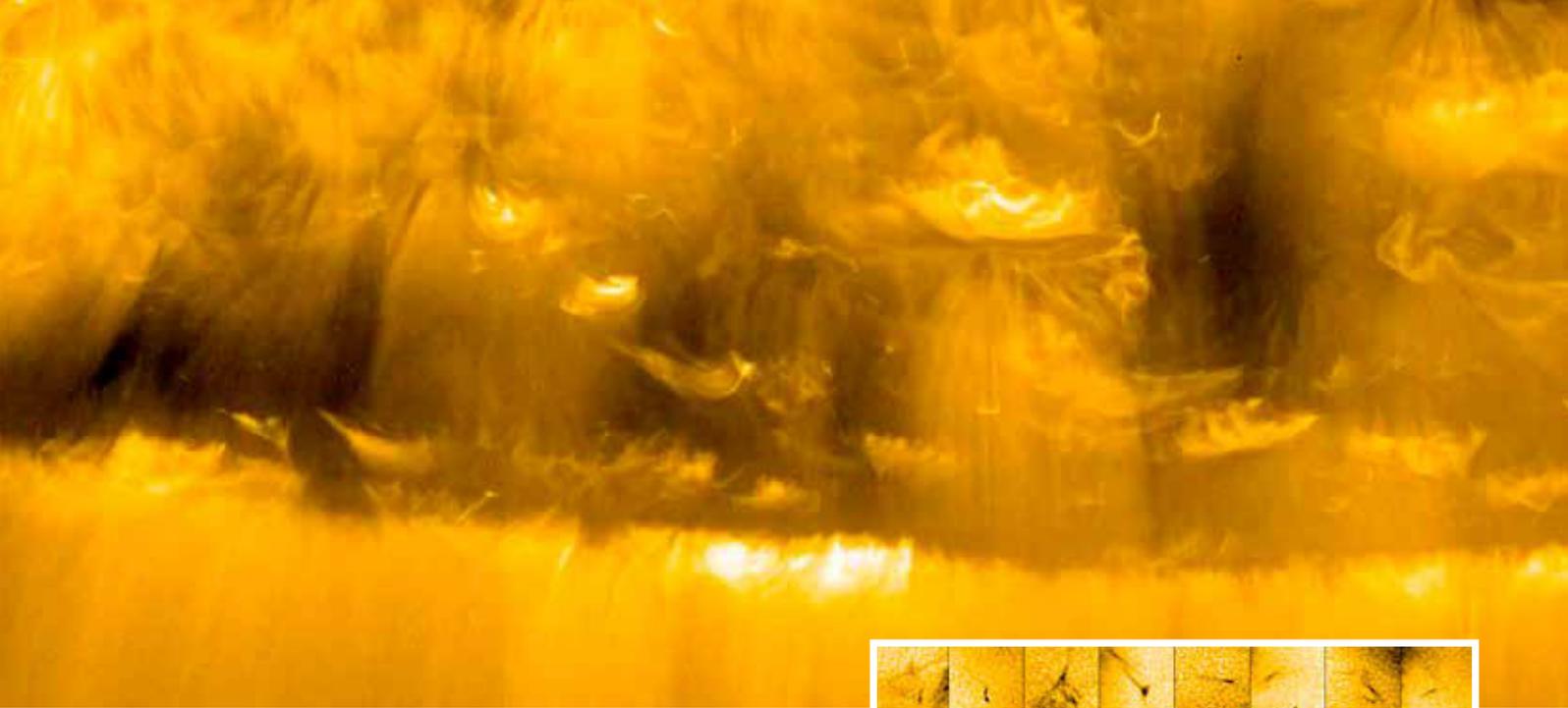
A 90-year-old Eugene Parker (center) visits the Parker Solar Probe — named for him — in a clean room at the Johns Hopkins Applied Physics Laboratory in Laurel, Maryland, in 2017, prior to its launch. Parker died in 2022 aged 94. NASA/JOHNS HOPKINS UNIVERSITY APPLIED PHYSICS LABORATORY



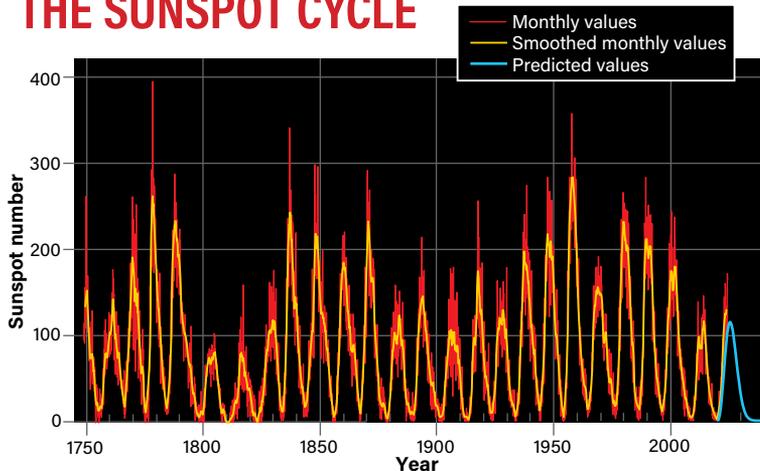
THE SUN'S MANY CROWNS

THE SUN'S GLOWING OUTER ATMOSPHERE is commonly referred to as the corona. But since the early 20th century, scientists have recognized that there are several coronae around the Sun, distinguished by the physical mechanism that causes their emission.

The K-corona lies closest to the photosphere and is generated by electrons scattering photospheric sunlight to produce emission at all wavelengths. This is mostly what we see during a total solar eclipse. Then there is the poorly understood E-corona, which is filled with plasma heated to millions of degrees and where iron atoms emit the light that generates the historic coronium line. Finally, the outer, cooler, dusty F-corona begins at about three solar radii and extends all the way out to the zodiacal dust belt (80 solar radii), and is visible in infrared light. — S.O.



THE SUNSPOT CYCLE



Counts of the number of sunspots date back to the mid-1700s. Based on these data, astronomers have noted an ongoing 11-year cycle in the number of sunspots; the next maximum — the 25th since counts began — is predicted to occur in late 2024 or early 2025. *ASTRONOMY*: ROEN KELLY, AFTER NOAA SPACE WEATHER PREDICTION CENTER

think this is a sign that magnetic reconnection is occurring closer to the Sun, as open and closed magnetic field lines interact and reconfigure themselves. These disturbances hurl globs of plasma into interplanetary space, though it's unclear whether this material can account for the solar wind.

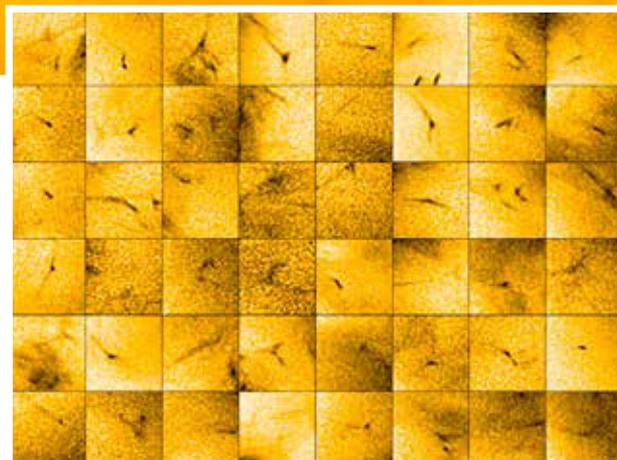
A separate line of evidence has emerged thanks to ESA's Solar Orbiter, which launched in 2020 and approached the Sun to about 28 million miles (45 million km) in March 2022. At that distance, its Extreme Ultraviolet Imager was

able to resolve the inner corona into a multitude of individual plumes and jets reaching upwards into the corona. These so-called picojets are only 62 miles (100 km) across and last just under 100 seconds, launching their plasma at 62 miles (100 km) per second. Future observations should provide a clearer picture of whether and how these jets might collectively generate the solar wind.

Many chapters left

So, where do we now stand?

As with Earth, the terra

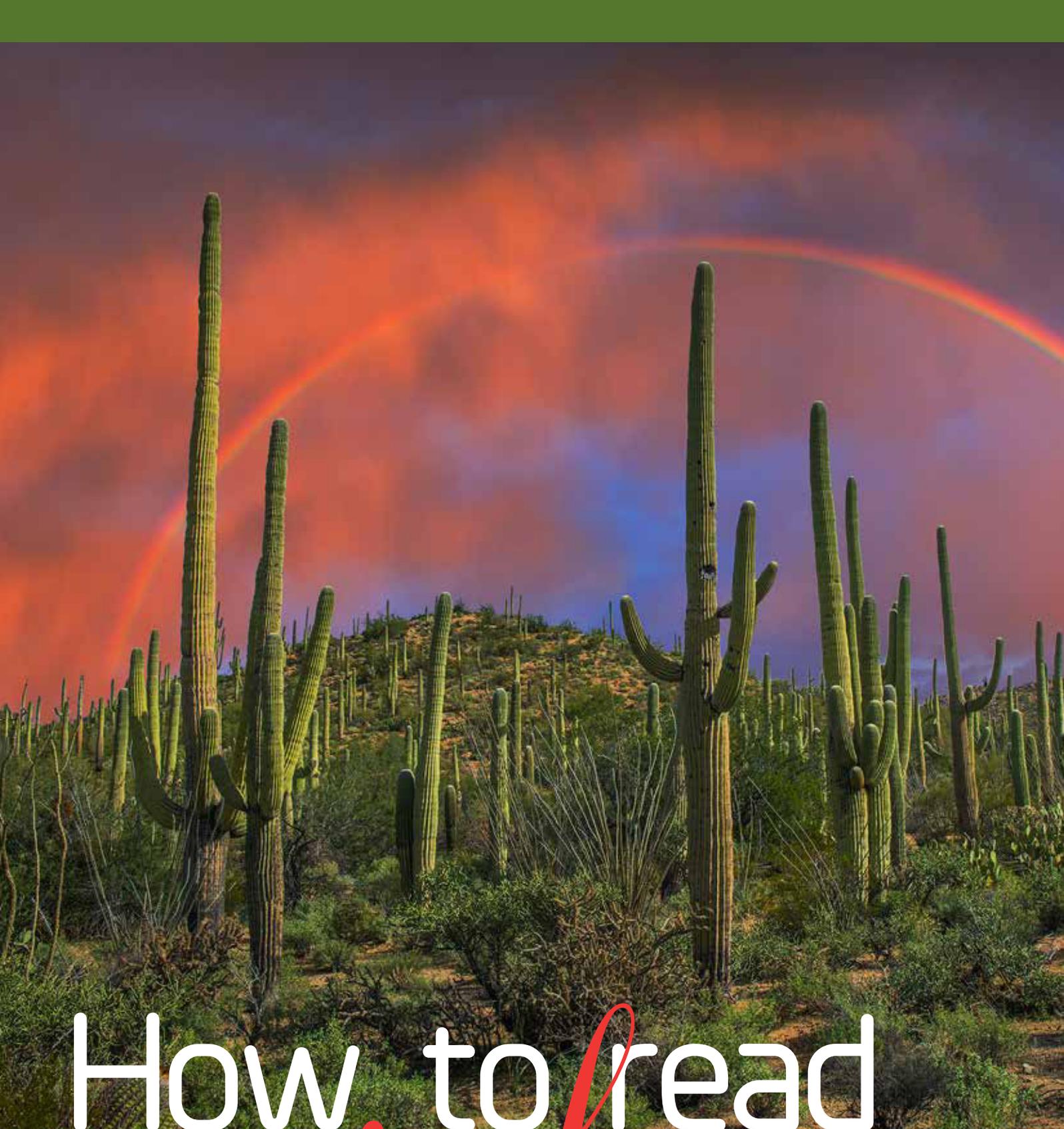


incognita of our star remains its interior. We only know what is generally occurring inside the Sun, while the details beg for study. Exactly what goes on in the vast radiative zone? Theory suggests a massive, primordial magnetic field there, dating to the Sun's formation. How do sunspot cycles come and go and what determines how active they will be? Is it all just unpredictable chaos? How often does our Sun release massive superstorms like the 1859 Carrington Event, and what prompts them?

There are plenty more questions to ask, and our state-of-the-art space missions are uncovering new details with every orbit. ☿

Sten Odenwald is an astronomer and a member of the NASA Heliophysics Education Activation Team (HEAT) program.

BOTH ABOVE: NASA and ESA dispatched the Solar Orbiter probe to take the closest-ever images of our Sun and help unravel several mysteries, including the composition and generation of the solar wind. In March 2022, the craft imaged the region inside a coronal hole near the Sun's south pole in ultraviolet light (top). Within the hole, researchers discovered numerous short-lived jets, called picoflares, each spewing plasma out into space — perhaps the origin of the solar wind. In the mosaic (above), which is shown in negative, each jet appears as a dark streak. ESA & NASA/SOLAR ORBITER/EUI TEAM; ACKNOWLEDGEMENT: LAKSHMI PRADEEP CHITTA, MAX PLANCK INSTITUTE FOR SOLAR SYSTEM RESEARCH



How to read *rainbows*



Rainbows may be a trick of the eye, but they're also based in fascinating optical physics.

BY RAYMOND SHUBINSKI

RAINBOWS DON'T ACTUALLY EXIST. You can't find the end of a rainbow (or its attendant pot of gold). It's not possible to walk across a rainbow as the Norse gods did on the Bifrost, the bridge for fallen warriors to reach Valhalla, or to travel over one like Dorothy to Oz.

Rather, rainbows and other similar phenomena are truly in the eye of the beholder — or, we might say, in the mind of the beholder. Seeing a rainbow is the result of a cosmic interplay between solar radiation, optical physics, billions of water droplets, and the ability of the human brain to separate white light into the visible spectrum.

It's easy to understand the awe and wonder — not to mention myth, religious devotion, and poetry — inspired by the appearance of a beautiful rainbow after a storm has cleared. Ancient cultures had their own stories about rainbows, such as the Greek belief in Iris, goddess and personification of the rainbow.

For most of human history, rainbows were considered tangible objects. But we now know these beautiful atmospheric apparitions are exactly that: visions caused by nature and physics. As the French astronomer Camille Flammarion said, the effects of light “produce a thousand optical phenomena, always curious, often fantastic, but all capable of explanation.”

We can see clearly now

Learning the truth of how sunlight interacts with the

A double rainbow seen from Saguaro National Park in Tucson, Arizona, features a bright primary and a faint secondary as a companion. In the foreground are giant saguaro cacti. TONY HALLAS

atmosphere to allow us to see rainbows took hundreds of years and a good deal of investigation.

The great Arab scientist Hasan Ibn al-Haytham, known in the West as Alhazen, performed groundbreaking work in optics at the end of the 10th and beginning of the 11th century. He did experiments on the dispersion of light and suggested that rainbows formed when sunlight struck the concave surfaces of clouds. At about the same time, the Persian mathematician Abu Sa'd al-'Ala' Ibn Sahl was describing the laws of refraction.

Building on Alhazen's work, in the early 14th century the German Dominican friar Theodoric of Freiberg began experimenting with water flasks to simulate drops. He realized that light was bent — refracted — and then reflected and refracted again within the water drops, while Islamic mathematician Al-Farisi, also known as Kamal al-din, was the first to determine the colors of the rainbow come from white light. In 1621, Willebrord Snel van Royen (also known as Willebrord Snell), a Dutch astronomer and mathematician, rediscovered Ibn Sahl's law of refraction, now known as Snell's law. René Descartes, a contemporary of Snell but working independent of him, also studied refraction in water and provided an accurate mathematical explanation for the rainbow.

Then, in 1666, Isaac Newton had a lot of time on his hands. Cambridge University had shut

down due to an outbreak of the plague. While at home, he performed one of the most famous experiments in physics. In a darkened room, he passed sunlight through a prism to study what he would call the spectrum. Newton demonstrated that white light is composed of the same colors as the rainbow, spreading from red to violet. His discovery was a culmination of the work of those who had investigated these phenomena before him.

Ingredients to make a rainbow

Four conditions are needed to see a rainbow: The Sun must be only a certain height above the horizon, it must be shining through the clouds, raindrops must be present in the atmosphere, and you need to look directly opposite the Sun. If all of these criteria are met, you will see one of nature's most beautiful sights.

Rainbows can never be seen when the Sun is high in the sky. This is because of the angles at which light is refracted as it enters a raindrop, reflects off its internal surface, and is refracted again as it exits the drop. The end result is that light emerges from the drop most concentrated near the maximum angle of about 42° , its colors slightly dispersed, to form the primary rainbow. This rainbow



Sometimes, a secondary rainbow can be seen above the primary bow. It is caused by an additional reflection within the raindrops.

appears to surround the antisolar point — the point opposite the Sun — at an angle of 42° .

Accordingly, the Sun needs to be 42° or less above the horizon for the rainbow to be visible. If it is higher, you will also need to be higher — on a mountain or in an airplane — to see the light at the angle at which it emerges from the raindrops.

Most commonly, a rainbow is seen as a single arching bow with colors ranging from red at the outer boundary to violet at the inside. We see red at the top of the rainbow because it is bent at the shallowest angle. Blue and violet are bent the most, and appear at the bottom of the bow. Usually, the primary bow is described as seven colors, represented

by the acronym ROYGBIV: red, orange, yellow, green, blue, indigo, violet. But depending on how intense the rainbow appears, you might see more gradations between each color.

Sometimes, a secondary rainbow can be seen above the primary bow. Because it is caused by an additional reflection within the raindrops, less light emerges, resulting in the secondary being only one-tenth as bright as the primary rainbow. Also, because of the number of reflections, the colors in the secondary bow are reversed. The sky between the two bows appears noticeably darker than the sky above the secondary and below the primary bow. This phenomenon is known as Alexander's Dark Band, named after Alexander of Aphrodisias, who described this strange phenomenon in the 3rd century.

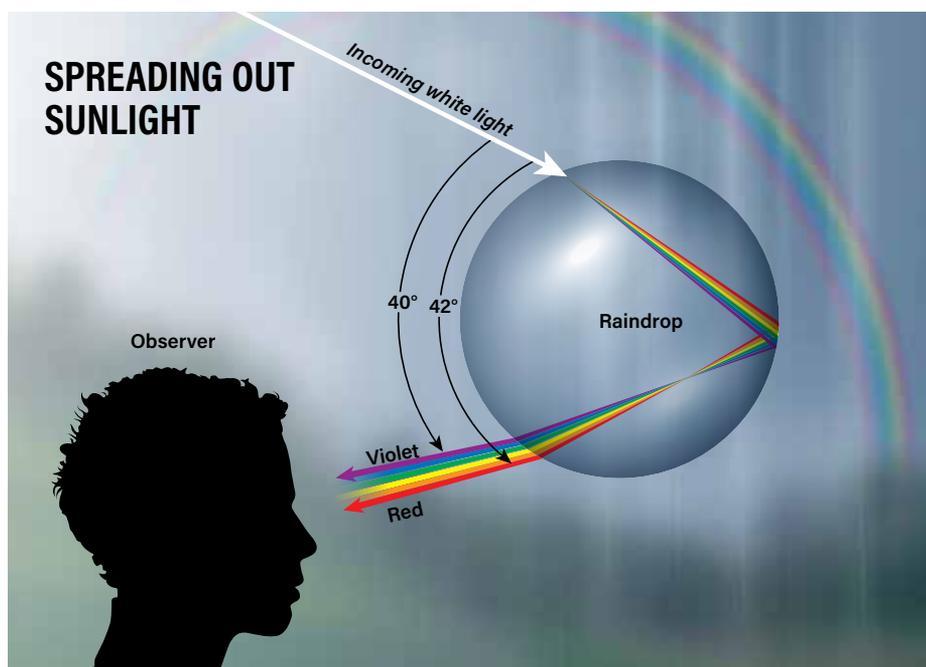
If conditions are just right, a third, or tertiary, rainbow may be seen above the secondary. It is even fainter than the secondary and is quite rare. In *L'Atmosphere*, Flammarion describes several other extremely unusual types of rainbows. He tells of Edmund Halley's observation of "three arches, one of which ... reflected upon a river. This arch first intersected the exterior arch so as to divide it into three equal parts. When the Sun sunk toward the horizon, the points of meeting were drawn close together. There soon was seen but one single arch, and as the colors were in inverse order, pure white was formed by the superposition of the two series."

Personalized rainbows

I was once asked to speak at a friend's Unitarian church while the minister was out. He told me I could talk on any topic I liked. The title of my "sermon" was "Everyone Sees Their Own Rainbow."

When you see a rainbow, your eyes are at the apex of a cone formed by the light rays that are being reflected by the raindrops that happen to be at a 42° angle from the antisolar point — from your perspective. (This cone is sliced off by the horizon, which means the average observer is only seeing half of the full circle of a rainbow; the full circle is sometimes visible from an airplane when the horizon is far below.)

If you are driving when you see a



As sunlight enters a raindrop, it first refracts, which separates the white light into its different visible wavelengths. It then reflects off the interior, and is finally refracted again out of the droplet. To form a full rainbow arc, an estimated trillion raindrops are needed. ASTRONOMY: ROEN KELLY

rainbow, it will seem to follow you. This is because your cone of vision is what is doing the moving. And if you and a friend are standing next to each other, you are both seeing your own personal rainbows. Admittedly, if asked, you will describe them the same way; your cone of vision, however, means it's all yours. I have always thought of this as a wonderful metaphor for individuality.

What about someone who is severely colorblind? How do they see this atmospheric phenomenon? In the most extreme cases of colorblindness, a person may only see 1 percent of the range of colors visible to someone with unaffected vision. To most colorblind individuals, rainbows may appear to have fewer hues or look more muted: Red may appear more brown and green might be an olive tone.

Rainbows in the night

If rainbows are caused by the interaction of sunlight and raindrops, how do we explain reports by Aristotle, Amerigo Vespucci, Benjamin Franklin, and others of nocturnal rainbows?

These individuals were not hallucinating. Lunar rainbows, or moonbows, are created by reflected sunlight from the Moon. Moonbows are quite rare because even more conditions must come together to create them.

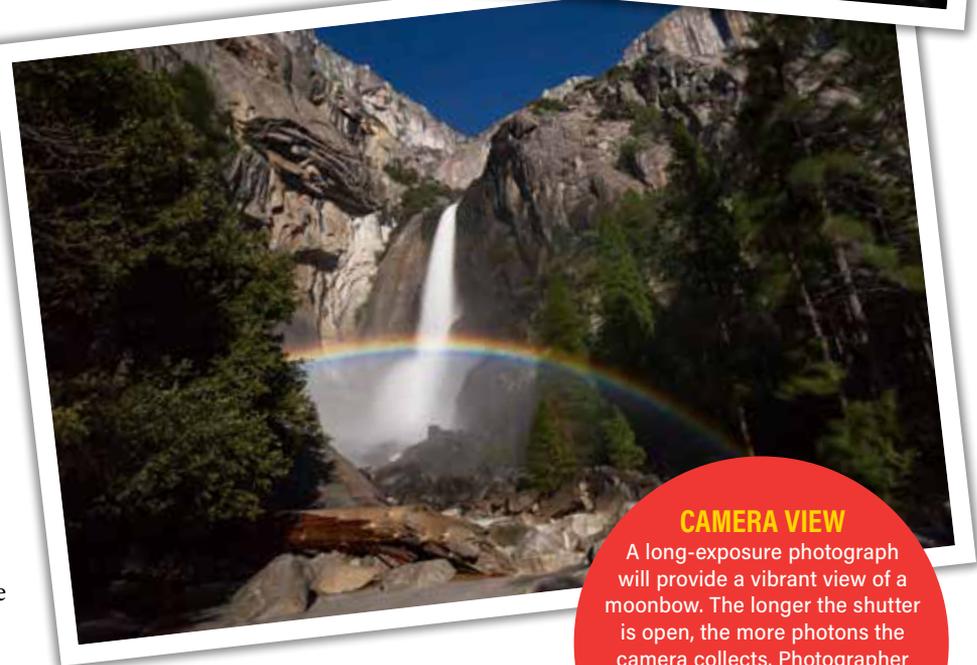
Moonbows can only be seen when the Moon is Full or very near Full, which happens 12 or 13 times a year. The Full Moon is about 400,000 times fainter than the Sun, so if you are in a light-polluted area, your chances of seeing a moonbow are almost zero. Just as with a daytime rainbow, the Full Moon must be no more than 42° above the horizon. That means you need to look for a moonbow shortly after the Full Moon rises or not long before it sets. And of course, water drops must be present in the atmosphere. If all these conditions are in place, you might see a faint gossamer moonbow opposite the Full Moon.

Our color perception decreases at low light levels. The color-receptor cones in our eyes need a fair amount of intensity

NAKED-EYE VIEW

A moonbow will appear at first as a nearly colorless arc to the naked eye. This is due to our eyes' poor color sensitivity under low-light conditions — but as our eyes adjust, the colors strengthen.

BRIAN HAWKINS



CAMERA VIEW

A long-exposure photograph will provide a vibrant view of a moonbow. The longer the shutter is open, the more photons the camera collects. Photographer Brian Hawkins offers tips for capturing moonbows at www.yosemitemoonbow.com.

BRIAN HAWKINS

to start distinguishing colors. Even though all the rainbow colors are present in a moonbow, it usually appears pale white to the naked eye. Photographs, however, can capture the colors. And don't confuse a lunar halo, which is a circle around the Moon formed by light refracted by ice crystals, for a moonbow. The moonbow is always opposite the Full Moon.

A continuing allure

Rainbows have long been the subject of myths and stories, of art and music. And despite our modern scientific

understanding, they remain part of our culture.

Even if the rainbow is only in our mind's eye, it is as real as the Sun's light and Earth's water, providing us with a wonderful cosmic connection. ♪

Raymond Shubinski is a longtime contributor to *Astronomy* who loves recovering the lost ephemera of astronomy.

SKY THIS MONTH

👁️ Visible to the naked eye
🔭 Visible with binoculars
📡 Visible with a telescope

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

BY MARTIN RATCLIFFE AND ALISTER LING



This month, Jupiter is making its way through central Taurus, as in this 2013 image. Here, Jupiter is the brightest point at center, with Aldebaran to its lower left. ALAN DYER

Improving views

» November brings many sights to explore, including Mercury in the early evening, Mars brightening, and the giant planets Jupiter and Saturn adding to the spectacle. Jupiter in particular is reaching its best apparition in a decade for Northern Hemisphere observers.

Let's start soon after sunset. **Mercury** hugs the southwest horizon and remains easily visible throughout the first half of the month, a steady magnitude -0.3 . The planet is 2° high 30 minutes after sunset on Nov. 1.

On Nov. 3, look for the waxing crescent Moon low in the southwest 30 minutes after sunset. Binoculars will show 1st-magnitude Antares, the brightest star in Scorpius, just off its northern limb, while Mercury stands 8° to the right of the Moon (just over one field of view in 7x50 binoculars).

By Nov. 9, Mercury stands 4° above the horizon at the same time. It is now 2° north of Antares. In bright twilight, however, binoculars will still be needed to spy the star to the lower left of Mercury.

Mercury wanders through southern Ophiuchus, reaching its greatest eastern elongation on the 16th, 23° east of the Sun. It sets a little over an hour after sunset. This is the best Mercury will be this month. A telescope shows a 62-percent-lit disk spanning $7''$. By the 20th, Mercury is exactly 50 percent lit.

After that, Mercury begins to dim in earnest. By the 23rd, it shines at magnitude 0. A week later it's plummeted to magnitude 1.4 and is lost from view.

Venus treks across the Milky Way and is easy to spot soon after sunset, starting the month at magnitude -4 . Check out the planet an hour after sunset with

Ophiuchus as a backdrop in the darkening sky. Venus remains visible about two hours after sunset.

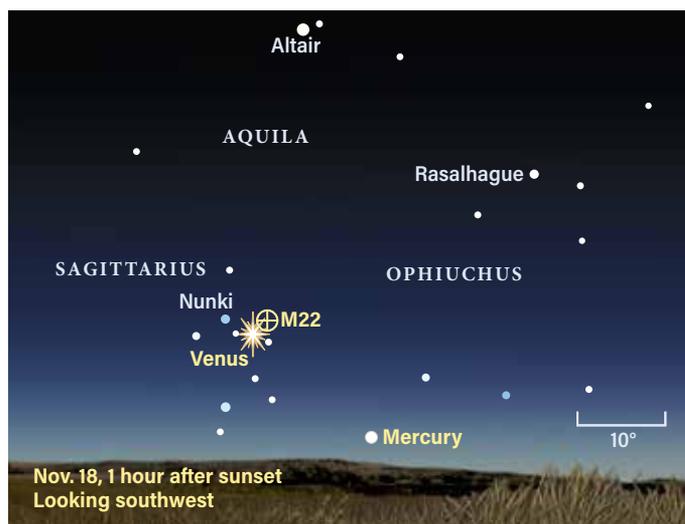
Venus stands 4° due north of a waxing crescent Moon on the 4th, an ideal evening to photograph it along with the Milky Way. A telescope shows a 76-percent-lit disk spanning $15''$.

Venus crosses into Sagittarius on the 8th. By the 11th it stands 1.5° south of M8, the Lagoon Nebula. Grab binoculars for a stunning view. On Nov. 18, scan 1.6° north of Venus to spy M22, one of the finest globular clusters in Sagittarius, glowing at 5th magnitude.

By the end of November the planet has gained 0.1 magnitude and remains up 3 hours after sunset. A telescope shows a $17''$ -wide disk now 68 percent lit.

As nightfall descends, **Saturn** stands high in the southern sky among the faint stars of Aquarius. It shines at magnitude 0.8. It's perfectly placed for observation, remaining above

Bright planets after sunset 👁️ 🔭 📡



Blazing Venus visits the Archer this month, standing close to globular cluster M22 on Nov. 18. Shortly before this date, Mercury reaches its best for the month. ALL ILLUSTRATIONS: ASTRONOMY; ROEN KELLY

RISING MOON | Lava, volcanos, and a dragon

OBSERVING HIGHLIGHT

URANUS reaches opposition Nov. 16 in western Taurus.



35° in altitude for a few hours. It stays within 2° of Lambda (λ) Aquarii all month.

A 10-day-old Moon wanders close to Saturn on Nov. 10. At 8 P.M. local time on the East Coast, Saturn is 1° north of Moon. By 8 P.M. local time on the West Coast, the Moon has moved to sit 1° east of Saturn.

Saturn's rings appear gossamer-thin to us now. This month the planet's tilt reaches 5.2°, the widest since March, and the narrow axis of the rings spans 3". The long axis stretches over 10 times that: roughly 40". By the end of this year, the tilt diminishes again to 3.9°.

Saturn's disk also shrinks this month, from 18" to 17", while its polar diameter dips to 16".

Titan, Saturn's largest moon, is an easy target for any telescope, at magnitude 8.5. It stands near the planet Nov. 3/4, 11/12, 19/20, and 27/28.

The smaller inner moons undergo transits, although these are difficult to see visually. Combine a telescope larger than 10 inches with high-speed video capture and good seeing for a chance at viewing these events.

Tenth-magnitude Tethys transits beginning in the evening on Nov. 7, 9, 24, and 26. Similarly bright Dione undergoes transits the evenings of the 4th, 15th (visible only from the eastern half of the U.S.), 23rd, and 26th. On the 23rd, Rhea transits the

— Continued on page 34

AS BRIGHT AS THE MOON IS on the 13th, darkness lurks along the terminator — perhaps there be dragons. The spackled strip of contrasts morphs with each passing hour. Tucked along the western shores of Mare Humorum in the lunar southwest is a broadly curving scarp centered on ground zero, where a massive impact formed the circular basin. As the Sea of Moisture sank under the weight of the lava, the floor cracked, leaving a nice cliff to catch the sunrise in a bright white arc. A smaller impactor arrived later to punctuate the scarp with a small crater.

Look for the couple of line segments on the west side, certainly not concentric to Humorum. They are part of a family of rilles that appear to be radial, like spokes on a bike, to a huge but now-buried basin. Deep cracks formed from that ages-old giant impact, then over time the walls slumped down and were further filled as later bombardments splashed material into them.

On the 13th, the modestly battered crater Mersenius is fully lit. A crater as wide as 50 miles ought to have a prominent peak, like the outstanding Tycho. It is there, but lies buried under lava that later oozed up through cracks in the floor in a most unusual way. Instead of being a flat pool, the surface is pushed upward in a broad dome, a bit puzzling to astronomers.

Can you see a Dragon's Mouth tucked south of the pair of Henry craters? The play of light and shadows on peaks and crater rims in that

Mersenius and the Dragon's Mouth 🔭



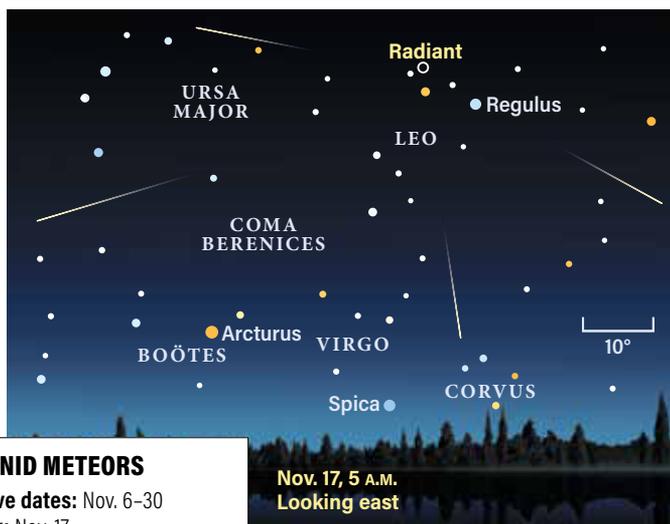
The Dragon's Mouth lies just south of the craters Henry and Henry Frères. What do you see?

CONSOLIDATED LUNAR ATLAS/UA/LPL. INSET: NASA/GSFC/ASU

location led observer Dave Gamble to imagine "a mouthful of very bright teeth." They are nothing more than random mountain peaks and the mind's fancy, but it's fun to observe and talk about them, especially when the illusion may come and go in a half-hour.

METEOR WATCH | Aim to be early

Leonid meteor shower 👁



LEONID METEORS

Active dates: Nov. 6–30

Peak: Nov. 17

Moon at peak: Waning gibbous

Maximum rate at peak:

10 meteors/hour

Nov. 17, 5 A.M.
Looking east

This year, the Leonids peak amid a nearly Full Moon's light, so consider looking for shower meteors a week earlier.

THE ANNUAL LEONID

meteor shower peaks Nov. 17 and is active between Nov. 6 and 30. The Full Moon on the 15th affects the visibility of this shower, so conditions are unfavorable for the peak. The zenithal hourly rate of 10 meteors per hour this year means that even by Nov. 16, very few shower members will be seen. Observing in the week prior to maximum is likely best, as the Moon will set earlier in the night and Leo rises near midnight. On Nov. 10, the Moon sets at local midnight just as Leo is rising in the east.

The Leonid meteor shower is associated with Comet 55P/Tempel-Tuttle, which last reached perihelion in 1998.

STAR DOME

HOW TO USE THIS MAP

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

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

10 P.M. November 1
8 P.M. November 15
7 P.M. November 30

Planets are shown at midmonth

MAP SYMBOLS

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

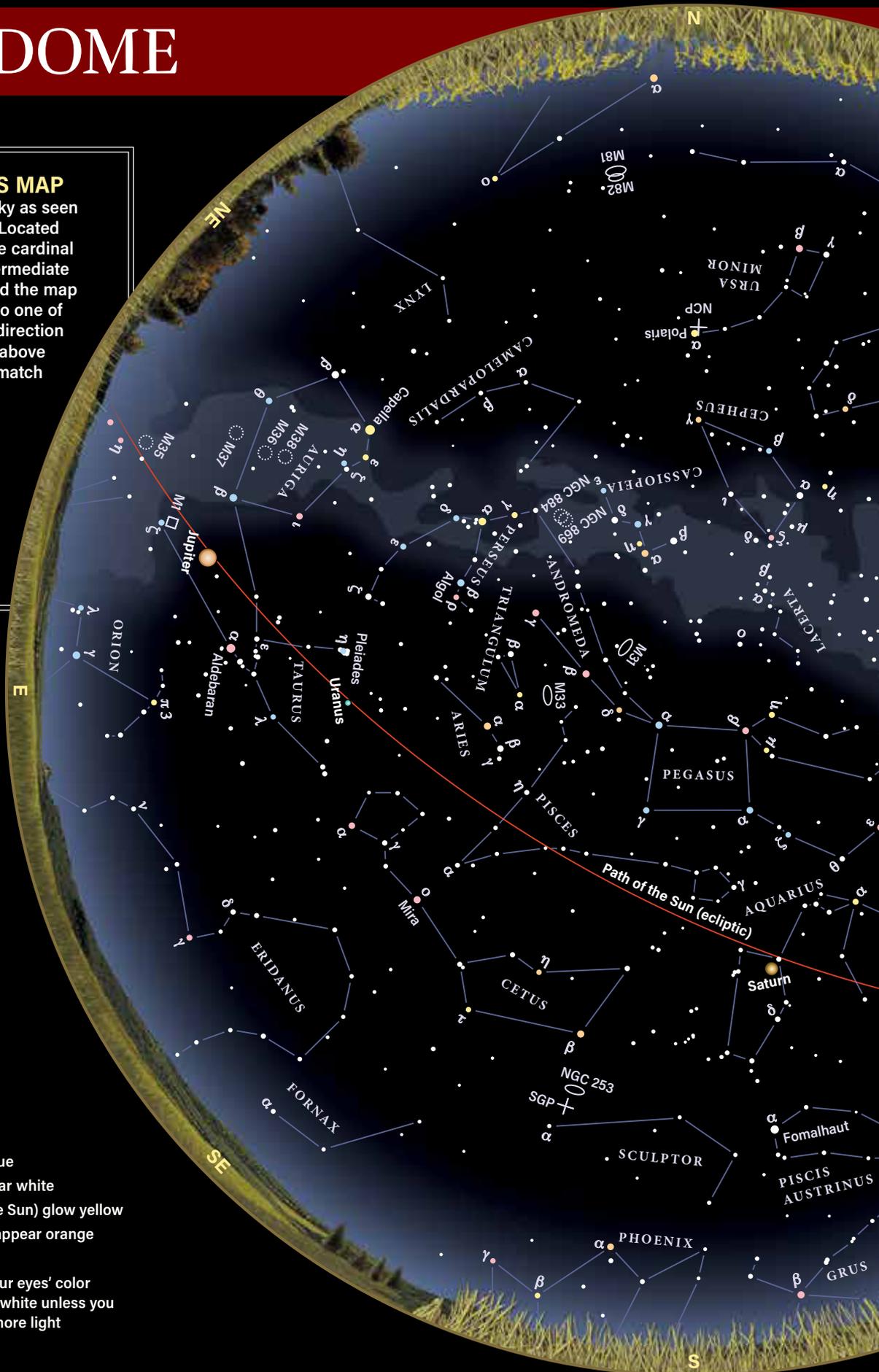
STAR MAGNITUDES

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

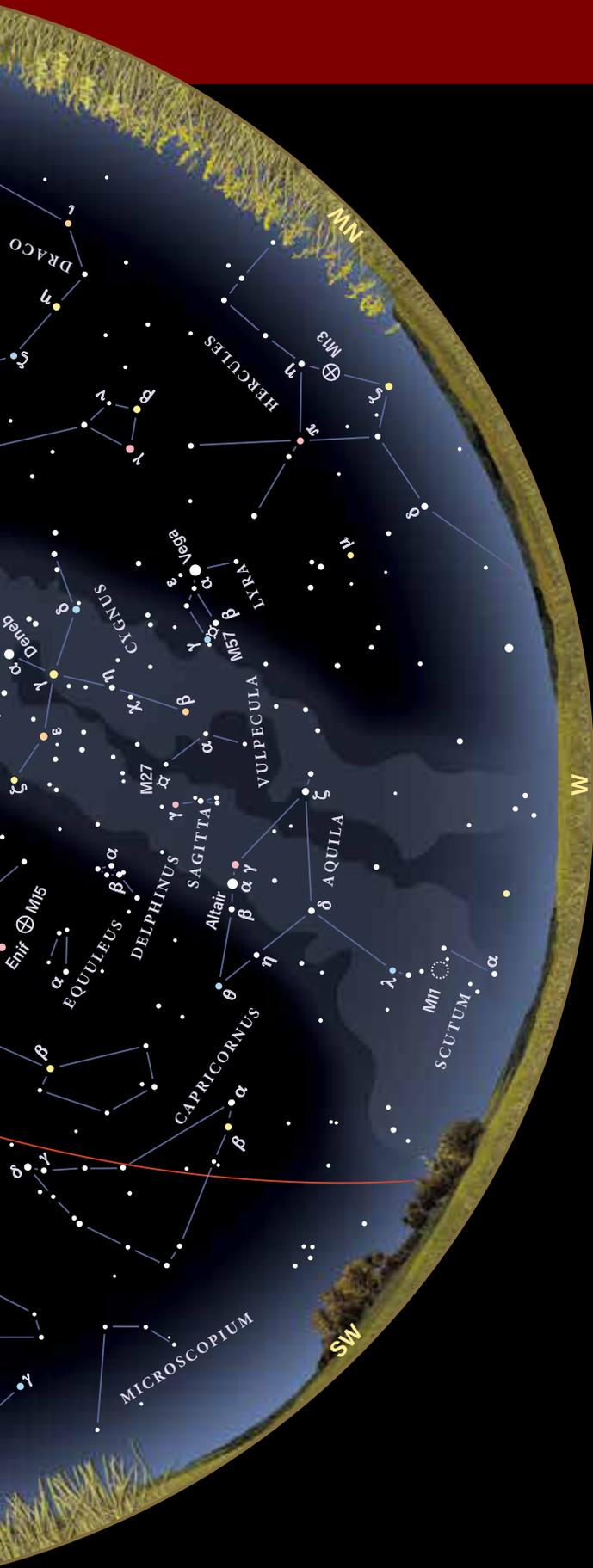
STAR COLORS

A star's color depends on its surface temperature.

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



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



NOVEMBER 2024

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

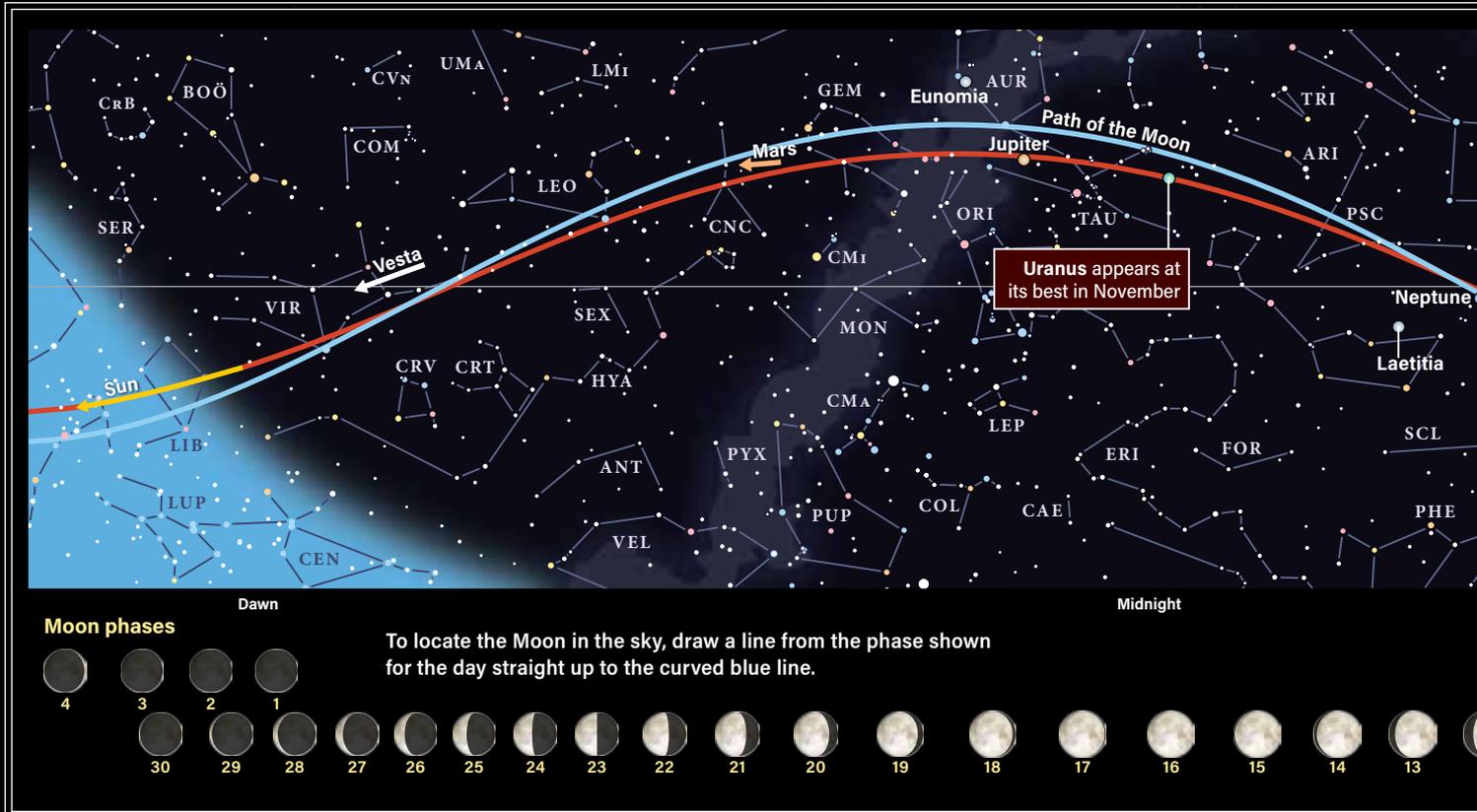
ILLUSTRATIONS BY ASTRONOMY ROBIN KELLY

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

CALENDAR OF EVENTS

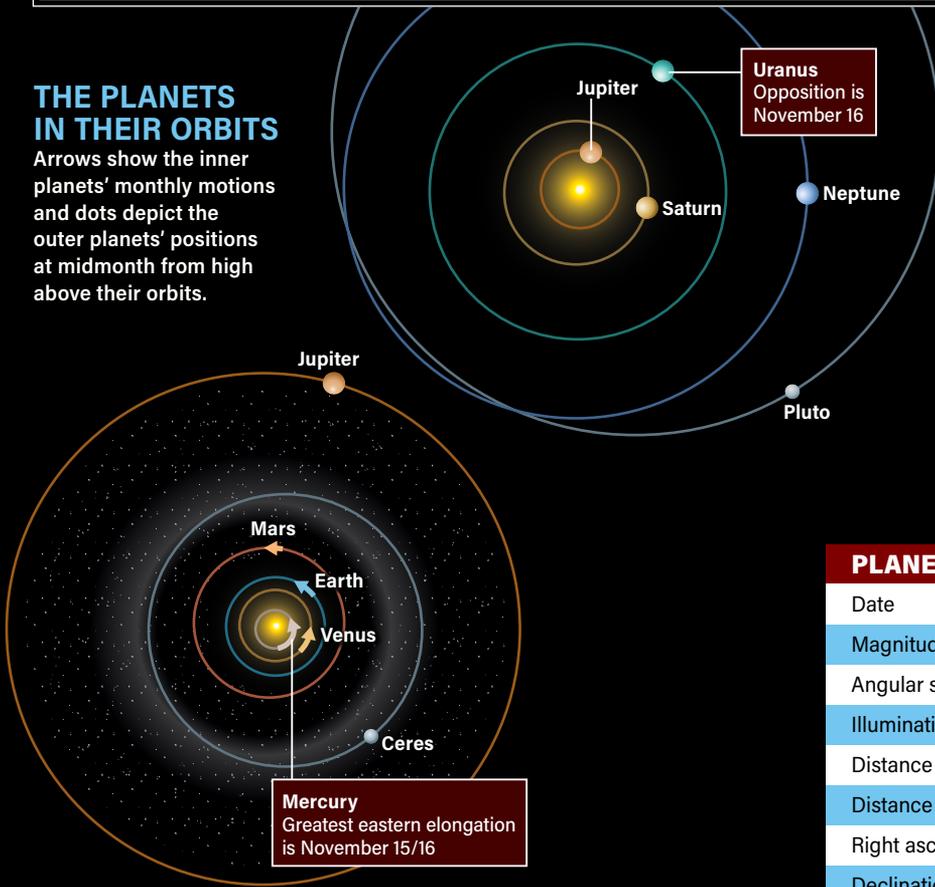
- 1  New Moon occurs at 8:47 A.M. EDT
- 3  The Moon passes 2° south of Mercury, 3 A.M. EST
The Moon passes 0.08° south of Antares, 8 P.M. EST
- 4  The Moon passes 3° south of Venus, 7 P.M. EST
- 9  First Quarter Moon occurs at 12:55 A.M. EST
Mercury passes 2° north of Antares, 11 P.M. EST
- 10  The Moon passes 0.09° north of Saturn, 9 P.M. EST
- 11  The Moon passes 0.6° north of Neptune, 9 P.M. EST
- 14  The Moon is at perigee (223,762 miles from Earth), 6:16 A.M. EST
- 15  Full Moon occurs at 4:29 P.M. EST
The Moon passes 4° north of Uranus, 8 P.M. EST
- 16  Saturn is stationary, 1 A.M. EST
Mercury is at greatest eastern elongation (23°), 3 A.M. EST
Uranus is at opposition, 10 P.M. EST
- 17  Leonid meteor shower peaks
The Moon passes 6° north of Jupiter, 10 A.M. EST
- 20  The Moon passes 2° north of Mars, 4 P.M. EST
- 22  Last Quarter Moon occurs at 8:28 P.M. EST
- 25  Mercury is stationary, 11 P.M. EST
- 26  The Moon is at apogee (251,850 miles from Earth), 6:56 A.M. EST
- 27  The Moon passes 0.4° north of Spica, 7 A.M. EST

PATHS OF THE PLANETS



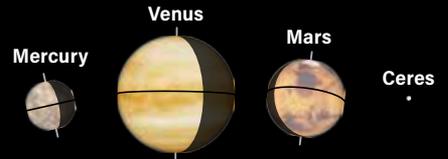
THE PLANETS IN THEIR ORBITS

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



THE PLANETS IN THE SKY

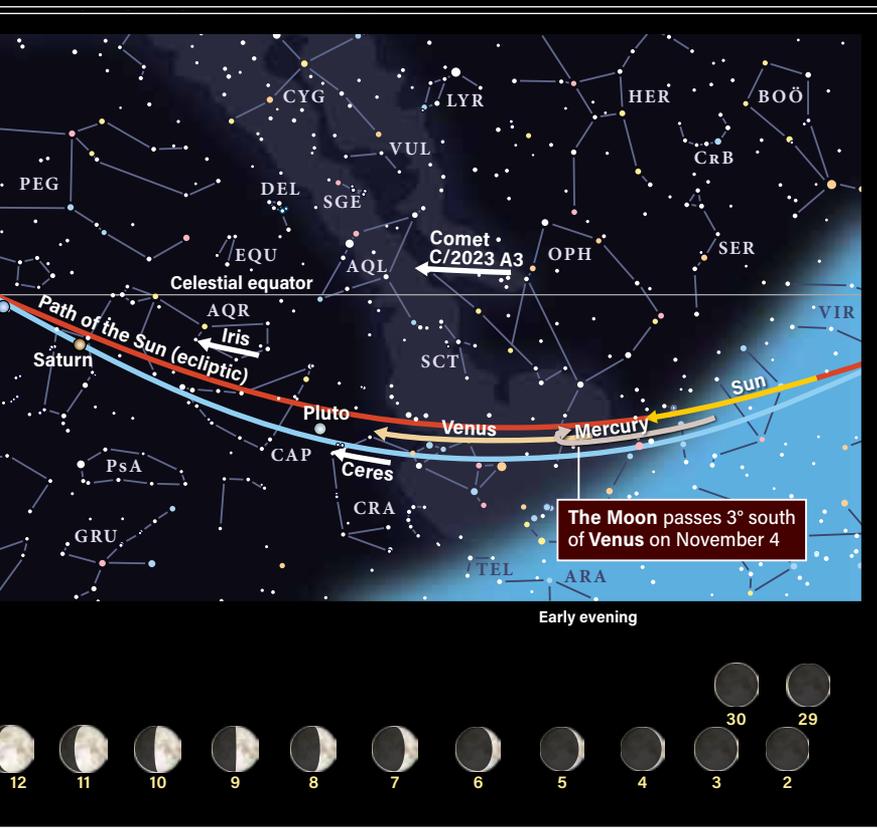
These illustrations show the size, phase, and orientation of each planet and the two brightest dwarf planets at 0h UT for the dates in the data table at bottom. South is at the top to match the view through a telescope.



PLANETS	MERCURY	VENUS
Date	Nov. 15	Nov. 15
Magnitude	-0.3	-4.1
Angular size	6.4"	15.4"
Illumination	66%	73%
Distance (AU) from Earth	1.046	1.084
Distance (AU) from Sun	0.401	0.728
Right ascension (2000.0)	16h54.1m	18h15.6m
Declination (2000.0)	-25°15'	-25°38'

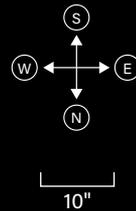
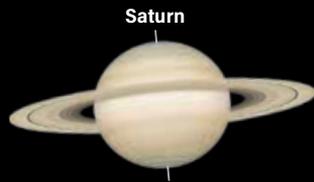
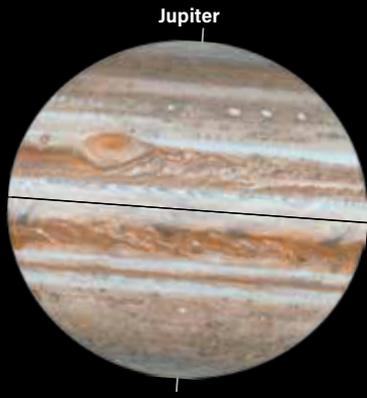
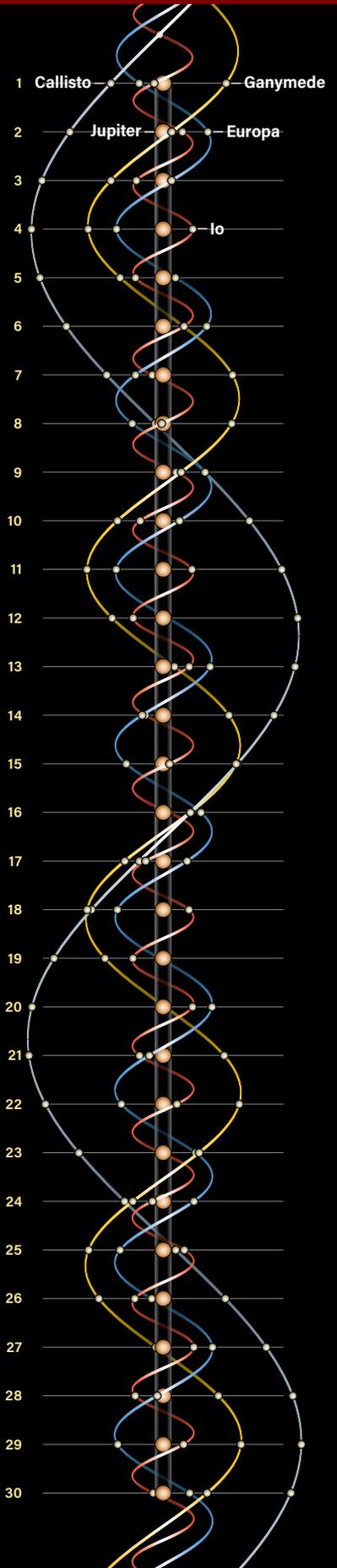
This map unfolds the entire night sky from sunset (at right) until sunrise (at left). Arrows and colored dots show motions and locations of solar system objects during the month.

NOVEMBER 2024



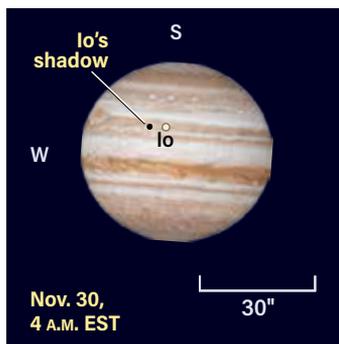
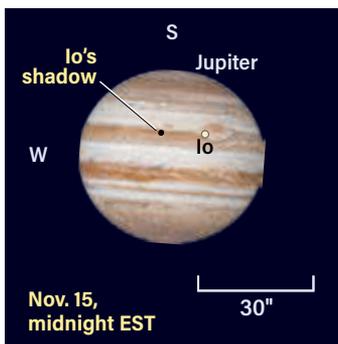
JUPITER'S MOONS

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



MARS	CERES	JUPITER	SATURN	URANUS	NEPTUNE	PLUTO
Nov. 15	Nov. 15	Nov. 15	Nov. 15	Nov. 15	Nov. 15	Nov. 15
-0.2	9.3	-2.8	0.8	5.6	7.7	15.3
10.2"	0.4"	47.4"	17.9"	3.8"	2.3"	0.1"
90%	98%	100%	100%	100%	100%	100%
0.917	3.338	4.160	9.268	18.573	29.329	35.516
1.561	2.964	5.067	9.645	19.561	29.896	35.139
8h22.5m	19h40.9m	5h11.7m	22h58.1m	3h30.8m	23h50.8m	20h09.9m
21°21'	-28°37'	22°16'	-8°52'	18°45'	-2°26'	-23°25'

Catching up



Note the shrinking gap between Jupiter's moon Io and its shadow as they transit the gas giant this month, once in mid-November and once at the end of the month. Although visible, the other Galilean moons are not shown here.

southern pole of Saturn prior to the Dione event. On the 26th, Dione leads Tethys across the disk. Not all events are listed.

Iapetus is close to Saturn the evening of Nov. 1, as it passes through superior conjunction. It lies 43" due south of Saturn, glowing near 11th magnitude. Track Iapetus until it reaches eastern elongation 8.5' east of Saturn on the 20th, when it glows near 12th magnitude.

Neptune is in Pisces, well placed for evening observing some 14° northeast of Saturn and near the Cirlet asterism. The distant planet shines at magnitude 7.7. Binoculars will show it forming a triangle with 20 and 24 Piscium, a pair of 6th-magnitude stars about 5° southeast of Lambda Psc in the Cirlet. Closer to Neptune is a pair of 8th- and 9th-magnitude stars sitting side by side. The planet's motion relative to these is evident from night to night.

A telescope reveals a 2"-wide disk with a bluish hue. A telescope is also needed to watch the Moon hide Neptune in an occultation the evening of Nov. 11, best seen from the eastern half of the U.S. Twilight will interfere farther west. The International Occultation Timing Association provides local timing of the event at

www.lunar-occultations.com/iota/planets/planets.

Uranus reaches opposition Nov. 16 and is visible all night. It's in western Taurus, about 6.5° southwest of M45, the Pleiades. At opposition, Uranus stands due south at local midnight; the planet rises by 7 P.M. local daylight time on the 1st

and three hours earlier (after the change to standard time) by the 30th. It moves slowly retrograde this month. The pre-dawn hours are a great time to view Uranus' 4"-wide disk with a telescope.

The easiest way to spot the magnitude 5.6 planet is with binoculars. Scan south of M45 to find 6th-magnitude stars 13 and 14 Tauri, aligned east-west. Uranus is 2.3° west and slightly south of 13 Tau on Nov. 1. The gap increases to 3.5° by the 30th. Uranus and 13 Tau are nearly the same brightness.

Jupiter rises by 8:30 P.M. local daylight time on Nov. 1 and by the 30th it's already up as twilight falls. Moving retrograde through central Taurus, Jupiter dominates the night sky. It's the best the gas giant has been for Northern Hemisphere observers in about a decade.

Jupiter brightens to

WHEN TO VIEW THE PLANETS

EVENING SKY

Mercury (southwest)
Venus (southwest)
Saturn (south)
Uranus (east)
Neptune (southeast)
Jupiter (east)

MIDNIGHT

Mars (east)
Jupiter (southeast)
Saturn (west)
Uranus (south)
Neptune (west)

MORNING SKY

Mars (southwest)
Jupiter (west)
Uranus (west)

magnitude -2.8 this month. At midmonth it stands 10° north-east of Aldebaran and nearly 19° northwest of Betelgeuse. A waning gibbous Moon joins Jupiter in Taurus Nov. 16 and 17. Jupiter remains above the

COMET SEARCH | Binocular bonanza

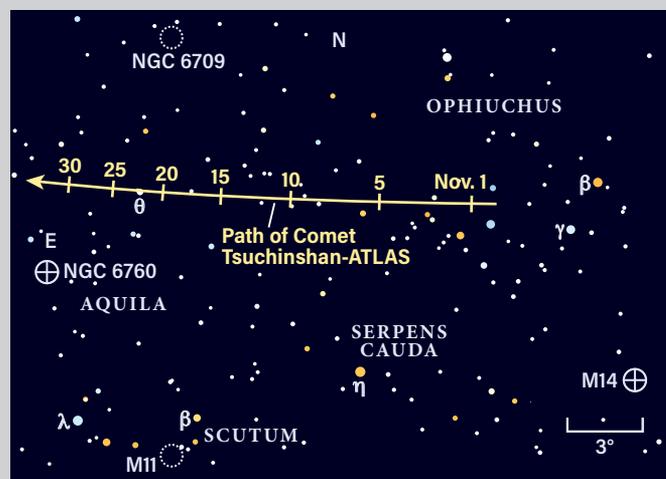
BEGINNING OCT. 28 and lasting through the first week of November, a short celestial sword crosses some of the most wonderful binocular star fields in the sky. Step outside and enjoy Comet C/2023 A3 (Tsuchinshan-ATLAS) with unaided eyes and see it next to splashy open star clusters with binoculars or a small telescope.

Travel to a dark spot on the 8th and 9th; ignore those who disparage the First Quarter Moon's light. If the sky is transparent, a 6th-magnitude comet will be a lovely binocular sight. Keep in mind it might be spring 2026 before we see another with unaided eyes.

Starting on the 19th, there's a whole hour of darkness before the Moon rises. But the comet's increasing distance from both Sun and Earth combine to quickly fade it past 8th magnitude by month's end as longer nights set in. Compare the fuzzball's shape and light profile to globular clusters M14 and NGC 6760. Which one is most pinpoint toward the center?

First detected only 21 months ago, Tsuchinshan-ATLAS reminds us that the comet of the decade could still be looping in from the depths, awaiting discovery.

Comet C/2023 A3 (Tsuchinshan-ATLAS)



Comet Tsuchinshan-ATLAS is fading, but not before it crosses the rich star fields of Ophiuchus and Aquila.

LOCATING ASTEROIDS |

Try your luck

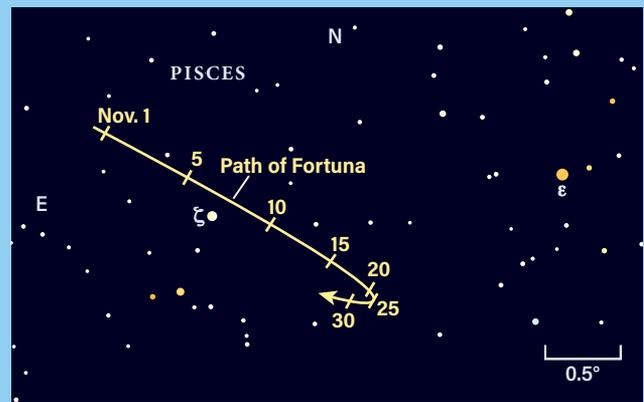
BY A STROKE OF LUCK, main-belt asteroid 19 Fortuna lies less than 2° from the showcase double star Zeta (ζ) Piscium. Easy at 25x in a 60mm scope, the slightly unequal stars glow with off-white shades in larger scopes, historically ranging from yellow to rose to lilac.

If you're star-hopping you'll know you're near the right spot because none of the other faintish stars of Pisces are similarly striking. From the suburbs, a go-to will really help. You'll want a 4-inch scope to pull the 10th-magnitude rock out of the pale gray sky. Orient yourself with the 6th-magnitude field star to the southeast and an 8th-magnitude star to the northwest, both about $30'$ away. Avoid the 11th through the 14th, when the Moon brightens the sky.

On the 5th, Fortuna forms an equal pair with a field star — Fortuna is the farther one from Zeta. It outshines any nearby stars on the rest of its track this month, except for the last week, when it fades below a 10th-magnitude star just to the south.

John Hind discovered Fortuna visually in 1852. It has a surface reflectivity darker than black dirt and is 140 miles across.

Brightest in the field



Fortuna passes close to double star Zeta Psc just after midmonth, before making a hairpin turn late in November.

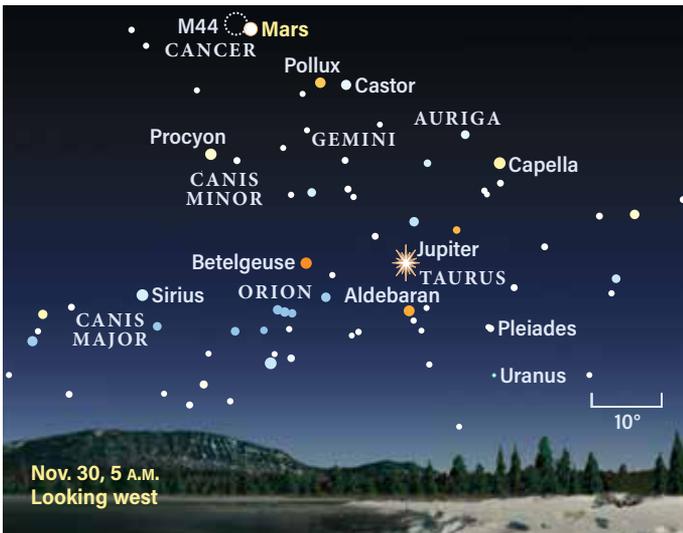
5th-magnitude Mu (μ) Cancri on the morning of the 2nd. Later in November, Mars stands 2° from the Beehive Cluster (M44). A waning gibbous Moon joins Mars in Cancer Nov. 20 and 21.

During the month Mars' disk grows from $9''$ to $12''$ and increases from 89 percent to 93 percent lit. The tiny disk is strongly affected by turbulence in Earth's atmosphere, but observing when Mars is highest in the sky (early morning) and using a high-speed planetary video camera can remedy this. Video capture takes practice — start now so you're ready for opposition early next year.

The Red Planet stands 70° high in the southern sky at 5 A.M. local time, with the following features visible at that time (determined for the mid-U.S.): Nov. 1 (local daylight time), Tharsis Ridge; Nov. 4 (local standard time), Valles Marineris; Nov. 9, Sinus Meridiani; Nov. 16, Syrtis Major and the Hellas Basin; Nov. 24, Mare Cimmerium. ☾

Martin Ratcliffe is a planetarium professional with *Evans & Sutherland* and enjoys planetary observing from Salt Lake City. **Alister Ling**, who lives in Edmonton, Alberta, is a longtime watcher of the skies.

Approaching the hive



By month's end, Mars stands near M44 in Cancer in the predawn sky. Uranus, below the Pleiades, requires binoculars to spot.

horizon for some 15 hours, allowing time to watch a full rotation (just under 10 hours) in a single night. By the 30th, the disk spans $48''$. Any telescope will show the pair of cloudy dark equatorial belts straddling the equator. If the Great Red Spot isn't visible, just wait a few hours. The wealth of detail visible is amazing — wait for those moments when our atmosphere settles and detail jumps out.

Io, Europa, Ganymede, and Callisto transit in front of or become hidden behind the disk from time to time. Here's a short review of some — but not all — of the month's events.

On Nov. 2/3, the giant shadow of Ganymede crosses the south polar region from 10:39 P.M. to 12:44 A.M. EDT. The transit is underway as Jupiter rises for the Mountain and Pacific time zones. (Note: Clocks change to Standard Time at 2 A.M. on the 3rd.) Shortly after 1 A.M. CDT (also 1 A.M. EST), Ganymede itself transits.

Europa and its shadow

traverse the planet Nov. 3/4. The shadow appears at 10:30 P.M. EST and Europa follows around 12:10 A.M. EST (on the 4th in the Eastern time zone only).

Ganymede and Europa repeat this sequence Nov. 9/10 and 10/11, respectively.

Io's shadow begins a transit on the 15th at 10:45 P.M. EST, followed 33 minutes later by the moon itself. Notice the gap between the shadow and the moon — it's diminishing as Jupiter approaches opposition. By Nov. 29/30, Io's shadow appears at 2:35 A.M. EST, just 12 minutes ahead of Io itself.

Mars is growing in brilliance in the morning sky as it crosses Cancer the Crab. As November opens, Mars glows at magnitude 0.1; it brightens to magnitude -0.5 by the 30th. Mars rises around 11:00 P.M. local daylight time on the 1st. By the end of the month, the Red Planet rises at 8:30 P.M. local time and stands 40° high in the eastern sky at local midnight.

Mars passes $7'$ north of



GET DAILY UPDATES ON YOUR NIGHT SKY AT www.Astronomy.com/skythisweek.

JWST discovers embryonic stars that retain the spin of their natal interstellar cloud.

BY RICHARD TALCOTT

SOMETIMES THEORY DOESN'T STAND UP TO observational scrutiny. The steady state model ended up on the ash heap of history when astronomers saw evidence that the cosmos is expanding. And the discovery that a mysterious force dubbed dark energy accelerates that expansion threw a monkey wrench into the idea that gravity alone shapes the universe's large-scale structure.

Yet theorists often hit the nail on the head. The latest example comes from the James Webb Space Telescope (JWST) and its deep image of the Serpens Nebula. Astronomers found 20 protostars there with their spin axes closely aligned, suggesting that they all formed at about the same time with the same spin that they inherited from a single filament of interstellar material.

GOING WITH THE FLOW

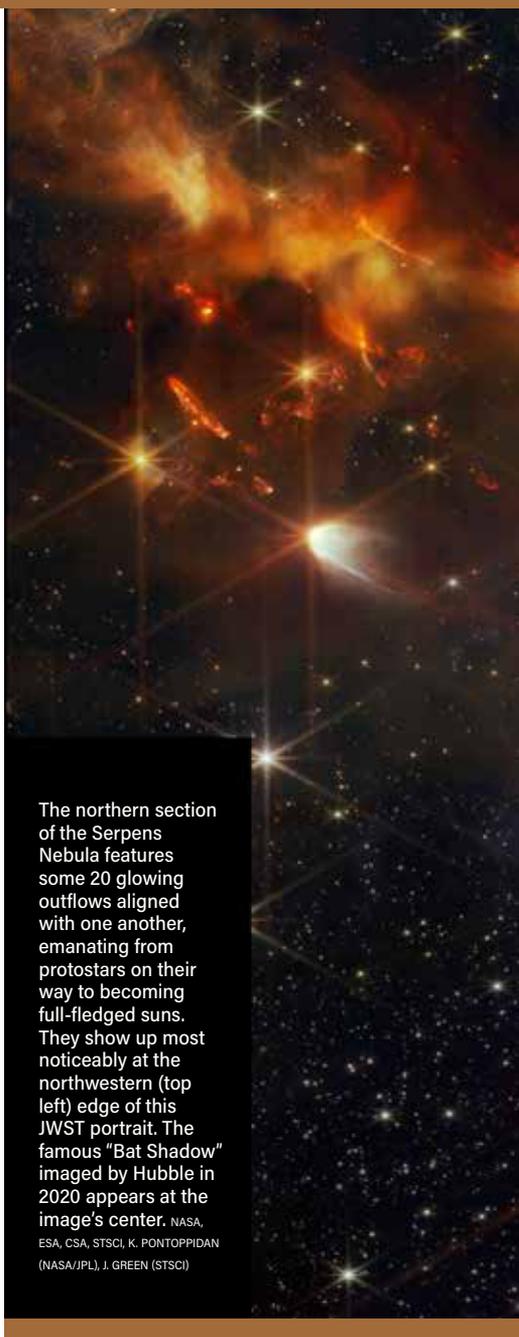
The Serpens Nebula lies about 1,300 light-years from Earth, making it one of the nearest regions of star formation. It began to coalesce 1 million to 2 million years ago and harbors a 100,000-year-old cluster of still-forming stars. The stellar grouping appears at the center of this JWST image, which encompasses the nebula's richer northern section. Most of the embryonic stars in this

region should grow into objects with the mass of the Sun or smaller.

JWST's unique combination of high resolution and sensitivity to near-infrared radiation allows it to penetrate the nebula's thick dust and see these protostars. "Webb is a young-stellar-object-finding machine," said Joel Green of the Space Telescope Science Institute in Baltimore in a press release. The lead author of a paper set to appear in *The Astrophysical Journal*, Green added, "In this field, we pick up signposts of every single young star, down to the lowest-mass [ones]."

These signposts appear as glowing outflows. In the early stages of a star's formation, matter falls toward the stellar embryo, causing it to spin faster. For gas to continue accumulating, the budding star must get rid of angular momentum. An accretion disk forms that lets material flow onto the growing sun like water circling a drain.

Magnetic fields in the inner part of the disk hurl some of the infalling matter into jets aligned with the protostar's spin axis and thus perpendicular to the disk. Moving at hundreds of thousands of miles per hour, the jets smash into clumps of surrounding gas, causing the molecular hydrogen and carbon monoxide there to glow.



The northern section of the Serpens Nebula features some 20 glowing outflows aligned with one another, emanating from protostars on their way to becoming full-fledged suns. They show up most noticeably at the northwestern (top left) edge of this JWST portrait. The famous "Bat Shadow" imaged by Hubble in 2020 appears at the image's center. NASA, ESA, CSA, STSCI, K. PONTOPPIDAN (NASA/JPL), J. GREEN (STSCI)

A STELLAR ALIGNMENT

If you look closely at the northwestern edge (top left) of the image, you'll see these glowing streaks have similar orientations, angling from upper left to lower right. They all fall within 24° of the long axis of the Serpens filament from which they

WHERE THE [PROTO]STARS



formed. The researchers estimate the chances of such a close alignment arising from a random sample of such jets to be 1 in 10,000.

“Astronomers have long assumed that as clouds collapse to form stars, the stars will tend to spin in the same direction,”

said principal investigator Klaus Pontoppidan of NASA’s Jet Propulsion Laboratory in Pasadena, California. “However, this has not been seen so directly before. These aligned, elongated structures are a historical record of the fundamental way that stars are born.”

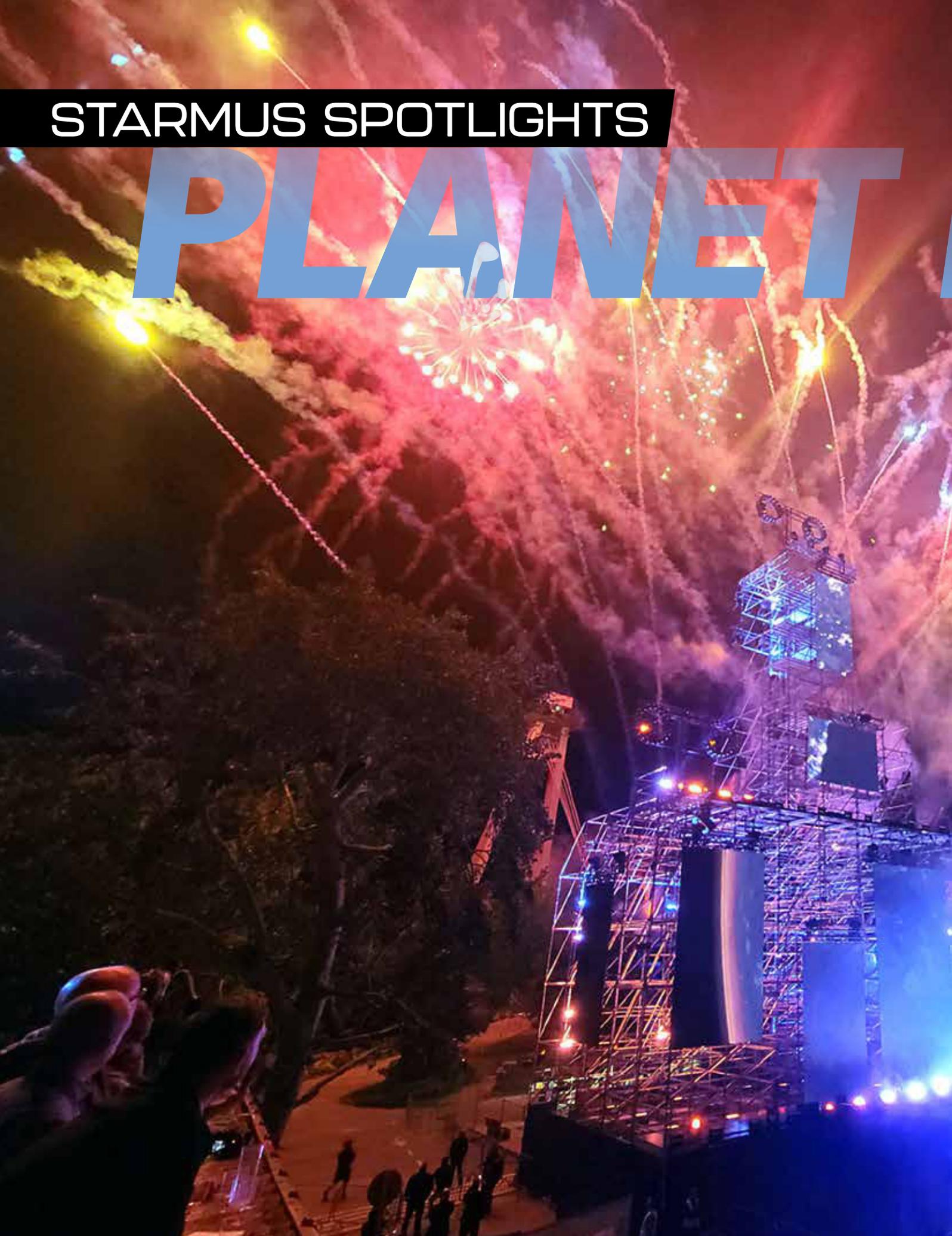
The researchers note that the jets align more closely in the northwestern sector compared with the southeastern. They suspect that the northwestern region is younger so that their spin axes have not had as much time for interactions with their surroundings to tweak them. The team next plans to investigate the nebula’s composition with JWST spectra. »

Contributing Editor **Richard Talcott** wrote about JWST’s observations of black hole and galaxy mergers in the infant universe in the October issue.

RS ALIGN

STARMUS SPOTLIGHTS

PLANET



EARTH



Starmus brought fireworks, music, and a focus on our fragile, wondrous world to the Slovakian capital of Bratislava.

BY DAVID J. EICHER

THE SEVENTH STARMUS FESTIVAL

took place May 12–17 in Bratislava, Slovakia, and was a smashing success all around.

Starmus stands for *stars* and *music*, and this celebration has grown into the greatest science festival in the world. It is the creation of astronomer Garik Israelian, the director, and his friend Brian May, who is an astronomer and the founding guitarist of the rock band Queen. The idea of Starmus is to exercise both the analytical and creative halves of the mind, exploring all the sciences and the arts to make the world a better place. The festival is famous for bringing together many Nobel laureates, astronaut-explorers, and top scientists and artists from all fields.

I've been delighted to be a member of the Starmus board along with Garik and Brian for years now, and was involved with the festival again this year. I hosted the opening day, delivered a talk on galaxies, participated in our press conference, and

◀ Starmus kicked off a spectacular concert event open to the public in Bratislava, which attracted some 25,000 to 30,000 people who flocked to the site. The brilliant electronic musician Jean-Michel Jarre took to the stage, aided by lasers and fireworks, and hosted special guest Brian May of Queen. DAVID J. EICHER



▲ Beautiful Bratislava, Slovakia, with its graceful castle, hosted Starmus VII, a short distance away from the metropolis of Vienna, Austria. DAVID J. EICHER. MAP BELOW: ASTRONOMY: ROEN KELLY

joined events centered on the board. It was my sixth Starmus, and once again a spectacular experience.

The stars come out

The night before the festival commenced, we staged a huge concert adjacent to one of the city's iconic features, the so-called UFO Bridge, which spans the Danube River and features a flying-saucer-shaped observation deck atop its pylon. The featured artist was the French master of electronic music, Jean-Michel Jarre, famous for some of the largest concerts in history. The amazed crowd swelled far beyond the arena that was built, spilling into the city and perhaps amounting to 25,000 to 30,000 people. Brian May joined Jean-Michel late in the show for some collaborative numbers, and it was a mesmerizing spectacle with countless lasers and a staggering number of fireworks. Luckily, it's not the last that we at Starmus will see of Jean-Michel: I am proud to say that he has joined our Starmus board.

The next day, Starmus began in earnest. This year's theme was Starmus Earth, and it reminded me of a saying we

have in the *Astronomy* magazine office — “Earth is a planet too.” It's the only one in the cosmos we know of that supports life, and we need to take care of it for future generations thousands and millions of years into the future. Climate change and associated topics were a big feature of the first day's talks, including the science of how putting so much carbon dioxide, methane, and other compounds into the atmosphere is transforming Earth in a bad way.



Opening-day speakers included the acclaimed primatologist Jane Goodall, celebrated for being the world's leading authority on chimpanzee behavior. (She's also a new member of our Starmus board.)

It is hard to think of many people in the world who are as inspiring to listen to.

We also heard from climate scientist Katharine Hayhoe of Texas Tech University, who gave an overview of where the climate change problem now stands, close to a dangerous tipping point. Nat Keohane, a former adviser to the Obama White House, described how capitalism has contributed to climate change — and may help to solve the



▲ *Astronomy* magazine Editor Dave Eicher, a member of the Starmus Board, opened the festival and hosted the first day of the talks. BRIAN MALOW

problem. International relations expert Mary Kaldor explored how war may be an anachronism. And legendary ocean explorer Sylvia Earle delivered a spectacular talk about the deep frontier of oceanography.

The talks rolled on, with a stellar lineup of scientific heavy hitters. Steven Chu — physics Nobel laureate, energy secretary under the Obama administration, and now professor at Stanford University — described the challenge of getting to net-zero greenhouse gas emissions. Columbia University climate scientist Maureen Raymo described the relationship between carbon dioxide and sea levels. Finally, panel discussions explored atmospheric rivers and the flow of temperatures and salinity in the oceans (climate researchers Ros Rickaby and Bob Bishop), as well as collapsing ice shelves in the Antarctic (climate scientists Svitlana Krakovska and Chris Rapley).



The festival's second day explored technological issues, beginning with a talk from Nobel-winning Norwegian neuroscientist Edvard Moser on whether humans are born with a sense of spatial awareness. Apollo 16 moonwalker Charlie Duke delivered a look ahead at

the Artemis program that will return humans to the Moon. Starmus board member Tony Fadell, inventor of the iPod and co-inventor of the iPhone, described how innovations could help to save the world. The world's leading expert on black holes, Kip Thorne, joined his artist

collaborator Lia Halloran to wow the audience with an illustrated exploration into the warped side of the universe.

The second day also included a talk by Richard Marko, CEO of the festival's primary sponsor, the Slovakian cybersecurity company ESET, on rethinking



▲ The Starmus director and founder, Garik Israelian, offers opening remarks to the festival crowd. DAVID J. EICHER

▲ A press conference describing the wide range of Starmus events featured board members including Eicher, Jarre, and May. MARIA FRIARGIU



▲ The mammoth Starmus opening night stage witnessed a crowd of about 30,000 in the city as Jarre and May lit up the night with an energetic show. DAVID J. EICHER

cybersecurity in the age of many global challenges. What does it take to keep all our data flowing across digital realms truly safe?

Two leading authorities on artificial intelligence then took the stage: Bernhard Schölkopf of the Max Planck Institute explored how intelligent AI really is, and his friend and colleague Philip Torr of the University of Oxford delivered a lecture exploring the future of this powerful tool. We concluded the second day of Starmus with a star party at Devin Castle, a magnificent medieval structure a short distance outside of the city. Two dozen or so telescopes were on hand, thanks in part to Scott Roberts of Explore Scientific and Franck Marchis of the SETI Institute and Unistellar. Their efforts enabled hundreds of participants to take in great views of the cosmos at a historic and visually overwhelming location.

Recognizing greatness

The third day of Starmus was a special one. We held the Stephen Hawking Medal Ceremony, in which we gave four special people the prize named for our beloved colleague. I was privileged to give the first to the great musician and avant-garde artist Laurie Anderson, a true lover of science and nature. We then awarded a Hawking Medal to Christopher Nolan, the Academy Award-winning filmmaker, and then another to the legendary David Attenborough, one of the world's foremost naturalists. The

final Hawking Medal went to pioneering oceanographer Sylvia Earle.

Following the Hawking Medal Ceremony, we presented what has become a Starmus tradition, the Sonic Universe Concert. This time, our amazing rock show featured The Offspring, along with Brian May (who offered a sizzling rendition of Queen's "Stone Cold Crazy"), the always-incredible keyboard work of Rick Wakeman, Tony Hadley of Spandau Ballet (who presented a spectacular rendition of the megahit "True," among others), and more.

On the festival's fourth day, we were back to business with talks. This day was heavy with Nobel Prize winners. Our

good friend Martin Rees, astronomer royal of Britain, delivered a talk about post-human intelligence. Renowned cosmologist George Smoot walked us through the history of cosmological thought and the known parameters of the cosmos. Michel Mayor, co-discoverer of the first exoplanet orbiting a Sun-like star, described the paradigm change we are undergoing in discovering vast numbers of planetary systems. And Laurie Anderson talked about building an ark for humanity. Can we somehow save the species we are endangering with the changing planet?

We continued with an array of imaginative and entertaining presentations. Anton Zeilinger explored randomness and reality, Donna Strickland described global environmental monitoring, and Kurt Wüthrich examined Brownian motion and protein dynamics in solution, investigating how proteins interact with their surrounding environments. Late in the day the group held a roundtable discussion in the restaurant atop the UFO Bridge featuring Jane Goodall, Tony Fadell, Laurie Anderson, Chris Hadfield, Dexter Holland, Garik Israelian, Katharine Hayhoe, and Steven Chu.

Our final day of Starmus festivities ended with a bang, and another full slate of talks. Astronauts led off, as Kathryn Thornton described the first Hubble servicing mission, which in 1993 fixed the optics of the now-iconic space telescope.

BRIGHT STARS MAKE A SHOWING



The legendary Jane Goodall, so well known for her research on chimpanzees, opens the festival with a talk about life on Earth and our planet's future.

DAVID J. EICHER



Rock stars aided Starmus with a series of concerts, including the leader and lead singer of Spandau Ballet, Tony Hadley, seen here with Maria Friargiu and Eicher. DAVID J. EICHER



▲ The opening festival concert featured priceless moments from Jarre and May.
DAVID J. EICHER

Chris Hadfield followed with a thought-provoking talk about space junk and how we can deal with the vast storehouse of debris in low-Earth orbit. Neil Lawrence of the University of Cambridge then spoke about what makes humans unique in the age of AI, and former NASA astronaut Garrett Reisman described innovation that he has experienced at both NASA and SpaceX.

I was privileged to help my old pal Robin Rees, publisher of the London Stereoscopic Company, with introducing

a film he has produced about the late, great Patrick Moore. We lost Patrick a decade ago, but this 40-minute film about his life, centered on an observational event to view the transit of Venus held at his house in 2004, will help us remember him well.

The final slate of talks commenced with Carole Mundell, science director for the European Space Agency (ESA), describing the wide range of recent and planned ESA missions and laying out plans for a truly exciting future. Dante Lauretta, the leader of NASA's OSIRIS-REx mission, delivered a report on its

findings at the rubble-pile asteroid 101955 Bennu and the samples the craft returned, as well as a vision for asteroid research in the future. (His recent 3D book on Bennu, co-authored with Brian May, was another stellar piece of work publicizing the mission's results.) Physicist Brian Greene gave us a forward look into the deep future of the universe.

A final panel discussion wrapped the event, this one discussing the sense and sensibility of pushing onward to human exploration of Mars. It featured an all-star cast of researchers and engineers, including planetary scientists Joel Parker, Patrick Michel, and Scott Hubbard, and astronaut Garrett Reisman.

Starmus will return

Thus we wrapped another edition of Starmus. I was exhausted at the festival's end, drained by a lack of sleep and a wealth of great discussions with renowned scientists and artists from all over the world. You'll see the results of some of these discussions in future editions of *Astronomy*. I invite you to stay tuned for those, and for news in the coming months on the next editions of Starmus, which will again bring incredible surprises. ♪

David J. Eicher is editor of *Astronomy*, author of 26 books on science and history, and a board member of the Starmus Festival and of Lowell Observatory.



The great oceanographer Sylvia Earle gives a state-of-the-art analysis of the crisis facing the world's oceans — and what we need to do about it. DAVID J. EICHER



One of the recipients of the Stephen Hawking Medal this year was Laurie Anderson, an amazing musician and avant-garde artist, seen here with Eicher, who gave her the award. DAVID J. EICHER



An authority on climate change, Katharine Hayhoe describes the current state of Earth as a planet and how we are affecting its future habitability. DAVID J. EICHER

MODEL ROCKETRY takes off in OREGON

The high desert offers the perfect launch pad for amateur rocketry enthusiasts.

BY LUCAS MARTIN; PHOTOS BY INGRID MARTIN



THE COMMUNITY OF BROTHERS is a place that seems to have slipped the passage of time. Located in central Oregon's arid landscape, it was once a stagecoach stopover for migrants bound for the Willamette Valley. The town eventually became one of the few to host a filling station in this great expanse, but today, the pumps stand empty.

Other than a clutch of prefab homes, a freshly painted historic schoolhouse, and a post office, the only indications of extant population are the pit toilets and picnic tables of the Brothers Oasis Rest Area. The view here is the same as from anywhere in Brothers: sage, greasewood, and cheatgrass spread to the horizon.

But look to the southwest on the right afternoon and you may see a

← FAR LEFT: A weathercocked rocket corrects course after launch.



surprise: the unmistakable snarl of rockets, trailing smoke as they streak across the sky.

Rockets in flight

Thanks to the nonprofit, member-based organization OregonRocketry, Brothers has found a new purpose as one of America's preeminent high-power rocket launch sites. OregonRocketry purchased the land in coyote country to create a mecca for amateur rocketry, and has a waiver from the Federal Aviation Administration to launch rockets nearly 20,500 feet (6,248 meters) into the air at any time. With approval, they can increase that height further, launching over 36,000 feet (10,973 m) above ground level. There are few places in the U.S. where amateur rocketeers regularly reach such altitudes.

"We get those high waivers because we're so remote; how high we can fly is dependent on our proximity to things like highways and occupied buildings," explains Robert Braibish, the equipment director of OregonRocketry.

To get to the launch site, a visitor must take a dirt access road 5 miles (8 km) south from Highway 20 to an area of rolling scrub land. OregonRocketry members were already fanned out among the sage, antennas and GPS receivers aloft, when my wife and I arrived to



↑ The rocket launch site is 5 miles southwest of Brothers, Oregon, far from any cities.

ASTRONOMY: ROEN KELLY

↓ Rockets are lined up at the OregonRocketry organization's launch site in Brothers.

Rocketober 2021. This was the club's largest launch of the year, and drought-induced fire hazard had closed the site all summer. Members were eager to fly.

I had never attended a rocket launch before, and anticipated something similar

to an especially technical fireworks show. This was no fireworks show, though; it was far more visceral. Countdowns were quick and staccato, like drumrolls over the loudspeaker, punctuated by the trumpet screech of launch. Again and again, 200 pairs of eyes followed smoke trails into the bright glare of the Sun, just able to catch the puff of gunpowder and flash of parachute that signaled a successful flight before returning to level to witness yet another fiery launch.

Safety first

There were five designated launch areas, or cells: one each for low- and mid-power rockets with five launch pads apiece, roughly 120 feet (37 m) from the tailgate line of tents and trailers and RVs; two for high-power rockets, with another five pads each, an additional 60 feet (18 m) out; and the last for the largest rockets allowed at the site, 900 feet (274 m) behind the line of people, cresting above the crowd atop a nearby butte.

Rocket motors are classified by their total energy. "Each designation doubles the total energy of the previous one, so a B is twice as powerful as an A, and C twice as powerful as B," Braibish explains.



Most model rockets run from Class A through E. High-power motors start at Class H and require federal certification to purchase. OregonRocketry regularly launches O-class rockets at Brothers, and though we didn't witness any of those, the handful of M- and N-class launches we saw mingled both awe and terror in my gut.

"We like to treat these things like weapons," Braibish says — and the club's procedures reflect that attitude. During a midmorning break, members registered a dizzying variety of rockets with the Range Safety Officer (RSO), the resident expert on rocket construction and site conditions. Each registration required a conference; some rocketeers left their slump-shouldered and frowning.

"The RSO is able to look at a rocket and ask: Have you connected all the parts? How is the motor built? How did you attach these fins? Is this the first flight? They ask all the questions that are relevant to ensuring a safe flight, which is obviously our highest priority," Braibish says.

Steady winds blew from the south both days of Rocketober, and one of the prevailing safety concerns involved weathercocking, an unwanted phenomenon that rocketeers try — and only sometimes manage — to mitigate. A rocket's fins stabilize its trajectory once in flight, but under the wrong conditions, they can divert it away from its intended direction. Wind currents blowing at ground level can catch fins at the moment of ignition, tilting the rocket's nose windward as it takes off. If high-altitude currents



↑ Gary Leach prepares his Aerotech ARCAS rocket for an early morning launch.

maintain the force of those nearer the ground, the rocket tends to correct course. If not, it continues on its weathercocked trajectory, blasting off in occasionally nerve-wracking deviations from plumb.

The landscape here challenges rocketeers in a way others don't. Though popular imagination focuses on the inferno of launch and elegance of ascent, rocketeers are equally concerned once a rocket reaches apogee — the point of maximum height above Earth. Gunpowder charges split the rocket soon after it begins descent, releasing a parachute or series of parachutes. It slows first to 50 feet (15 m) per second then to 25 feet

(7.6 m) per second, gyrating across the blue sky before crumpling into the sage. That's when the fun begins.

"Our site on a map looks kind of flat, but in reality, it's not," says Jack Caynon, the current president of OregonRocketry, who has flown at Brothers since 2005. "You think your rocket's in that flat area over there when actually it's in a crevasse. Sighting along the sagebrush is difficult because there's a thousand of them and one looks just like another."

To make recovery easier, Caynon uses an onboard radio tracker. "By sweeping the antenna, I can pinpoint the direction of the rocket. It takes me 10 or 20 minutes maybe to get to the rocket, but I find it without fail."

Not all recoveries go so smoothly. Over the course of a windy October day, I watched half a dozen rocketeers return to camp emptyhanded, kicking dust and cursing deceptive sightlines or faulty transmitters. I witnessed a dozen more bearing crippled rockets. Parachutes didn't deploy in time or at all, and months of work culminated in crash landings on high-desert hardpan.

But the biggest danger at Rocketober, lurking between the thirsty sage, is fire. Between the use of highly combustible materials and an ignition source, the hobby can lead to dangerous consequences.

"Fire has become the No. 1 concern out here over the past five years. We've been here 20 years or so, and even five years ago we launched throughout the



↑ Chuck and Karen Fauser search late-season sage for their rocket using a handheld radio antenna.

summer, no problem,” says Gary Goncher, a former president of OregonRocketry. “But we don’t launch in July, August, or September anymore.”

The club is proactive about fire safety — they keep a water truck and several dozen extinguishers nearby during launches. Equipment is maintained and stored by the local Rangeland Fire Protection Association (RFPA), a volunteer group that works with federal agencies to suppress and respond to wildfires.

“We’ve become very active in our local RFPA. About 20 rocketeers are actually

Flying toward the future

Amateur rocketry in America’s high desert is an expression of both our enigmatic past and our technological, heat-ridden future.

The rocketeers carefully follow launch rituals before experiencing the ecstasy of apogee and the agony of recovery. Hearts quicken as eyes turn skyward, hands ubiquitously raised to brows, warding off midday desert sunlight. After the parachutes deploy, rocketeers wander the withered sage with errant sunspots still swirling in their eyes, and antennas aloft.

Rockets are a symbol of modernity,

“Fire has become the No. 1 concern out here over the past five years.”



members now, and I think we outnumber the locals,” Goncher says.

A learning experience

Goncher served as RSO the second day of Rocketober, and he had his hands full. Because Brothers is one of the country’s premier sites for high-power rocketry, college students from across the Northwest flock here to get certified with the National Association of Rocketry before competing in the annual intercollegiate Spaceport America Cup in New Mexico. They come in fresh-faced droves, draped in school colors and determined to push the boundaries.

“Sometimes students want to be so spectacular, and to do things off the wall, but they don’t need to,” Caynon explains. “But the Blue Origin and SpaceX people show up to a banquet [after the Spaceport America Cup]. They’re looking for people who can think outside of the box and solve problems on the fly.”

The names of private space agencies rang from every tongue with a talismanic quality out on the steppe. “As a society, we’re starting to get to a point where rocketry seems the next step,” Braibish says. “You see where things are going with SpaceX and Blue Origin; there is obviously going to be an increase in demand for that kind of engineering and that type of student.”

and of our new gilded Space Age. But while a ticket on a SpaceX or Blue Origin ride remains out of reach for all but the ultra-wealthy, amateur rocketry evokes a vision of the future where anyone can be a citizen rocket scientist and explore their environment.

Caynon says the amateur rocket community is eager to work with students or researchers to put their expertise to scientific use. “We can launch several types of packages for scientific purposes on our rockets, like how to measure the ozone or monitor sunspot activity, and we can run the same types of sounding rocket experiments as NASA,” he says. “Maybe college students have come up with a CanSat” — a miniature satellite-style payload small enough to fit in a Coke can — “and they just need someone to fly it for them. Our guys would be happy to do that, and I think both students and rocketeers would learn something.”

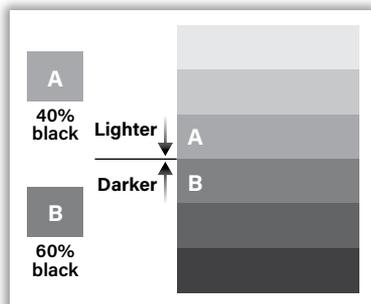
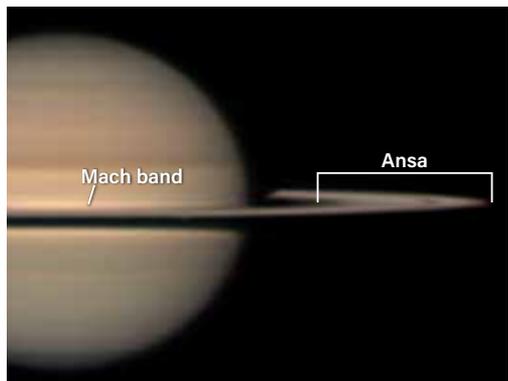
So while some of the young scientists getting certified at Rocketober may one day settle Mars for Musk or build space casinos for Bezos, it may be the planet Earth that is the true beneficiary of these wild-eyed rocketeers roaming the high desert. ♡

Lucas Martin is a freelance writer working out of Oregon, with a focus on astronomy and the high desert.



A Saturn ring mirage

Averted vision can result in unexpected effects.



TOP: A photo-illustration of the optical illusion known as Mach bands, as seen on Saturn.

ASTRONOMY: ROEN KELLY AFTER ETHAN CHAPPEL

ABOVE: The Mach effect occurs when a light and dark object are adjacent, causing brighter and darker bands to appear at the edges. ASTRONOMY: ROEN KELLY



BY STEPHEN JAMES O'MEARA
Stephen is a globe-trotting observer who is always looking for the next great celestial event.

→ Roughly every 15 years, Earth passes through the plane of Saturn's rings, causing them to nearly disappear from view — not to mention generating a variety of other interesting phenomena. The next such edge-on appearance will be in March 2025, though Saturn will unfortunately be too close to the Sun

(only 9.5° away) for us to enjoy it.

This year, though, the rings narrowed to a minimum on June 25, tilted just 1.9° from edge-on. This is when I found a fascinating optical phenomenon at play — one that might make you think twice as to whether what you are seeing is real.

On the morning of June 9, I was showing my wife, Deborah Carter, Saturn in bright twilight through my 3-inch Tele Vue refractor. As I described the planet and the near-edge-on appearance of the rings (2.0°), she picked out several features, including the narrow rings on either side of the planet, the shadow of the planet on the rings, and vice versa. However, neither of us could see the rings passing in front of the globe.

After a prolonged study of the ring's shadow with direct vision, I averted my gaze toward one of the rings' ansae — the bright "handles" that appear on either side of Saturn where the rings arc around the planet. Suddenly and fleetingly, I saw what appeared to be the full extent of the rings cutting across the face of the planet. They appeared bright against the planet's equatorial belt and hugged the northern edge of the ring's shadow — although I was suspicious.

At and near the center of the planet, the rings appear highly foreshortened, appearing much thinner than they do at the ansae. Furthermore, ring-particle shadowing effects make that projected section of the ring appear darker at center than they do at the ansae. What I saw had to be an illusion.

Indeed, I later recalled an observation made by American astronomer Edward Emerson Barnard. On Oct. 26, 1891, Barnard used the 12-inch refractor at Lick

Observatory to study Saturn when the rings were tilted only 1.6° from edge-on. Even with magnifications of 150x, 175x, and 500x, he reported the rings were invisible. He was struck, however, by an important visual effect: "Looking at the black trace on the ball, and then glancing at the sky near the sides of the planet, I could, apparently, see the rings for a moment as a faint line of light on the dark sky. I satisfied myself beyond question that this was an optical phenomenon."

Barnard believed the faint line of light was an after-image of the ring's shadow. "I mention this," he wrote, "as it might some time mislead an observer, who would think he had glimpsed the real ring. Perhaps this same phenomenon has a bearing on other kinds of astronomical observations."

With these words in mind, I observed Saturn again on the mornings of June 18 and 19, following the planet well into twilight. While my observation and Barnard's were different, both dealt with the ring's shadow. After staring at the ring's shadow for a prolonged period of time and then averting my gaze to the side of the planet, I could create a similar, albeit fleeting, optical illusion that exaggerates the edge of the bright equatorial zone next to the ring's shadow. This phenomenon is known as a Mach band, or the Mach effect. It's an optical illusion where the edge of a bright object next to a dark object appears even lighter, and vice versa.

One can also see Saturn's rings projected a short way across the face of the planet, where they taper like pinners. I found that the best time to see this ring aspect is during bright twilight when contrast between the planet and the sky is at its lowest. I call it "ghosting" because the appearance through a small telescope looks like a ghostly apparition.

Saturn's rings opened from about 2° in June of this year to between 4.5° and 5° in October. So it should now be possible to resolve Saturn's ring across the planet under sufficient magnification and excellent seeing conditions. This gives us a splendid opportunity to observe the visual aspect of the narrowly opened ring before it starts to close by the beginning of December. By the time we lose

Saturn to the Sun's glare in February 2025, the rings will be less than 3° from edge-on. I'll be most interested in knowing what you see or don't see before this time. The real challenge will start when Saturn reemerges into the morning twilight in early May 2025 and the rings will be opening to 2° again.

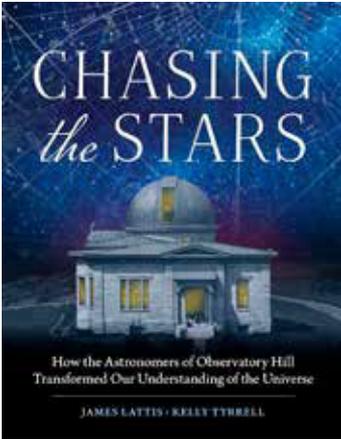
Be sure to send observations with time and date, telescope used, magnifications, and the state of the atmosphere to sjomeara31@gmail.com.

What I saw had to be an illusion.



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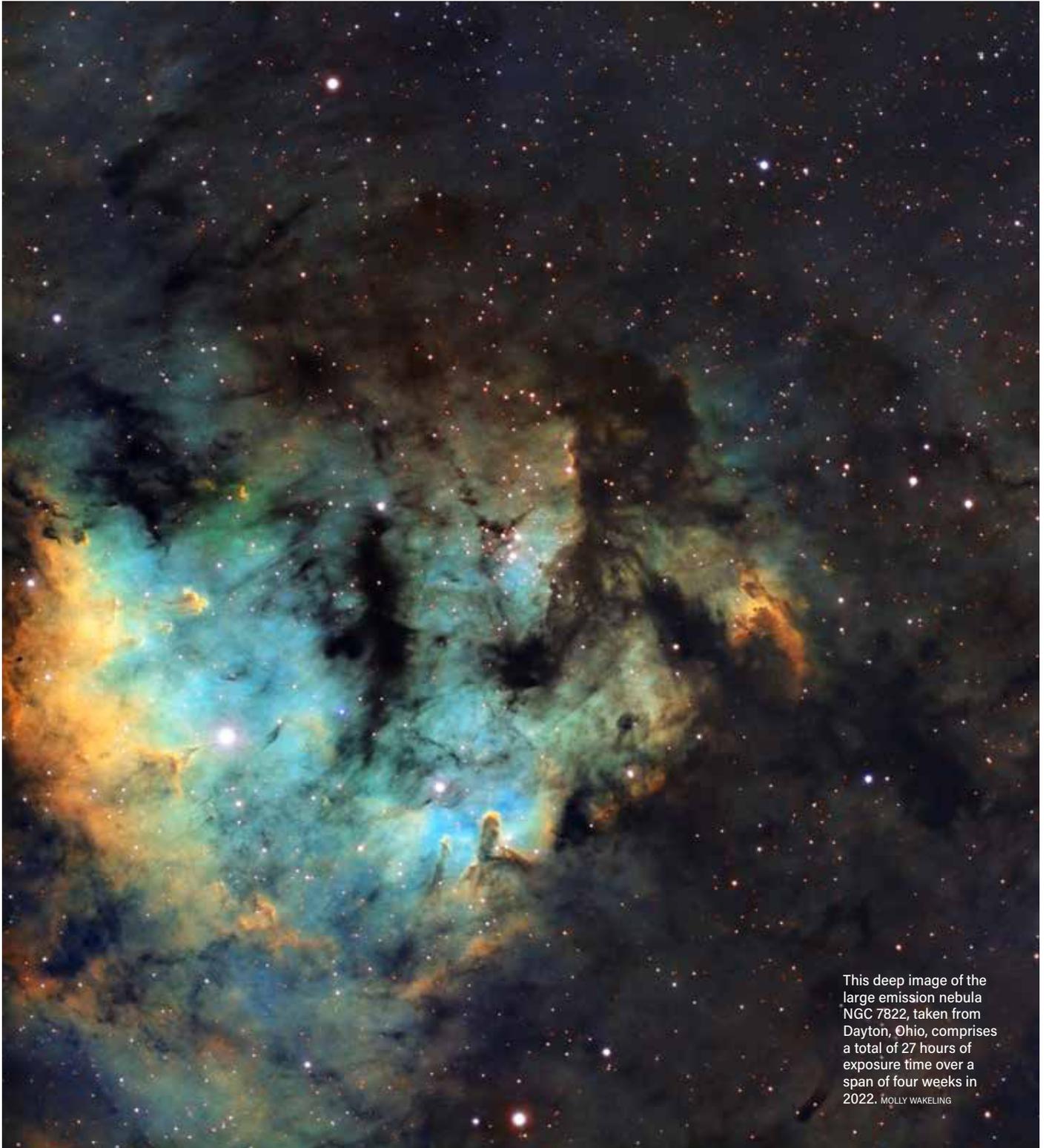
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Long-exposure astrophotos



This deep image of the large emission nebula NGC 7822, taken from Dayton, Ohio, comprises a total of 27 hours of exposure time over a span of four weeks in 2022. MOLLY WAKELING

Q | MANY ASTROPHOTOS FEATURE EXPOSURES OF 12 HOURS OR MORE. SINCE NIGHTTIME DARKNESS IS ONLY ABOUT THIS LONG, THIS IMPLIES MULTIPLE EXPOSURES ON DIFFERENT NIGHTS. HOW DOES ONE SET THINGS UP TO GET THE EXACT SAME LOCATION, AND AVOID PARALLAX ERROR DUE TO EARTH'S ROTATION AND ORBIT?

*Jose G. Riera
St. Augustine, Florida*

A | You are correct, many long-exposure astrophotos span multiple nights. I typically stay on a target for months at a time, especially when I'm living in a cloudy place. Plus, viewing locations often have a tree or a building or some other obstruction, meaning that many objects are only visible a few hours per night. And because it is best to image objects that are at least 20° or so above the horizon to avoid the thickest lines-of-sight through the atmosphere, your window may be further limited.

Astrophotos usually consist of dozens to hundreds of multiple-minute exposures that are "stacked" together to reduce noise and bring out the dim celestial object being imaged. The computerized telescope mounts astrophotographers use to track the sky know where to point based on the mount's latitude and longitude, and the date and time. With the help of plate-solving software that uses star patterns to identify where an image is located on the sky, it is easy to return

WE CANNOT TRULY SAY THE UNIVERSE IS EXPANDING "INTO" ANYTHING ELSE.

to the exact same celestial location every night.

The effect of parallax, the shifting of nearer stars relative to those farther away as Earth travels around the Sun, is negligible — the nearest star, Proxima Centauri, only appears to move 0.77" over the course of a year, which is only a few camera pixels with long-focal-length telescopes and is less

than 1 pixel for shorter telescopes.

*Molly Wakeling
Contributing Editor*

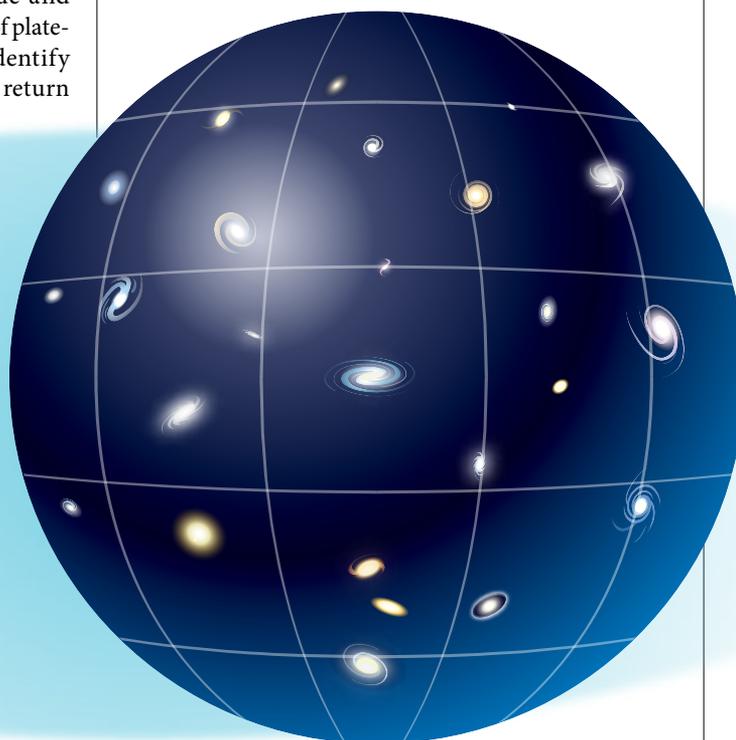
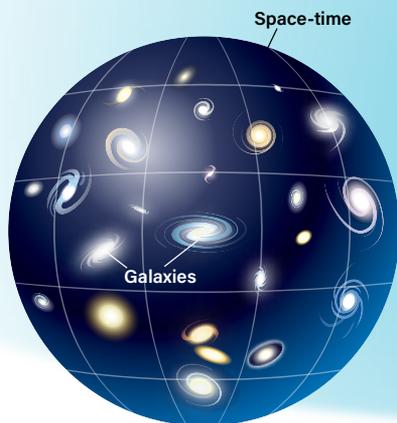
Q | WHAT IS THE UNIVERSE EXPANDING INTO?

*Euan Tobin
Edinburgh, Scotland*

A | This excellent question forces us to confront a region beyond the bounds of our intuition, so please bear with me. When you inflate a balloon, the balloon's membrane moves outward, closer to the boundaries of whatever room encloses it. You can easily visualize this expansion because one object is inflating relative to a fixed enclosure.

The notion of the expansion of the universe is more problematic because the universe contains everything — it is a closed space-time system. One could say that the universe isn't expanding into anything because the

THE EXPANDING UNIVERSE



If you imagine the expanding universe like the surface of a balloon, you can see that as the balloon (our stand-in for space-time) expands, galaxies are carried along with it. Because space-time itself is expanding, the universe is not expanding into anything. *ASTRONOMY:*

ROEN KELLY

question implies that something exists “outside” the universe, which is nonsensical, as “outside” is a spatially relative term.

However, such an answer is unsatisfactory. Let’s return to the balloon. This time, let’s draw a series of black dots along the membrane. As the balloon inflates, the dots appear to be moving away from each other. From the perspective of one dot, the more distant dots move away more quickly than those closer to it. As the membrane expands, the dots grow farther apart. In this example, the dots represent the galaxies, while the membrane represents the finite yet unbounded universe. You could travel along the balloon but never come to the “end,” as it is literally unbounded. And though the balloon’s surface might not be infinite in extent, it is not defined by an outer boundary. (Note that a shortcoming of this balloon analogy is that it tries to represent three-dimensional reality along a two-dimensional shell.)

Universal expansion causes galaxies to recede from each other. Galaxies close to us recede at a slower rate than those farther away. As demonstrated by the balloon model, the space-time “fabric” is what is expanding, and the material embedded within it — namely galaxies — moves apart in response to this expansion. We cannot truly say that the universe is expanding “into” anything else. There is no fixed center, nor is there any rigid outer boundary. It is merely expanding, just as the balloon membrane expands — albeit in three spatial dimensions instead of two.

Edward Herrick-Gleason

Astronomy Educator, St. John’s, Newfoundland and Labrador

Q | WITH THE MOON’S TERMINATOR MOVING ALMOST 10 MPH (16 KM/H) ACROSS ITS EQUATOR, HOW LONG WOULD IT TAKE FOR AN OBSERVER USING BINOCULARS TO NOTICE A CHANGE IN LUNAR FEATURES?

Gary Garchar
San Jose, California

A | The lunar terminator, the sunset/sunrise line that sweeps across the Moon’s surface as the Moon orbits Earth, travels at a rate of 9.6 mph (15.4 km/h) along our satellite’s equator. Taking the average Earth-Moon distance to be 239,000 miles (384,600 km), those miles translate to an angular shift of just over 8” per hour.

So how much time would have to elapse before binoculars could detect a shift that an observer could detect? The resolving ability of a telescope is dictated by aperture, assuming high-quality optics. The low magnification of binoculars, however, usually makes that value the determining criterion.

Assuming the observer has 20/20 vision, we can estimate the minimum resolution value for binoculars by dividing its magnification into 240. Using this, we find that 10x binoculars have a resolution threshold of 24”, while 15x binoculars can resolve 16”, and so on.

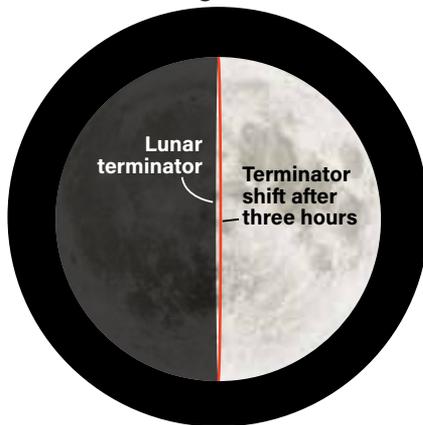
So, given all these facts and figures, steadily mounted 10x binoculars should be able to detect a shift in the terminator after about three hours.

But that’s only on the Moon’s equator for when the terminator is exactly on the lunar meridian, at the quarter phases. As soon as we move off that point, then the foreshortening effect caused by the Moon’s spheroidal globe comes into play. In other words, the terminator’s speed slows down as you move toward the lunar poles. For the terminator’s speed at other lunar latitudes, multiply its equatorial speed by the latitude’s cosine.

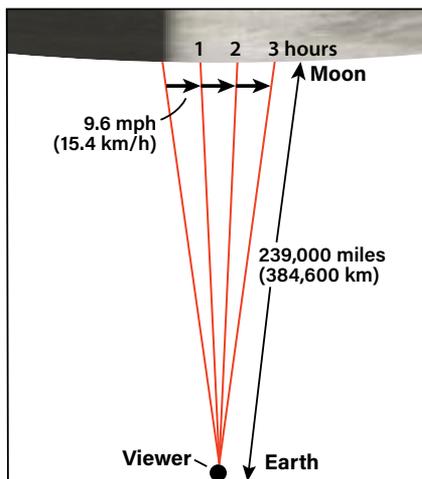
For instance, at 45° north or south lunar latitude, midway between the equator and the poles, the terminator moves at about 70 percent of its speed at the equator. At the Moon’s average distance, that translates to

TRACKING THE TERMINATOR

View through binoculars



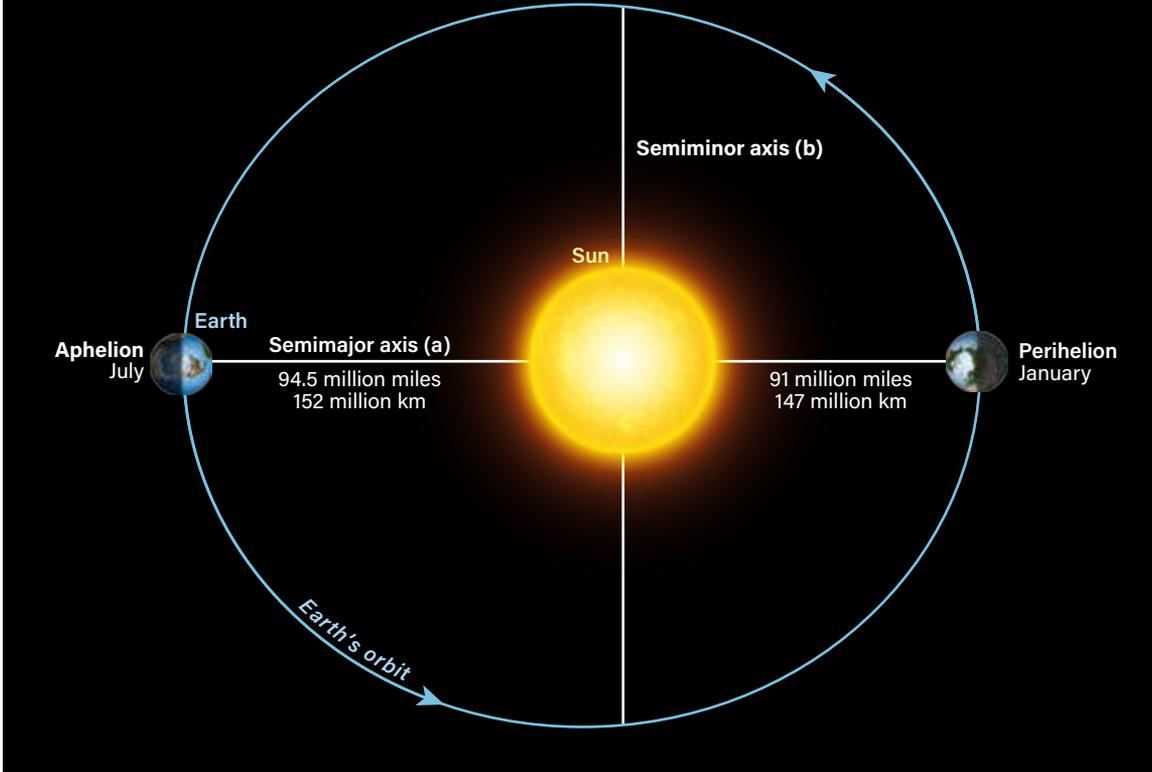
Top view looking down on Earth



The Moon’s terminator appears to move about 8” in an hour at its equator, which means it takes several hours before a viewer will notice new features using binoculars. *ASTRONOMY*

ROEN KELLY

EARTH'S ELLIPTICAL ORBIT



Earth's orbit is not a circle, but an ellipse with the Sun at one focus. Using the semimajor and semiminor axes of our planet's orbit, we can estimate the perimeter of the ellipse it traces out each year. To calculate this, the axes are measured from the center of the ellipse.

ASTRONOMY: ROEN KELLY

6" per hour. Therefore, it would take about four hours to see the effect of motion there through our 10x binoculars.

The same would be true for a shift in longitude, either east or west of the lunar meridian.

Phil Harrington
Contributing Editor

Q | HOW BIG IS THE ELLIPSE THAT OUR PLANET TRAVELS IN A YEAR AROUND THE SUN?

J.J. Müdspacher
Mexico City, Mexico

A | Earth's orbit around the Sun is not circular, but an ellipse that is slightly elongated with an eccentricity of 0.017. (An eccentricity of 0 is a circle, while the dwarf planet Pluto has a relatively high orbital eccentricity of 0.244. The maximum eccentricity possible is 1, which forms not a closed orbit but a parabola, meaning the object will never complete a full orbit but instead be flung off into space.)

The difference between perihelion, when Earth is closest to the Sun, and aphelion, when Earth is farthest from the Sun, is only about 3 percent, or roughly 3 million miles (4.8 million kilometers). At perihelion, which occurs in January, Earth is generally about 91 million miles (147 million km) from the Sun; at aphelion in July, Earth is about 94.5 million miles (152 million km) from the Sun.

To calculate the size (perimeter) of the ellipse Earth travels each year, we need its semimajor axis (a) and semiminor axis (b). NASA gives the semimajor axis of our planet's orbit as nearly 93 million miles (149,598,000 km). From this value and the eccentricity e of Earth's orbit (0.017), we can calculate the semiminor axis of Earth's orbit by rearranging the equation to calculate eccentricity:

$$e = \frac{\sqrt{a^2 - b^2}}{a}$$

into

$$b = a\sqrt{1 - e^2}$$

From this, we find that Earth's semiminor axis is 92.9 million miles (149,577,140 km).

Although there is no simple formula to calculate the perimeter C of an ellipse, it can be approximated by

$$C \approx \pi(a + b) \left(3 \frac{(a - b)^2}{(a + b)^2 \left(\sqrt{-3 \frac{(a - b)^2}{(a + b)^2} + 4} + 10 \right)} + 1 \right)$$

This gives us a perimeter for Earth's orbit of roughly 584 million miles (940 million km).

Alison Klesman
Senior Editor

SEND US YOUR QUESTIONS

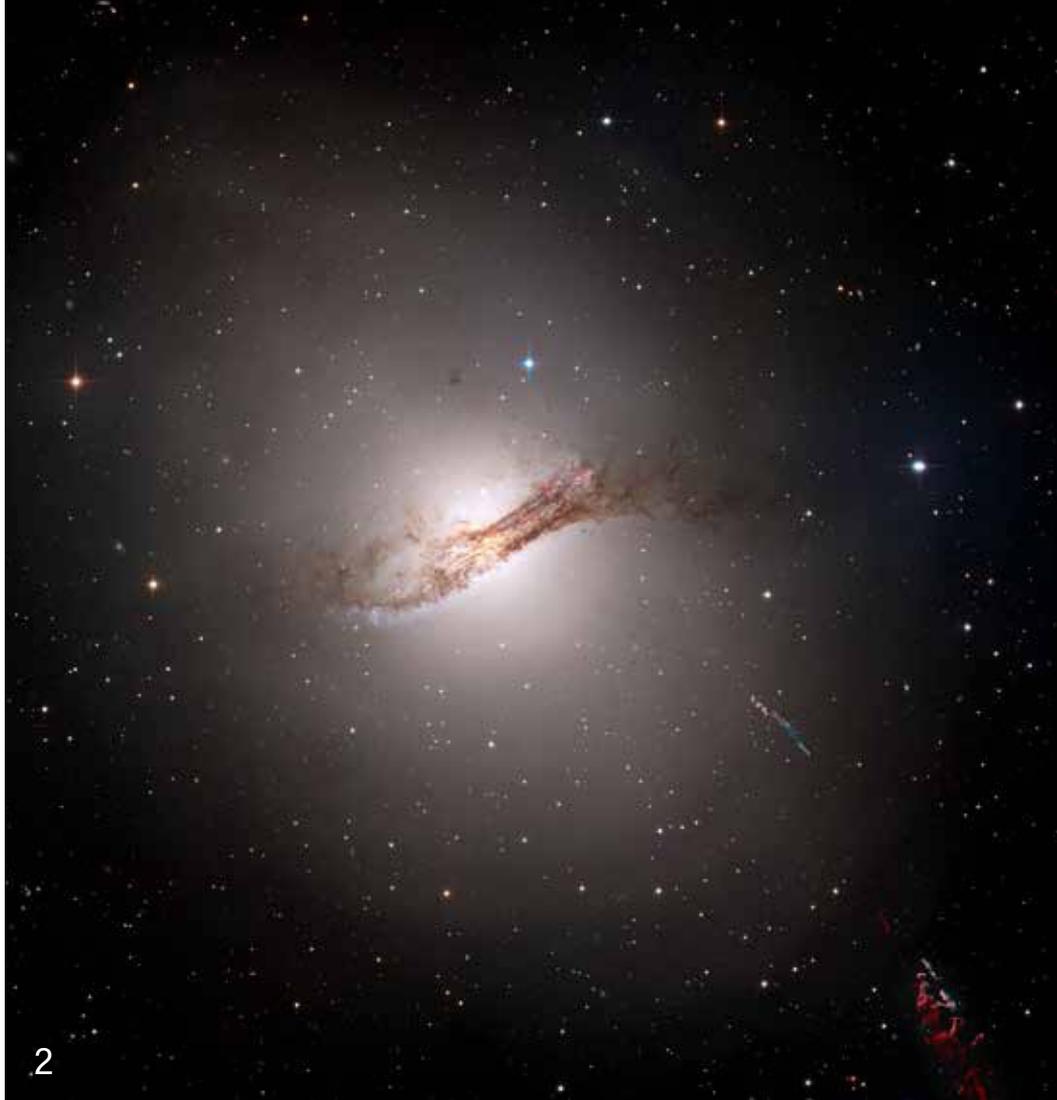
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1. HALF DOME AGLOW

Half Dome in Yosemite National Park is backlit by the glow of aurorae on Aug. 11/12, as Perseid meteors streak overhead. The imager used a Nikon mirrorless camera to image the foreground, sky, and meteor streaks in one half of the field of view; a Nikon DSLR captured additional meteor streaks in the other half of the field.

- Abhijit Patil



2. CENTAURUS A'S EJECTIONS

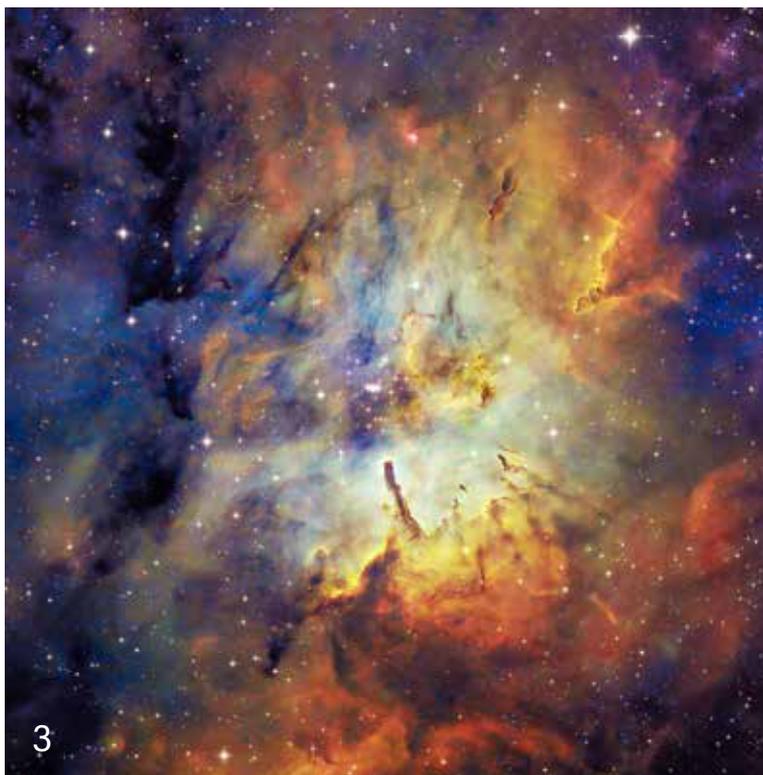
Centaurus A (NGC 5128) is the nearest galaxy with an active supermassive black hole at its core, spitting out material. Famously, these outflows can be seen as lobes of radio emission. However, this H α /OIII/LRGB image taken from the Atacama Desert in Chile with a 24-inch scope and nearly 24 hours of exposure gives a detailed view of ejections of matter in visible light at bottom right. • *Vikas Chander*

4. IN LIVING COLOR

The open cluster NGC 6823 in Vulpecula is ensconced within the emission nebula Sharpless 2-83, bursting with color in this Hubble-palette rendition. Reaching inward toward the cluster are pillarlike tendrils of star-forming, cold, dense dust. The imager used an 8-inch f/4.9 scope to take 12 hours of exposure. • *Daniel Phillips*

5. BIRD OF MANY NAMES

M17 in Sagittarius is usually called the Swan Nebula or the Omega Nebula, though it also goes by the Checkmark Nebula and the Horseshoe Nebula. The resemblance to the profile of a swan is much stronger with visual observations. This SHORGB image was taken over 4.5 hours with a 2.8-inch f/5.6 refractor. • *Katelyn Beecroft*



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5. A SUCCESSFUL COURTSHIP

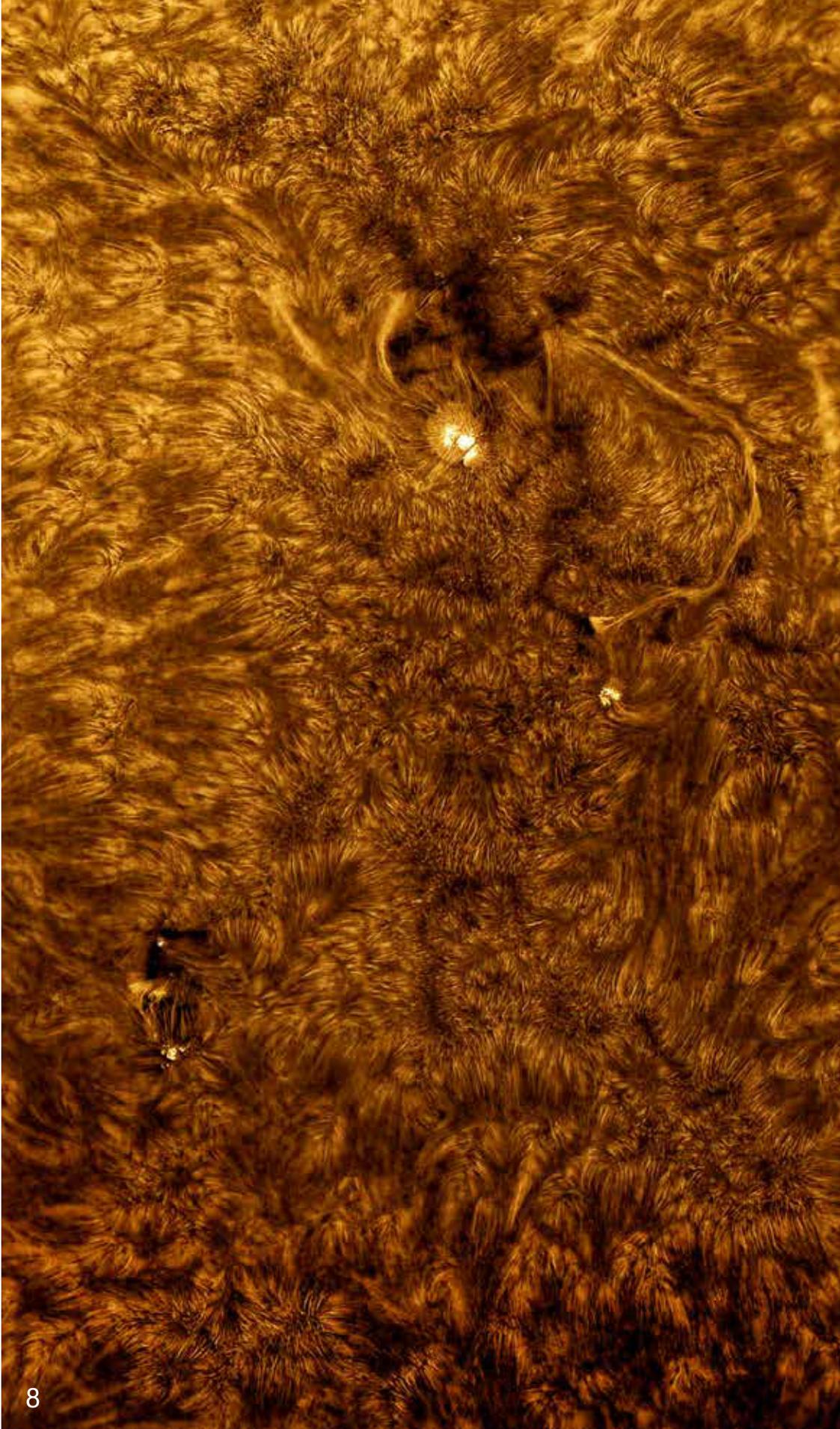
NGC 1360 — also known as the Robin's Egg — in Fornax lies roughly 1,400 light-years distant. Observations in 2017 showed this planetary nebula has not one but two white dwarfs at its center. Earlier in their lives, these stars shared their outer layers in a common envelope, which may explain the Egg's oblong and mottled appearance. This image was taken with a 24-inch f/4.5 scope in H α /OIII/RGB filters with exposure times of 15, 45, 5, 5, and 5 minutes, respectively.
- Haim Huli



6



7



6. JUST LIKE OLD TIMES

The subject of this shot holds an astrolabe — an ancient star chart and computer — under the Perseid-filled sky of Egypt's White Desert. The photographer used an astromodified Nikon mirrorless camera to take a sky mosaic of 12 panels, each with exposures of two minutes at $f/2.8$ and ISO 800. • *Osama Fathi*

7. BLOWING BUBBLES

The Bubble Nebula (NGC 7635) is an emission nebula surrounding the star SAO 20575 in Cassiopeia; the faint shell is created by its intense winds. The imager used a 4.5-inch $f/5.7$ refractor to take 24 hours of SHO data and three hours of RGB data. The final image blends a Hubble-palette rendition with a dynamic Foraxx palette, which uses a nonlinear combination of channels. • *Steve Leonard*

8. CHROMOSPHERIC DAZE

The myriad strands of plasma in the Sun's chromosphere pulsate with magnetic energy, creating a mesmerizing textural tapestry. This image is a stack of 300 $\frac{1}{200}$ -second frames taken with a 4-inch refractor and Daystar H α "eyepiece." • *Rich Ruffini*



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Please include the date and location of the image and complete photo data: telescope, camera, filters, and exposures.



HUNTING FOR COSMIC STRUCTURE

Although not the most famous deep-sky object in Orion the Hunter, M78 still dazzles. The reflection nebula dominates the center of this new image while its companion, NGC 2071, appears at top. They glow because dust within them scatters and reflects light emitted by massive young stars forming deep inside. Dust normally obscures visible light, but the European Space Agency's Euclid spacecraft views infrared radiation that penetrates this shroud. Released earlier this year as part of Euclid's initial observations, the image records at least 300,000 new objects. The spacecraft will survey more than one-third of the sky, creating a 3D map that will allow astronomers to study the evolution of dark matter and dark energy over the past 10 billion years of cosmic history. ESA/EUCLID/EUCLID CONSORTIUM/NASA

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