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SKY & TELESCOPE

THE ESSENTIAL GUIDE TO ASTRONOMY
SEPTEMBER 2025

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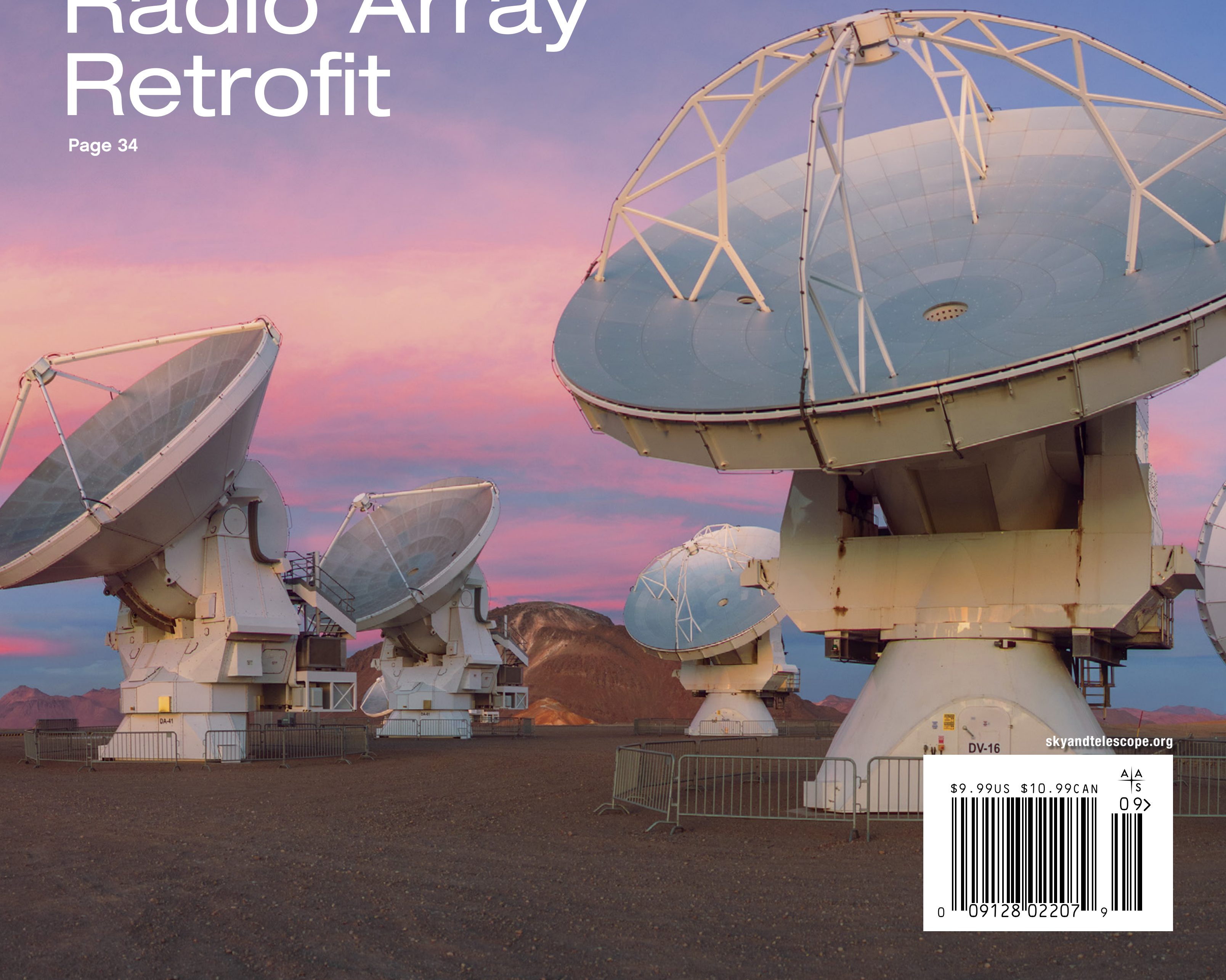

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NASA

ON THE COVER

Dusk falls over ALMA's dishes in the Atacama Desert.
PHOTO: P. HORÁLEK / ESO

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Farewells

FAREWELLS ARE a common occurrence in astronomy. As astronomers, we regularly bid farewell to space missions. On October 17, 2002, I along with several other white-knuckled colleagues watched a live stream of the launch of the European Space Agency's gamma-ray telescope, the International Gamma-ray Astrophysics Laboratory (INTEGRAL). It went on to play an (ahem) integral part in my research. With many sniffles, I and thousands of other astronomers forever said goodbye to INTEGRAL on February 28th this year.

The following month, the Gaia spacecraft shut down. But before mission scientists forever banished it into an orbit around the Sun, Gaia scientists called on the amateur community to help them perform "end-of-life" tests and at the same time pause to say farewell (see the Pro-Am Conjunction column on page 58 in the January issue).

▲ ESA's INTEGRAL mission

ESA

Some farewells are splashier than others. I'll never forget the day when NASA engineers deorbited the Compton Gamma-Ray Observatory, which splashed down in the middle of the Pacific Ocean on June 4, 2000. As one of NASA's Great Observatories, the mission unlocked so many secrets of the universe. It was sad to see it go.

As human beings, we astronomers also say goodbye to people. It is with a heavy heart that I have to let you know of two recent passings that have affected us deeply. Pediatrician and visual observer extraordinaire Dave Tosteson passed away on May 5th at the age of 69. Dave's first *S&T* feature article, on observing astrophysical jets, appeared in the March 2013 issue. Beginning in 2018, he focused on Going Deep, publishing nine columns between 2018 and 2024.

Just before going to press, we learned of Fred Espenak's passing on June 1st (page 11). Most of you likely know him as Mr. Eclipse — he practically singlehandedly introduced the world to the concept of eclipse chasing. Fred was a giant in the field, and a truly gracious human being. Please join all of us at *Sky & Telescope* in sharing our deepest condolences with Dave's and Fred's families.

On a less sad note, we're bidding a fond farewell to Jerry Oltion, the prolific and creative author of Astronomer's Workbench. For nearly 10 years, Jerry has inspired multitudes with delightful ideas on how to make the observing experience more satisfying and comfortable. He has always infused his columns with vitality and a sense of fun. This is the last month Astronomer's Workbench will carry Jerry's byline — but not to worry, he has a successor (you'll meet him next month). We wish Jerry all the best in his new endeavors!

Diana

Editor in Chief

SKY & TELESCOPE
The Essential Guide to Astronomy

Founded in 1941 by Charles A. Federer, Jr. and Helen Spence Federer

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Subscription Rates:
U.S. and possessions: $59.46 per year
Canada: $75.38 (including GST)
All other countries: $91.29, by expedited delivery
All prices are in U.S. dollars.

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Comet Capture

Thank you for Sean Walker's wonderful "Tsuchinshan-ATLAS Shines" (*S&T:* Mar. 2025, p. 34)! Due to the ubiquity of cameras in mobile phones and their improved sensitivity, Comet ATLAS (C/2023 A3) may have been the most photographed comet of all time. My wife Carol's iPhone 14 Pro produced impressive photos of the comet, even better when using the camera's 3× zoom.

◀ This image of Comet Tsuchinshan-ATLAS from New York on October 17th, captured on an iPhone 14 Pro, shows that one doesn't need a special camera to take attractive comet photos.

When observing the comet with other people at our local park, the best way to help them find the comet was to ask them to hold up their mobile phone in the general direction of the comet. Then we used the resulting photos of the comet and stars near it to guide them to the comet's location for viewing with binoculars or a telescope. "Oh, that's where it is!" was the common excited refrain from our new friends.

Everyone went home with at least one souvenir to share with friends.

Bob Kelly • Ardsley, New York

Messier Marathoner

Congratulations, Jan Hattenbach and Ronald Stoyan, on your achievement in "Mastering the Messier Marathon" (*S&T:* Apr. 2025, p. 20). It stirred my nostalgia for my first steps in observing.

In 1996, I purchased a 10-inch Meade Starfinder Dobsonian and John H. Mallas and Evered Kreimer's *The Messier Album*. Every clear night I set out to log the whole list, observing from the Prealps in northern Italy, overlooking the light-polluted Po Valley. Stirred by articles in *Sky & Telescope* and *The Year-Round Messier Marathon* by Harvard Pennington, I ran two "half Marathons" in 2002 and 2004. I completed a full one in 2006, logging 103 objects.

In 2020, during lockdown, I held a virtual Marathon on YouTube using the main telescope of the Verona Astronomical Club in remote mode (**https://is.gd/MessierVerona2020**). It garnered a large audience and was very successful.

Lorenzo Burti
Verona, Italy

Pareidolia Party

While reading the April issue, I noticed the letter "The Big Chomp" by Dave Ross and a comment by Jerry Oltion (page 6).

My Pac-Man appeared to me in May 2018 (10 years after I spotted the "Basketball Player in the Moon") and can be seen during the gibbous and full phases each month. He is just to the left of Mare Vaporum beginning with the Montes Apenninus. Palus Putredinis is his eye. If one adds the crater Archimedes, it turns into a lizard's face.

Happy moongazing!

P. Edward Murray
Via email

Jurassic Observing

Every Canadian amateur astronomer I know looks forward to reading Mathew Wedel's Binocular Highlight in *S&T*. In column after column, as light slowly crosses the universe, he connects astronomical abstractions such as time, distance, and the formation of stellar objects with specific historical markers on Earth. Behold: "By coincidence, most of my research these days is on dinosaurs from the Late Jurassic Period (about 150 million years ago), including *Allosaurus*, *Brachiosaurus*, and *Diplodocus*. It's a heady thought to observe NGC 1647 and imagine such bizarre animals existing when the cluster formed, while our shrew-sized ancestors hid in burrows and trees and waited for their turn to rule the world" (*S&T:* Dec. 2021, p. 43).

S&T should arrange his effulgent 280-word essays into a book.

Julian Samuel
Toronto, Canada

The Greatest Show

We observe the universe — as professionals and amateurs. We look at it through telescopes, sensitive cameras, spectrographs, specialized filters, and our eyes.

We should pause now and then to reflect on how special a privilege this is. It takes a long time to develop an observer, at least on this planet. The Earth is about 4.5 billion years old. Some ancient predecessor of modern humans may have looked up and began observing stars perhaps 5 million years ago. The universe is 13.8 billion years old. If our experience is typical, then for about a third of the universe's existence, nobody anywhere observed it. It was a performance without an audience. But then the universe evolved and produced observers. How special is that?

Ted Wolfe
Naples, Florida

Mystery Solved

I noticed Arthur C. Perry's occupation was listed as "not known" in the sidebar "Careers and Telescopes of Brooklyn AAS Members (as of 1885)" in Trudy E. Bell's "The First 'American Astronomical Society'" (*S&T:* Apr. 2025, p. 28). But in his obituary in the January 7, 1930, edition of *The Brooklyn Daily Times*, it says, "In 1876 he went to the United States Life Insurance Company and became cashier in 1888, remaining in that position until his retirement in 1922."

Ed Norris
Lancaster, Massachusetts

Planets Gone Rogue

Thank you for the wonderful article "Black Holes from the Dawn of Time"

BOB AND CAROL KELLY

by Camille M. Carlisle (*S&T:* Apr. 2025, p. 34). One item that particularly caught my attention was the discussion about microlensing results from the Optical Gravitational Lensing Experiment team who eliminated objects in various mass ranges as significant contributors to dark matter. Given the stated lower limit of the mass range of 10^{-5} solar masses (about several Earth masses), have astronomers sought to use these same results to place limits on the estimated number of free-floating rogue planets in our galaxy?

Jason Buczyna
Fairfax, Virginia

Camille M. Carlisle replies: *You're correct: Microlensing is also used to look for exoplanets, including rogue planets wandering the galaxy. Microlensing is sensitive to planets in wide orbits (think Jupiter's orbit), which are tough to find with the more prolific transit or radial-velocity methods. Astronomers have found more than 200 exoplanets using microlensing, all of which have host stars:* **https://is.gd/ExoplanetsMicrolensing**.

The tally of free-floating planets is vaguer, but candidates number in the hundreds at least. It's vague because mass estimates sometimes put the objects on the boundary between gas giants and brown dwarfs. Another problem is that microlensing is a one-shot wonder: You see a little flash, and it doesn't repeat. So astronomers usually need to add another method to determine whether an object is a free-floater. Astronomers also find rogue planets by imaging them directly. But I haven't found a good estimate for how many free-floaters inhabit the Milky Way.

The Solar Variable

Is our Sun a variable star? And is climate change (*S&T:* Mar. 2025, p. 12) caused by the fact that our Sun is a variable star with random periods lasting from decades to centuries? The historical pattern seems to indicate this is likely.

Lewis Brackett
San Diego, California

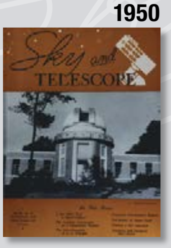
Camille M. Carlisle replies: *Although solar activity does affect Earth, it doesn't seem to be strong enough to explain the data scientists have reported — to my knowledge, no attempts to link solar activity with the climate change we're now seeing have been successful. Here is a plot showing the difference between the two trends since the late 1800s:* **https://is.gd/SunWarming**.

I also recommend the book A Global Warming Primer: Pathway to a Post-Global Warming Future *by Jeffrey O. Bennett. He discusses various hypotheses and counterarguments in a clear, approachable way.*

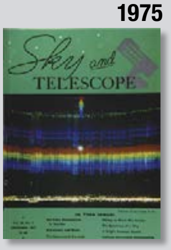
SUBMISSIONS: Write to *Sky & Telescope*, 1374 Massachusetts Ave., 4th Floor, Cambridge, MA 02138, USA, or email: letters@skyandtelescope.org. Please limit your comments to 250 words; letters may be edited for brevity and clarity.

75, 50 & 25 YEARS AGO by Roger W. Sinnott

1950



1975



2000

◖ September 1950

Martian Geology "The ruddy color of Mars may be due to naturally red rhyolitic igneous rock on desert surfaces [says] Clyde W. Tombaugh, of White Sands Proving Ground. . . . The round oases found on Mars could be impact craters caused by collisions with small asteroids. . . . The dark color and seasonal behavior should undoubtedly be due to a low form of vegetation which finds favorable environment in the pulverized igneous rock and shelter in the craters and fractures.

"Stern geological consideration of the planet's natural resources is highly unfavorable to the economics required for an intelligent civilization on Mars. Nevertheless, Mr. Tombaugh added, the canals cannot be entirely relegated to the realm of illusions."

Experienced observers gave similar assessments right up to 1965, when Mariner 4 first imaged the planet's bleak desolation.

◖ September 1975

Moonwatch Era "A pioneer of the space age passed away on June 30th. Moonwatch, the international satellite tracking network composed of amateurs and other volunteers, was [disbanded by] the Smithsonian Astrophysical Observatory in Cambridge, Massachusetts . . .

"Typically, a team would set up a 'fence' of observers, using several wide-angle telescopes trained on the meridian at different altitudes. When an observer at one 'picket' saw a satellite cross the meridian . . . he signaled the team's timekeeper, thus obtaining a fix on the object. The team leader would then relay the information to the SAO. . . . The compact Moonwatch telescope . . . gave a 6.8-degree field of view [in a] tube 8½ inches long. An aluminized or silvered mirror was set at 45 degrees in front of the objective, permitting the observer to look downward . . . in relative comfort."

In nearly two decades of operation, this remarkable example of pro-am collaboration logged some 400,000 observations of 6,000 artificial satellites.

◖ September 2000

Primordial Water "When James Whitby (University of Manchester) and his team began probing the Zag meteorite that fell two years ago in Morocco, they [found] common table salt (halite) inside. . . . Within the salt crystals the team found traces of xenon-129 [and other isotopes]. Analysis of these implies that the salt crystals are 4.571 billion years old, dating to within just a few million years of the oldest known solar-system minerals.

"The salt in the sample indicates the presence of liquid water brine even earlier. When the water evaporated, it left the salt behind. According to Whitby, the extremely ancient salt crystals suggest that 'the formation of about 10-kilometer-sized planetesimals — necessary to provide conditions suitable for liquid water — must have occurred faster than was hitherto thought.'"

◀ While Celestron showed off telescopes at this year's Northeast Astronomy Forum, the company has had to put many of its products on hold due to tariffs.

SEAN WALKER / S&T

ASTRONOMY & SOCIETY

Tariffs Alarm Amateur Astronomy Industry

THE HISTORIC TARIFFS levied against China by the Trump administration are threatening the small, passionate industry of amateur astronomy gear.

Tariff conversations permeated April's Northeast Astronomy Forum, the world's largest astronomy exposition. From boutique manufacturers to large telescope distributors, the astronomy industry relies on Chinese manufacturing for glass, electronics, and other telescope parts. Tariffs have become "all we talk about," says Franck Marchis, Chief Scientific Officer at Unistellar. But "the problem we have is not really the tariffs, it's the uncertainty that it's bringing."

Since February, when the Trump administration announced the first tariffs against China (and when China enacted retaliatory tariffs), the fluctuating situation has made it difficult for companies to determine whether they should accelerate manufacturing, raise prices, cancel orders, or just wait it out.

"Things are changing on a daily, if not hourly basis, so there's no way to come up with any kind of cohesive strategy," says Jeff Simon, director of brand development at Sky-Watcher North America. "It's like trying to work out a dance routine on quicksand."

Some companies, like Celestron and Sky-Watcher, froze shipments from China for nearly two months; some of those shipments have since resumed. Ben Hauck, Celestron's senior vice president of sales for North America, estimates that the company has held up \$10–\$15 million worth of product (in terms of cost, not retail pricing) since the tariffs took effect.

One of the administration's stated goals is to increase American manufacturing. However, even astronomy companies that rely on American labor and factories are feeling the squeeze.

Karen Christen, business administrator for Astro-Physics, says the tariffs are still an issue for the family-run, high-end telescope and mount company based in Illinois. "Is the company more insulated? Yes," she says. "Entirely insulated? By no means." While Astro-Physics conducts nearly all of their manufacturing and assembly in the U.S., they import their electronics from Asia, since virtually none are made in America.

"We monitor the news every day, trying to get some idea of what's going on," says Vic Maris, president of Stellarvue, an American manufacturer of refractors based in California. Due to the tariffs, they've had to halt shipments of specialty optical glass made in China. While Stellarvue has six months to a year's supply stocked up, the glass takes four months to manufacture, meaning that future orders will face waitlists even when (or if) tariffs resolve. And new product designs that contain such glass cannot move forward, Maris says.

At the end of the day, tariffs will most impact consumers looking in the lower price range, around a couple hundred dollars. That's not least because the U.S.-based manufacturers produce equipment at the higher end of the market, compared to Celestron and Sky-Watcher, says Christen.

"The idea that some families and some kids won't have the ability to experience the wonders of the nighttime sky . . . because of high prices [and] policies from this administration," Hauck says, "is deeply depressing."

■ HANNAH RICHTER

EARLY GALAXIES

A Barred Spiral in the Young Universe

THE DISCOVERY OF a barred spiral galaxy 2.6 billion years after the Big Bang, published in the May 22nd *Nature,* adds to a growing challenge facing our notions about how — and how fast — galaxies can form.

The universe's first galaxies were once thought to be fluffy, turbulent messes. But astronomers using the James Webb Space Telescope discovered spiral structure in earlier epochs than they thought they would, just 2 billion years after the Big Bang (*S&T:* Oct. 2024, p. 8). Now, the next stage of galactic evolution, in which stars' orbits organize into a thick central bar, has been spotted at similarly early times, with the discovery of the barred spiral galaxy dubbed J0107a.

The distant barred spiral initially turned up in data from the Atacama Large Millimeter/submillimeter Array (ALMA) in Chile. Further observations using ALMA and Webb as well as the Karl G. Jansky Very Large Array in New Mexico helped Shuo Huang (National Astronomical Observatory of Japan) and colleagues examine its structures.

The new data show us J0107a as it was 11.1 billion years ago (at a redshift of 2.467). Yet its bar appears just like the bars we see in the Milky Way's galactic neighbors. Its stars, gas, and dust suggest that the bar has been around for about 1 billion years.

Like bars in local galaxies, J0107a's bar rearranges its host over time. The bar draws gas from the galaxy's outer arms into its heart, shoveling about 600 Suns' worth of mass into the central regions every year. The gas inflow is 10 times the rate in local galaxies, Huang explains, because there was more gas available at earlier cosmic times.

SPACE WEATHER

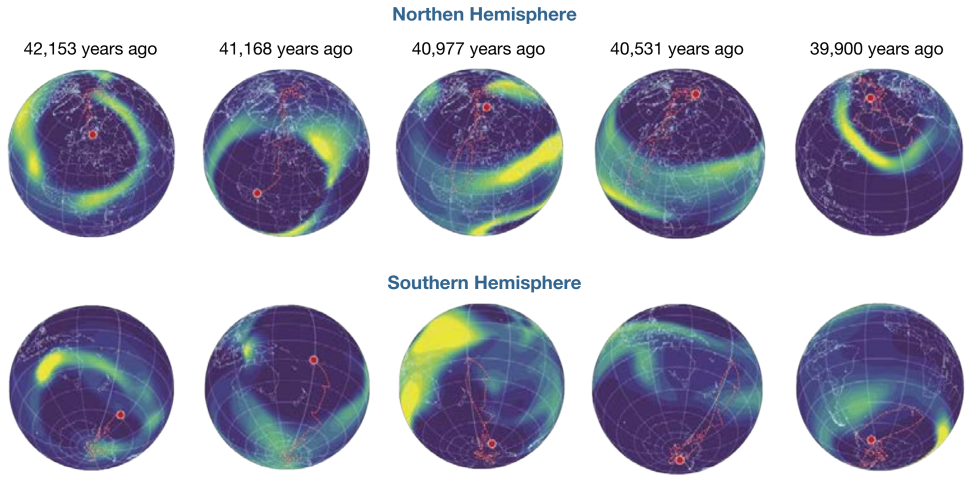
41,000 Years Ago, Aurorae Appeared Across the Globe

EARTH'S PROTECTIVE magnetic shield nearly collapsed the last time the magnetic poles significantly shifted. As a result, early humans around the globe saw skies ablaze with aurorae.

This *geomagnetic excursion* was already known, but in the April 16th *Science Advances*, Agnit Mukhopadhyay (University of Michigan, Ann Arbor) and colleagues used models to visualize the event.

Earth's magnetic field protects us from speedy charged particles, which enter our atmosphere along *open magnetic field lines* around the magnetic poles. Nowadays, those open lines create *auroral ovals* less than 3,000 kilometers (2,000 miles) in diameter.

To understand the effects of a weaker field, such as the one that occurred during the Laschamps geomagnetic excursion about 41,000 years ago, Mukhopadhyay and colleagues combined paleomagnetic data with two models, one that describes the space environment around Earth and another that predicts how charged particles were funneled into the atmosphere.



▲ A combination of data and simulations show the spread of aurorae the last time Earth's magnetic poles shifted. Red dots mark the location of the north and south magnetic poles; dashed lines show their migration.

The team's findings depict dramatic changes over 2,000 years: During that period, Earth's magnetic field weakened to just a tenth of its current strength and tilted relative to Earth's spin axis by 76°, moving the magnetic poles to Northern Africa and just northeast of Australia, respectively.

The protective shield this field provided also shrank in size. At the excursion's peak, the magnetosphere extended a meager 15,000 km on the day side, compared to about 60,000 km today. The auroral ovals in turn grew to have diameters of about 8,100 km. As a result, charged particles had almost free entry into most of Earth's atmosphere.

"It's an exciting study," comments Joseph Stoner (Oregon State University), who was not part of the study. "It begins to fill a conceptual gap, but a lot more needs to be done to quantitatively put it together and test it."

What the study doesn't provide is a new lead into what causes excursions in the first place. They're probably associated with the liquid iron sloshing in Earth's outer core, but which precise mechanisms are involved remains an open question, Mukhopadhyay notes. There's no indication of an imminent geomagnetic excursion today, but the Laschamps example suggests one could occur within a human lifetime — yet perhaps without disastrous effects.

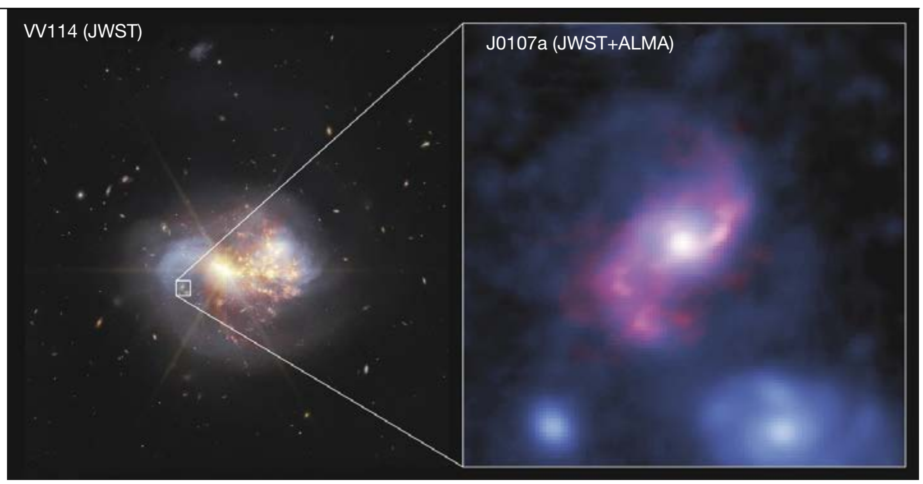
"Many people say that a planet cannot sustain life without a strong magnetic field," Mukhopadhyay says. It's comforting to know that, 41,000 years ago, humans were able to survive.

■ **JAN HATTENBACH**

It's no surprise, then, that the galaxy is experiencing a stellar baby boom.

While J0107a is only one example, it pushes back the time when bars began to form, which in turn informs the formation process itself. "Current models posit that the gas-rich environment of galaxies in the early universe prevented the conditions that lead to bar formation," writes Deanne Fisher (Swinburne University of Technology, Australia) in a perspective piece that accompanied the *Nature* study. "By showing that bars do exist in early galaxies, Huang et al. directly confront this theory."

■ **MONICA YOUNG**



▲ The JWST image at left shows a nearby galaxy, VV114, as well as distant background galaxy J0107a. The inset at right zooms in on J0107a, revealing its barred spiral shape.

AURORA ON EARTH 41,000 YEARS AGO: A. MUKHOPADHYAY ET AL. (UNIV. OF MICHIGAN) / *SCIENCE ADVANCES* 2025; BARRED SPIRAL GALAXY IN EARLY UNIVERSE: NASA / ALMA (ESO / NAOJ / NRAO), HUANG ET AL. / *NATURE* 2025

SOLAR SYSTEM

Titan's Methane Clouds on the Move

ASTRONOMERS HAVE made a series of key breakthroughs in understanding the methane cycle on Saturn's largest moon, Titan. Besides observing cloud convection, they've also spotted a molecule key to the moon's chemistry.

Titan is the only world in the solar system other than Earth to host rivers, lakes, and seas; however, the bodies hold not water but liquid methane. To understand the moon's methane cycle (equivalent to Earth's water cycle), Conor Nixon (NASA Goddard Space Flight Center) and colleagues used the James Webb Space Telescope (JWST) and the W. M. Keck Observatory in Hawai'i to examine the moon's northern atmosphere. The team published the findings May 14th in *Nature Astronomy.*

"Since the different filters on the Keck [near-infrared] camera see to different depths in Titan's atmosphere, we were able to see . . . that the clouds had moved upwards in altitude, like a convective cell on Earth," Nixon says.

Astronomers have seen this type of cloud convection on Titan before, but that was in the southern hemisphere (*S&T:* Mar. 2003, p. 24). Now the seasons have changed, and cloud convection appears in the north, where the largest lakes and seas of methane are.

In the JWST observations, the team also detected a molecule called *methyl radical* (CH_3). It's created when sunlight breaks methane (CH_4) apart and forms the basis for the creation of other organic molecules on the moon. Astronomers can thus use it to watch chemical processes unfold on Titan.

"The JWST Titan observations are exquisite," says Martin Cordiner (Catholic University of America). "These are some of the most spectacular hydrocarbon spectra I have ever seen — they open up a new era in our ability to monitor Titan's atmospheric gases and clouds."

The moon could well present more surprises in the near future, as this May marked the northern fall equinox on Titan. According to Nixon, "dramatic changes are predicted."

■ COLIN STUART

GALAXIES

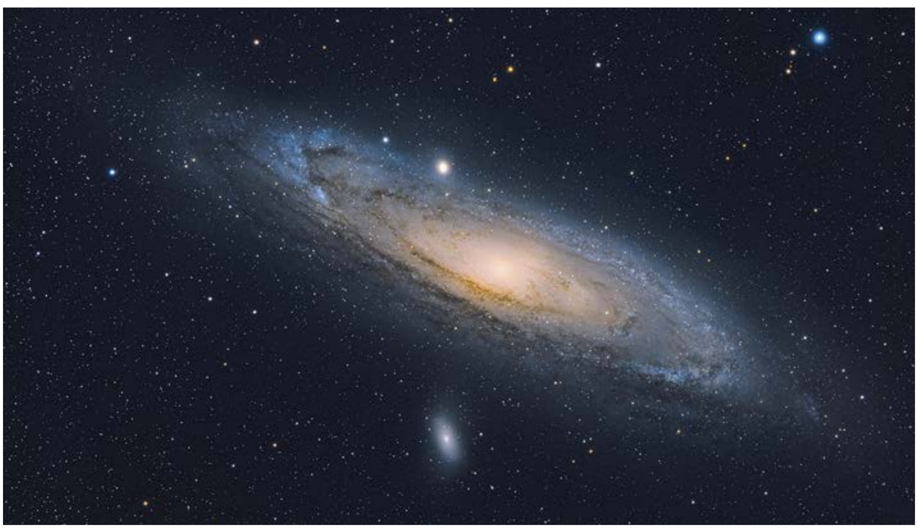
Why Andromeda's Dwarf Galaxies Cluster on "Our" Side

THE ASYMMETRIC arrangement of dwarfs around the Andromeda Galaxy (M31) is rare, a new study shows, hinting at the arrangement's origin.

Most of Andromeda's satellites lie between it and our Milky Way Galaxy. Yet galaxies are known to form and grow along giant filaments of dark matter, so it's perhaps unsurprising that dwarfs in those filaments simply fall in along certain, preferred directions.

To answer how unexpected the imbalance of Andromeda's satellite swarm is, Jamie Kanehisa and colleagues (all at Leibniz-Institute for Astrophysics Potsdam, Germany) developed a new way of quantifying the lopsidedness. They then compared it with two cosmological simulations: Illustris TNG and the Evolution and Assembly of Galaxies and their Environments (EAGLE).

What they report April 11th in *Nature Astronomy* is that, while the Illustris and EAGLE simulations both turned up some systems as unbalanced as Andromeda's, those systems were few and far between.



Importantly, the researchers accounted for systems in which a few dwarf galaxies clustered together as they fell in toward the larger galaxy — unlike the arrangement found around Andromeda. Discarding those systems, the team found that only 0.1% galaxy systems match Andromeda's. That rarity "requires either a very unique evolutionary history, or otherwise may hint at an insufficiency in our current cosmological model," Kanehisa says.

Amandine Doliva-Dolinsky (Dartmouth College), who wasn't involved with the study, leans toward the former explanation. "This is an exciting result that raises many questions about M31's evolution and the origin of this anisotropy," she says. "Could it be linked to M31's recent merger history?" She adds that the nearby Triangulum Galaxy (M33) might also be interacting with Andromeda in a way that helps rearrange the smaller galaxies.

Doliva-Dolinsky tempers her excitement with caution, noting that the lopsided arrangement might be short-lived on a cosmic timescale, which might be difficult to capture in simulations. "Nevertheless," she says, "these findings show the importance of studying systems like M31 to better understand galaxy formation and evolution."

■ MONICA YOUNG

OBITUARY

Fred Espenak (1953–2025)

FRED ESPENAK, who laid the foundation for modern-day eclipse chasing, died of idiopathic pulmonary fibrosis on June 1st. He announced his diagnosis and impending passing on April 15th on social media and on the Solar Eclipse Message List forum as he prepared to enter hospice care, sparking an outpouring of sorrow, good wishes, and thank-you's for his life's work.

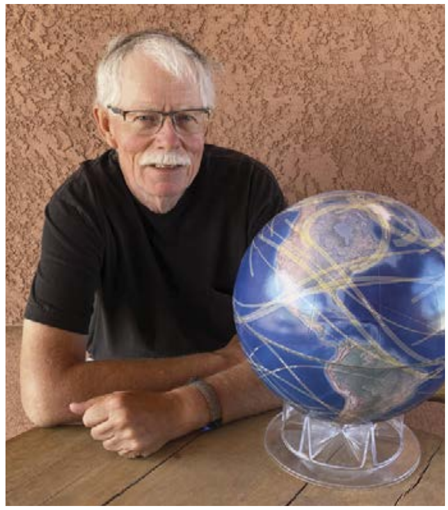
Fred's fascination with the lunar shadow began with a partial eclipse in 1963. He ended up witnessing 52 solar eclipses of various types, of which 31 were total. He also helped countless others prepare for and experience the wonder of totality.

Of the many stories collected along the way, he was fond of recounting a trip to India in 1995 to catch 41 seconds of totality, during which he noticed a high-school chemistry teacher watching her first eclipse. "Nice hair," he thought. Several eclipses and a decade later, he and Patricia Totten, the lady with the hair, were married. It was a particularly fond pairing, as visitors to his Arizona home could attest.

As a NASA scientist at the Goddard Space Flight Center, Fred's research focused largely on planetary atmospheres using infrared spectroscopy. But to most of us, he is best known for his calculations of solar and lunar eclipse circumstances and the many platforms he used to spread that information globally to scientists, eclipse chasers, and the public. In recognition of his efforts, asteroid 14120 was named Espenak in 2003. To the public, he became "Mr. Eclipse."

With Jean Meeus, he published two major reference works: in 2006, the *Five Millennium Canon of Solar Eclipses*, which covers all types of solar eclipses from 2000 BC to AD 3000, and the similar *Five Millennium Canon of Lunar Eclipses* in 2009. Other canons and eclipse guides followed, totaling 30 publications in all, many of which he printed and distributed through his own publishing company, AstroPixels. More recently, he coauthored *Totality: Eclipses of the Sun* with Mark Littmann and Ken Willcox. In a lighter vein, he partnered with Patricia to write *TOTAL Eclipse or Bust! A Family Road Trip*. He was also a regular contributor (with me) to *Sky & Telescope*, providing predictions to help readers make the most of their eclipse experiences.

After his retirement, Fred and Patricia moved to the Arizona Sky Vil-



lage, where Fred took on the hobby of astrophotography. In 2018, the Royal Photographic Society honored him with their Award for Scientific Imaging.

Although his passing brings an end to an important era, Fred has left us with a trove of offerings for the future. Among them, *The Guide for the Total Solar Eclipse of 2045* highlights the next shadow path that crosses the United States. Although he won't be there with his flock of cameras, Fred Espenak — Mr. Eclipse — will be with us in spirit, guiding us with his careful calculations for many Saros cycles to come.

■ **JAY ANDERSON**

PATRICIA TOTTEN ESPENAK

IN BRIEF

Another Dwarf Planet for the Solar System?

A new object discovered in the outer solar system is the largest found in more than a decade. Dubbed 2017 OF_{201} for now, the object is approximately 700 kilometers (400 miles) wide. Its size puts it in the category of dwarf planets, along with Pluto and the asteroid Ceres; the International Astronomical Union currently recognizes only five dwarf planets in the solar system. The discovery, posted on the astronomy arXiv preprint server on May 21st, came as the result of a painstaking analysis of 200 terabytes of data collected for the Dark Energy Camera Legacy Survey. Based on that data, Sihao Cheng (Institute for Advanced Study) and his team computed the object's orbit and determined that it should also show up in another public dataset available from the Canada-France-Hawaii Telescope. Ultimately, the researchers found the object in a total of 19 observations spanning 2011 to 2018. Interestingly, the object does not belong to the group of other outer solar system objects whose clustered orbits could indicate the presence of a major far-out planet, sometimes dubbed Planet X or Planet 9 (*S&T:* Oct. 2017, p. 16). But the object interacts with Neptune, which makes it unclear whether it ought to cluster with the others. The team hopes to carry out additional observations of 2017 OF_{201} using the Hubble or James Webb space telescopes.

■ **DAVID L. CHANDLER**

The Origin of Kalliope

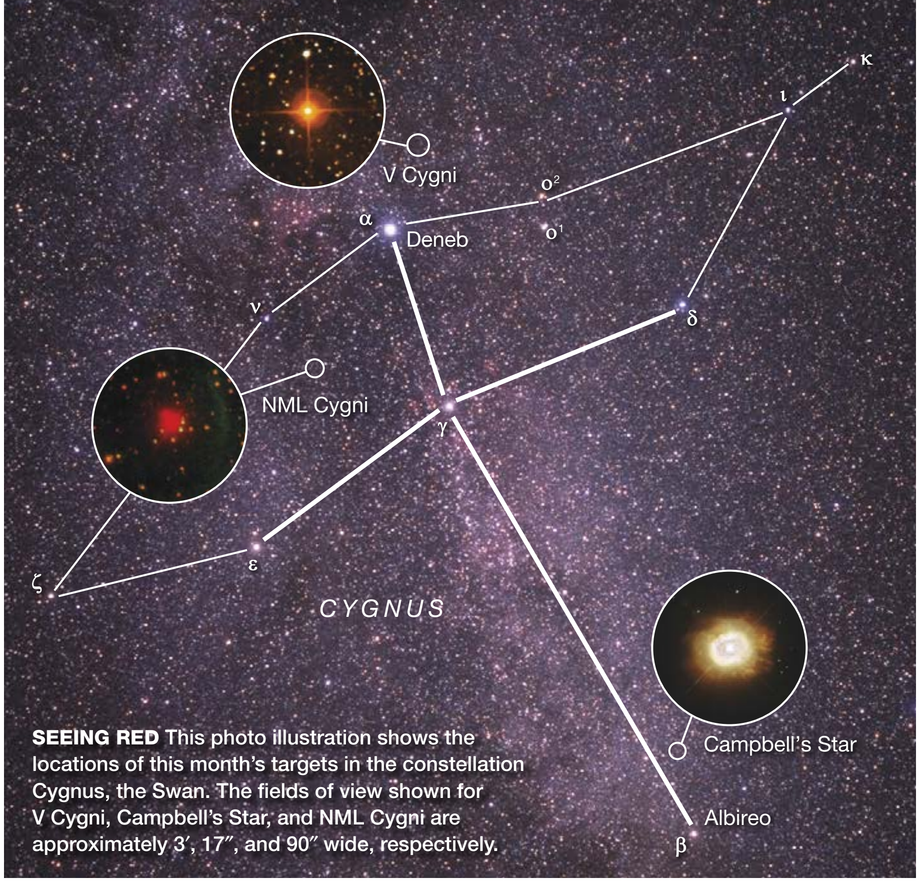
Small shards related to 22 Kalliope, a metallic main-belt asteroid, shed light on their mutual origin early in solar system history. Chrysa Avdellidou (University of Leicester, UK) reported analysis of several small asteroids with orbits similar to Kalliope's at the European Geosciences Union in Austria as well as in the June issue of the *Monthly Notices of the Royal Astronomical Society*. Avdellidou compared spectra of the smaller asteroids to meteorites found on Earth, demonstrating that the asteroids, like Kalliope, are made mostly of iron. She thinks all of the metallic pieces were struck from the core of a planetesimal early in the solar system's history during a violent collision. That scenario would put the parent planetesimal of Kalliope in the category of differentiated objects in the solar system — those that, like Earth, became hot enough for material to melt, causing iron and other heavier elements to sink to the core.

■ **BAS DEN HOND**

by Stephen James O'Meara

Three Red Wonders in Cygnus

Be sure to explore the celestial Swan's Red Region this fall.



SEEING RED This photo illustration shows the locations of this month's targets in the constellation Cygnus, the Swan. The fields of view shown for V Cygni, Campbell's Star, and NML Cygni are approximately 3′, 17″, and 90″ wide, respectively.

CYGNUS CONSTELLATION PHOTO: AKIRA FUJII; V CYGNI: WIKISKY.ORG; CAMPBELL'S STAR: ESA / HUBBLE & NASA / JEAN-CHRISTOPHE LAMBRY; NML CYGNI: SLOAN DIGITAL SKY SURVEY / APACHE POINT OBSERVATORY / ASTROPHYSICAL RESEARCH CONSORTIUM

CELESTIAL OBJECTS WITH rich shades of red — like drops of blood against the black velvet of night — have long fascinated observers. One area rife with these "bleeding stars" is the Red Region of Cygnus.

Irish astronomer John Birmingham (1816–1884) was the first to recognize the region. In 1879, he noted that, "As a hint to observers, I would remark that a space of the heavens, including the Milky Way, between Aquila, Lyra, and Cygnus, seems so peculiarly favoured by the Red and orange Stars, that it might not inaptly be called 'the red region,' or 'the red region of Cygnus'."

One notable star is the variable V Cygni, located less than 3° north of Deneb at right ascension 20^h 41.3^m and declination +48° 09′. Birmingham, who discovered it on May 22, 1881, reported how he detected the star's "deep crimson color" through a 4½-inch refractor at 53×.

Today, we know that V Cygni is a carbon star (spectral type C5-C7) whose deep-red hue comes from an abundance of carbon in its atmosphere. As only red wavelengths can penetrate this dusty veil, we see the star as red.

V Cygni varies in brightness from magnitude 7.7 to 13.9 over a period of 421 days. This year, the star is predicted to reach maximum brightness on August 1st, so it should still be relatively conspicuous in September.

Near Albireo

Campbell's Star is a 10.4-magnitude wonder that lies a bit more than 2½° north-northeast of Albireo, Beta (β) Cygni, at right ascension 19^h 34.8^m and declination +30° 31′. Despite its stellar appearance, it's not a star at all but a highly compact, 5″ planetary nebula (cataloged as PK 064+05.1) surrounded by glowing plumes of reddish gas, including hydrogen and nitrogen. American astronomer William Campbell (1862–1938) discovered this peculiar object in 1893, while using a visual spectroscope on the 36-inch refractor at Lick Observatory on Mount Hamilton, California.

While the slightly swollen form of Campbell's Star is visible through small telescopes, you'll need magnifications of 200× or greater to see the disk well. A hydrogen-beta (Hβ) filter, even at lower powers, will help boost the nebula's visibility and color. At the center of its expanding shell lies HD 184738, a 10.4-magnitude [*WC*]-type star. It's a member of a rare class of low-mass, Sun-like stars at the end of their lives that have ejected much of their original mass, leaving behind a hot core that's still losing mass at a high rate and creating a hot stellar wind.

An Observing Challenge

Our third object, NML Cygni, is located about 4½° east of Gamma (γ) Cygni at right ascension 20^h 46.4^m and declination +40° 07′. Also listed as V1489 Cygni, it's a red supergiant about 40 times more massive and 100,000 times more luminous than our Sun, making it a near twin of VY Canis Majoris, one of the largest and most luminous stars known in the Milky Way. NML Cygni is estimated to be some 5,200 light-years away on the far side of the Cygnus OB2 association, which is possibly the largest collection of *O*- and *B*-type stars in our galaxy.

The NML designation honors American astronomers Gerry Neugebauer, Dowell Martz, and Robert Leighton, who co-discovered the star in 1965 as part of an infrared sky survey at Mount Wilson Observatory. NML Cygni varies in brightness between magnitudes 16 and 18, every 3.5 years. As of 2024, its visual magnitude was 16.7. Like Betelgeuse, NML's dimming is likely due to massive ejections of dusty material that temporarily blocks light from the star.

Be sure to stop by the Red Region of Cygnus and experience the sheer joy of personal discovery.

■ Contributing Editor **STEPHEN JAMES O'MEARA** loves to share the visual marvels of the day and night skies.

Daniel K. Inouye Solar Telescope: Stan Jones / dreamstime.com

Cosmic Mapper Extraordinaire

Europe's Euclid space telescope is creating a vast map of the cosmos to investigate the natures of dark matter and dark energy.

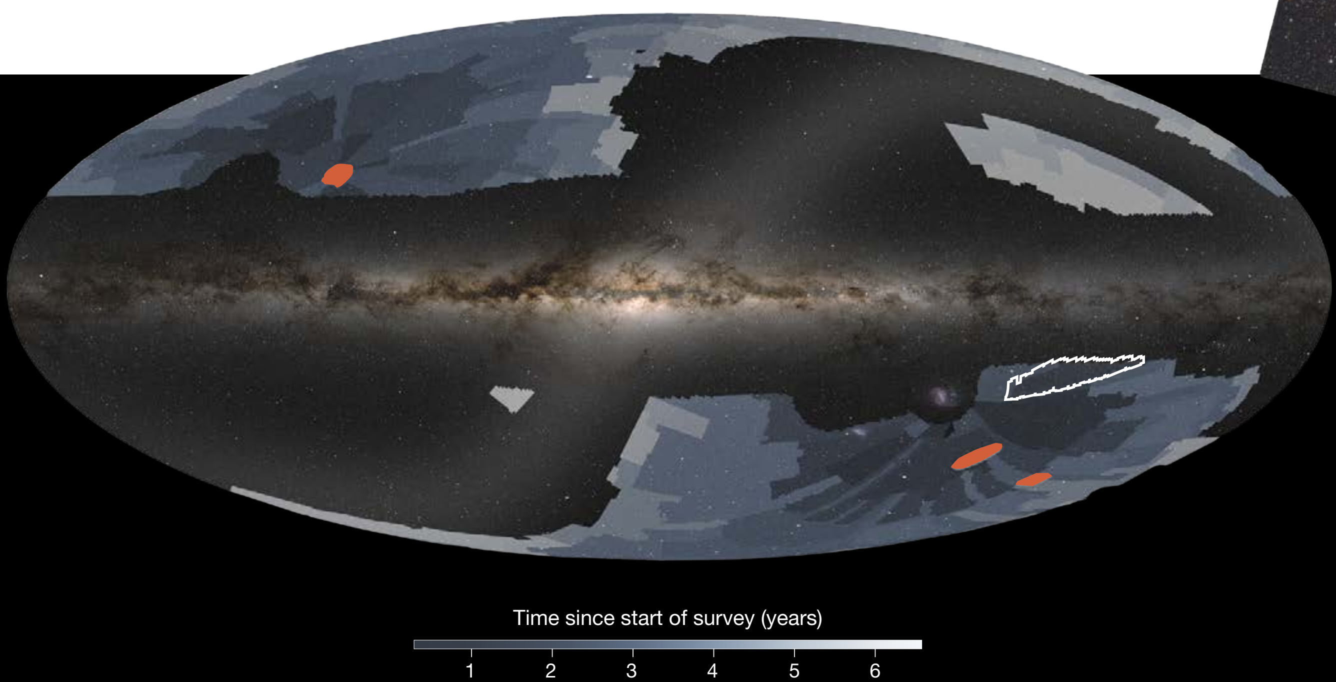
In 1915, Einstein's general theory of relativity fundamentally changed our understanding of the universe, demonstrating the connection between gravity, spacetime, and matter (or energy). This theory laid the foundation for modern cosmology and, for a while, it looked like the universe's origin and fate could finally be understood.

However, the subsequent search for the basic constituents of the cosmos revealed that ordinary visible matter — the stuff of stars, planets, and ourselves — makes up just a tiny fraction, roughly five percent, of the universe's total matter and energy. A vast and unseen domain exists beyond our perception. An invisible form of matter, which nevertheless has mass and therefore gravity, is five times more abundant than normal matter. On top of that, a mysterious energy seems to infuse space itself, pushing the universe into an accelerated expansion. Befuddled, scientists have dubbed these independent components dark matter and dark energy. Both are essential ingredients of our standard model of cosmology (called *lambda cold dark matter*, or ΛCDM), currently our best interpretation of how the universe works.

As their names suggest, dark matter and dark energy are undetectable by normal telescopes, since they do not interact with light in the same way that ordinary matter does. But their effect on the visible universe is measurable.

Measuring this effect is the primary goal of Euclid, a space telescope developed by the European Space Agency (ESA) to produce a gigantic 3D map of the universe's structure. Euclid will scan one-third of the sky, capturing

▼ **SIX-YEAR SCAN** Euclid will scan about one-third of the sky (shaded areas), avoiding the Milky Way, Large Magellanic Cloud, and the dust and sources in the plane of the solar system (visible here as the faint diagonal strip crossing through the image's center). It will spend extra time looking at three deep fields (orange); from top left to bottom right, they are EDF North, EDF South, and EDF Fornax. The footprint for the mosaic on page 16 is marked with a white outline.



ESA / EUCLID / EUCLID CONSORTIUM, ACKNOWLEDGEMENT: WORK PERFORMED BY ATG UNDER CONTRACT FOR ESA / CC BY-SA 3.0 IGO, ADAPTED BY BEATRIZ INGLESSIS / S&T

ESA / EUCLID / EUCLID CONSORTIUM / NASA, IMAGE PROCESSING BY J.-C. CUILLANDRE, E. BERTIN, G. ANSELMI

▲ **EUCLID DEEP FIELD FORNAX** One of three deep fields Euclid will probe, this patch of sky spans 12.1 square degrees and is located in the constellation Fornax, the Furnace. It encompasses the much smaller Chandra Deep Field South (0.11 square degree), studied by several ground- and space-based observatories. So far, astronomers have identified 4.5 million galaxies in this field.

sharp images in near-infrared and visible light of more than 1.5 billion galaxies and, crucially, measuring many of those galaxies' distances. With this map, researchers aim to determine the distribution of dark matter by observing its gravitational effects on the stuff we can actually see. From how this large-scale structure evolves over cosmic time, they will then infer the behavior of dark energy.

In general relativity, gravity is geometry: Gravity is the curvature of spacetime, warped by mass. For this reason, planners named the mission after Euclid of Alexandria, the mathematician from around 300 BC who's considered the father of geometry. Ultimately, cosmologists expect that Euclid will lead to a precise measurement of cosmic acceleration. Current measurements have too much wiggle room to confirm whether this parameter is a constant (the lambda in ΛCDM) or evolves over time, leaving open fundamental questions about the history and fate of the universe. If scientists can show that dark energy changes over time, it would be a groundbreaking discovery: the first confirmed crack in the standard model.

The Dark Universe Detective

Launched in July 2023 aboard a SpaceX Falcon 9 rocket, after the originally planned Soyuz became unavailable due to Russia's invasion of Ukraine, ESA's €1.4 billion ($1.6 billion) Euclid mission represents a 16-year collaborative effort to advance cosmological research. The 2-ton space telescope, equipped with cutting-edge instruments, was developed by a consortium of universities and companies from 15 European countries, Canada, Japan, and the U.S. Consortium members include more than 1,000 researchers in astrophysics, cosmology, and theoretical and particle physics, as well as many more individuals in other roles.

"Euclid is a very healthy manifestation of humanity," says Carlo Baccigalupi (International School for Advanced Studies, Italy). Scientists like him don't think of other nations as rivals, he says, but as potential collaborators. "When the objective is for the entire humankind, then borders are seen as a disturbance."

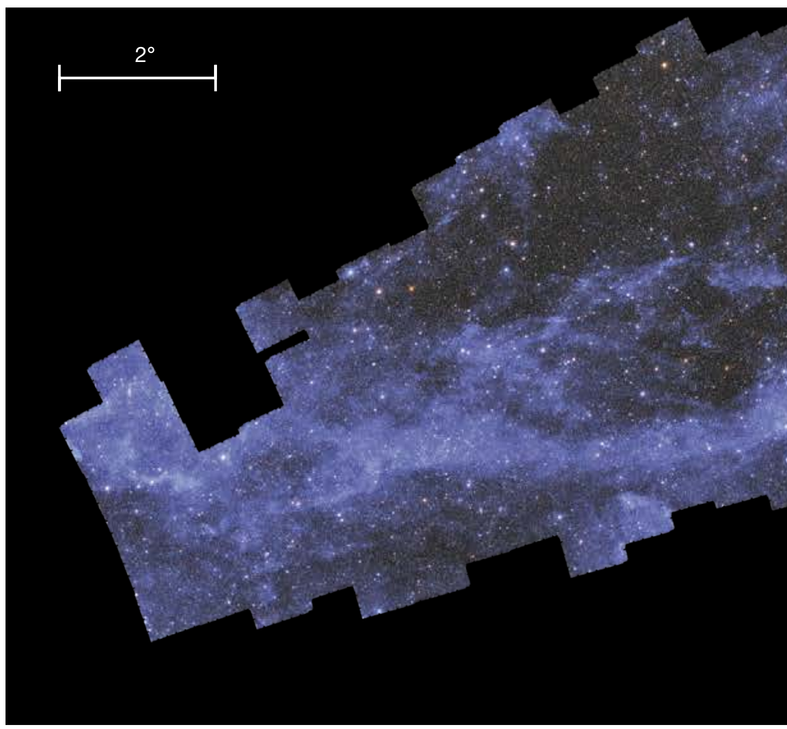
The mission employs two main methods — or "probes" in cosmologists' lingo — to map the universe's geometry and determine the influence of dark matter and dark energy on its evolution.

Euclid's first probe, *galaxy clustering*, examines the distribution of matter throughout space and time. At cosmic scales, matter isn't evenly spread out. Instead, it forms a vast network known as the cosmic web, composed of luminous filaments and nodes where galaxies and clusters reside, separated by vast, empty voids. The precise structure of this cosmic web — the number of filaments and clusters, the sizes of voids — as well as the web's growth rate are influenced by the properties of dark energy and dark matter.

Euclid will map this cosmic web by pinpointing the locations and distances of around 35 million galaxies, reaching out to billions of light-years from Earth. Looking at farther distances means looking further back in time (because light travels at a finite speed); Euclid will detect galaxies out to more than 10 billion years ago, reaching three-quarters of the way back in the age of the universe. By mapping objects at such vast distances, as they were billions of years ago, researchers hope to unravel how the large-scale structure of the universe has evolved over time.

The second probe is *weak gravitational lensing*. As light from distant sources travels toward Earth through the cosmic web, the gravitational pull of matter along the way bends its path, a phenomenon predicted by general relativity. While strong gravitational lensing can create dramatic arcs and rings, most lensing is weak, causing only small distortions too faint to see when looking at individual galaxies' images. So Euclid will measure the shapes of about 1.5 billion galaxies, enabling a statistical analysis that will reveal the warping effect of intervening matter on these galaxies' perceived shapes. Since the vast majority of matter is dark, this mapping will show where the dark stuff lies, how much of it there is, and what its properties are.

"The way that dark matter has clustered can tell you something about the evolution of the universe," says Euclid Consortium scientist Mark Cropper (University College London). As Euclid observes galaxies farther and farther away, Cropper



▶ **SLICE OF THE SKY** Captured in early 2024, the images in this mosaic cover 1% of Euclid's ultimate survey area. They contain observations by both the visible and near-infrared instruments; blue is 700 nanometers, green 1100 nm, and red 1700 nm. Zooming in by a factor of 36 reveals the core of the galaxy cluster Abell 3381 (inset). The second inset shows Euclid's field of view compared with the apparent size of the full Moon and the field of the near-infrared channel of Hubble's Wide Field Camera 3.

explains, it can reveal how the interplay between dark matter and dark energy has changed over time. "If there is a lot of dark energy, then it's fighting against the gravity, so it makes it hard for the matter to clump. If, on the other hand, the dark energy is weak, then the gravity always wins, and you end up with a lot of clustering quite early on."

Both methods are complementary. By taking two different attack angles, researchers can be sure that their results are consistent. "It's important that Euclid uses both, because it's their combination that helps us to test gravity, to test dark energy and dark matter," says Euclid project scientist Valeria Pettorino (European Space Agency).

Tools of the Trade

To achieve its goal, Euclid observes with a relatively modest 1.2-meter telescope, paired with two simple but extremely precise instruments. Euclid's visible-light camera, or VIS, is one of the largest digital cameras ever launched into space. It uses an array of 36 CCDs to form a 600-megapixel detector. (For comparison, a typical smartphone camera has 54 megapixels.) This combination allows Euclid to capture hundreds of well-resolved galaxies in a single snap with a resolution comparable to that of Hubble.

"The difference [with Hubble] is that Euclid has a very wide field of view," Pettorino says, which enables speedy surveying. "What Hubble could observe in 30 years, Euclid can measure it in a week." Each image Euclid takes covers more than half a square degree, hundreds of times larger than the field of view of Hubble's wide-field camera and equivalent to three times the area of the full Moon. "It's amazing," she adds.

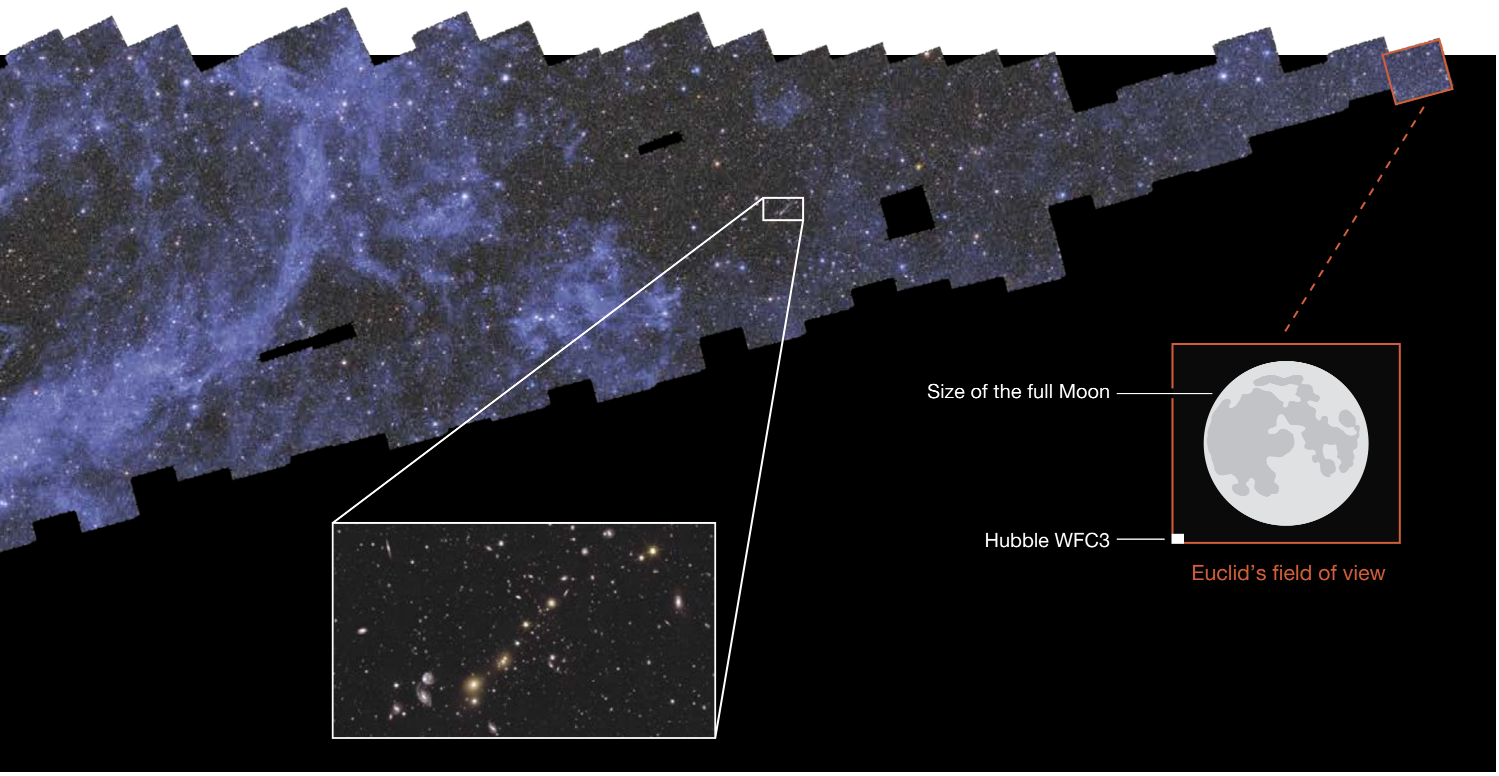
The combination of a small-ish telescope and a large detector is what enables Euclid to cover a wide area of sky. In comparison, the Nancy Roman Space Telescope, Euclid's American competitor expected to launch in 2027, will have a 2.4-meter telescope, resulting in a smaller field of view. "So even if Euclid's is smaller, it's better," Cropper says.

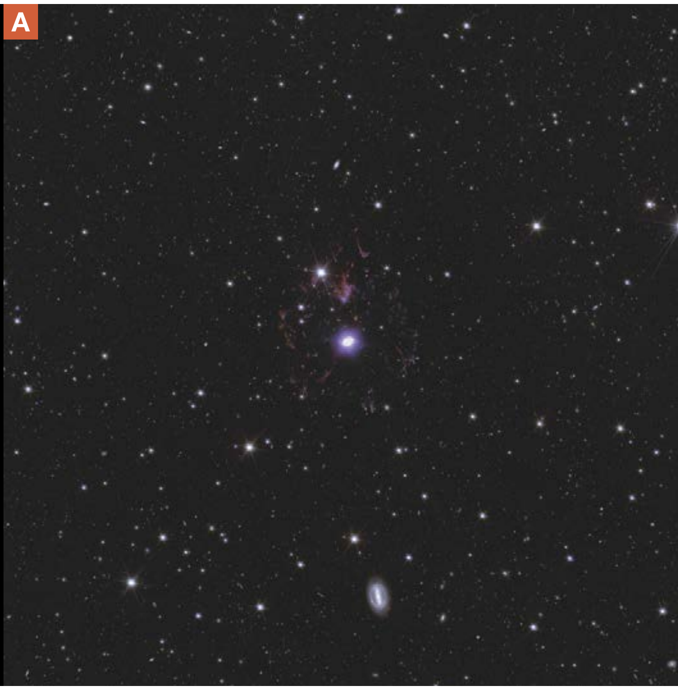
The second instrument, the Near-Infrared Spectrometer and Photometer (NISP), is in charge of both infrared imaging and measuring distances by estimating objects' redshifts, the stretch in light's wavelengths caused by cosmic expansion as the photons travel from their source to reach us. NISP employs a slitless spectrograph that analyzes the light of all the objects within its field of view simultaneously and spreads each source's light into a spectrum. This design offers lower resolution than slit-based spectrographs, which observe objects individually, but it's much faster.

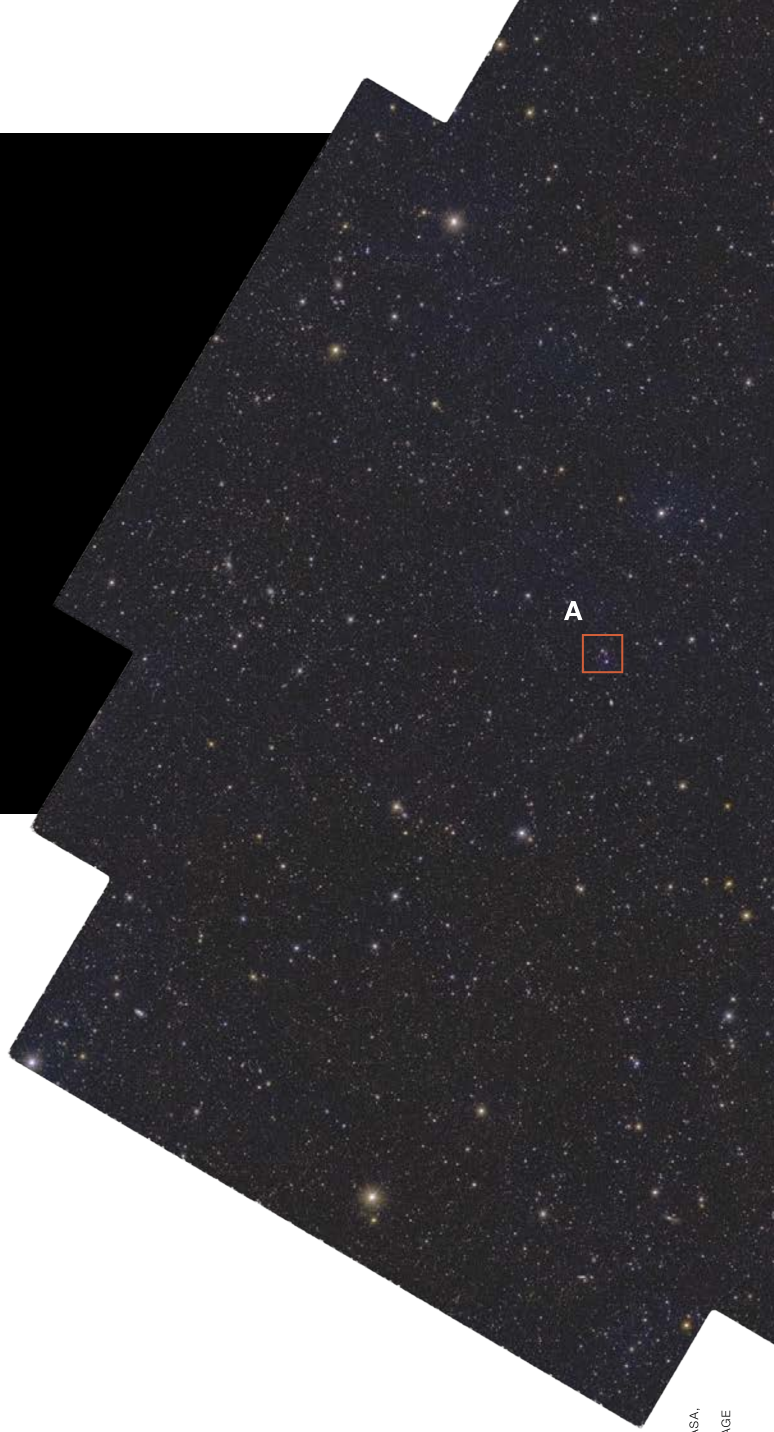
"It's not high-resolution spectroscopy, but it's excellent for everything that has to do with galaxies," says NISP instrument scientist Knud Jahnke (Max Planck Institute for Astronomy in Heidelberg, Germany).

Euclid also needs to be extremely stable, with exquisite instrument calibration and predictable "noise" over time, so that researchers know that the data not only are consistent but also correspond with reality. Images taken today have to be comparable to those taken four or five years down the road. For this reason, Euclid and its instruments rely on simple designs. "Simple in the sense that they don't have too many variable functions, and they are very stable in time," Jahnke explains.

The spacecraft's placement at the L_2 Lagrangian point,







about 1.5 million km (1 million miles) behind Earth's nightside, contributes to this stability. Additionally, the observation routine is always the same. "We go to a location, we take images, we move to the next spot, same thing again," he says. This is because actions like reading sensors or moving the telescope generate heat from electronic components. "If we do that always in the same way, then the thermal impact on the telescope [. . .] will always be the same."

This stability requirement "drives how you operate the whole satellite," Cropper says. These temperature changes "could be just one-tenth of a degree, but that still changes things," he adds.

Euclid's six-year primary wide-field survey will cover more than 14,000 square degrees. Excluded from the survey are the plane of the Milky Way and regions affected by zodiacal light, the latter created by sunlight scattering off dust in the inner solar system. These areas are too bright for precise imaging of background galaxies.

Such a large survey area is necessary to maximize precision. "It's really a question of beating down variability," Jahnke says. Observing just a few clusters at a given distance (and, thus, time) isn't representative enough to tell you what the large-scale structure looks like or how it's growing at that particular point in the universe's history. "So you need to cover a huge amount of sky," he adds.

Euclid will also repeatedly observe three patches of sky, totaling approximately 63 square degrees, to produce "deep fields" that reach two magnitudes fainter than the regular survey will. By showing researchers what they could be missing in the larger survey, these deep fields will allow scientists to calibrate the overall data. The deep fields will also enable astronomers to look for transient phenomena such as supernova explosions. Two of these deep fields were selected

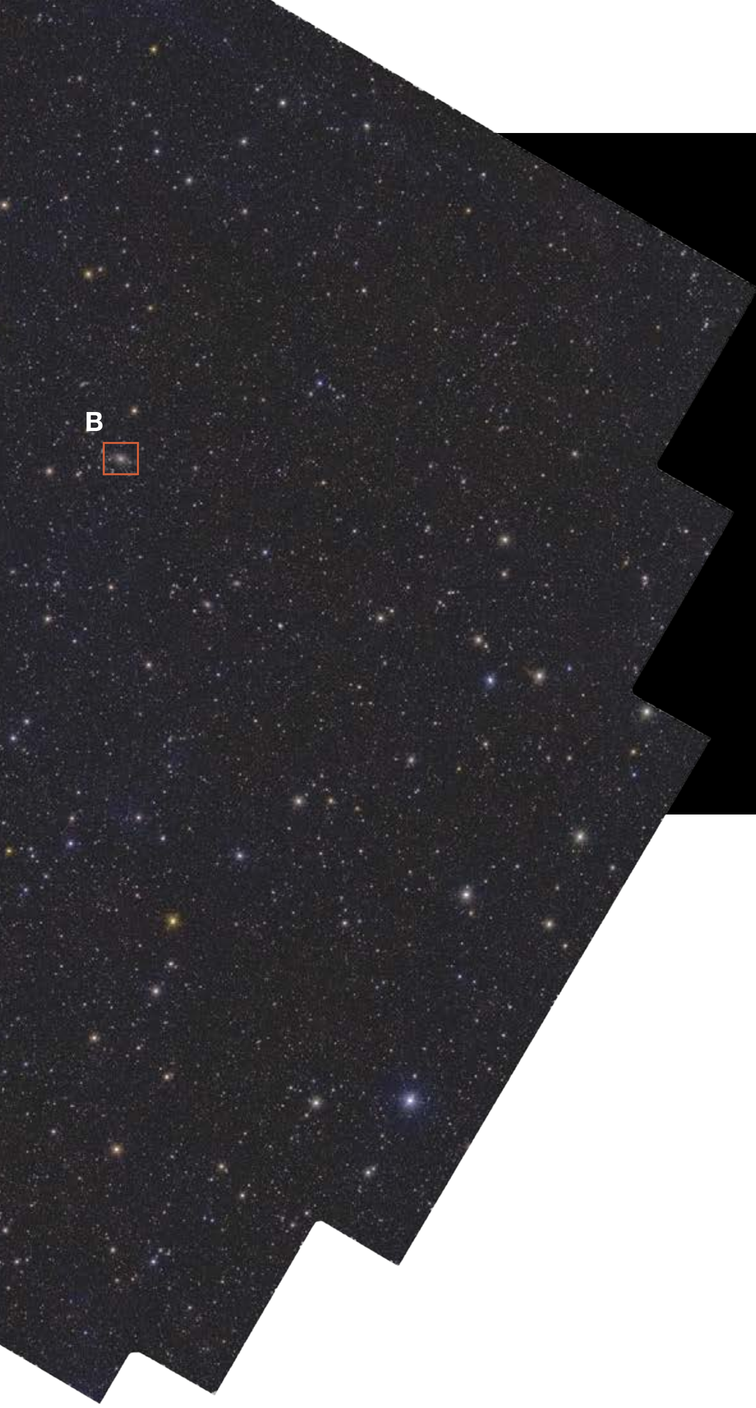
▲ **DEEP FIELD NORTH** Astronomers have already found more than 10 million galaxies in Euclid's Deep Field North, which lies in the constellation Draco, the Dragon. It overlaps a deep field surveyed by NASA's now-retired Spitzer Space Telescope. The insets zoom in on the Cat's Eye Nebula (NGC 6543) and NGC 6505, an elliptical galaxy that acts as a gravitational lens, bending the light from a background galaxy into a ring of light (*S&T:* June 2025, p. 10). The field covers 22.9 square degrees.

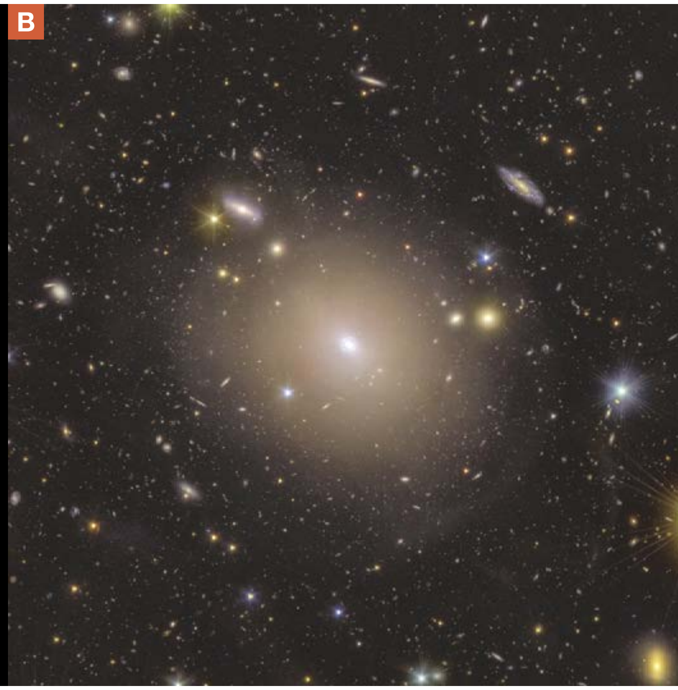
EDF NORTH AND CAT'S EYE: ESA / EUCLID / EUCLID CONSORTIUM / NASA, IMAGE PROCESSING BY J.-C. CUILLANDRE, E. BERTIN, G. ANSELMI; ELLIPTICAL GALAXY: ESA / EUCLID / EUCLID CONSORTIUM / NASA, IMAGE PROCESSING BY J.-C. CUILLANDRE, G. ANSELMI, T. LI

to overlap with deep observations from other space observatories, such as NASA's Spitzer, Chandra, and Hubble as well as ESA's XMM-Newton.

A Software Machine

Euclid's survey is producing a deluge of raw data, which requires advanced technical capabilities and substantive





computing power to unravel. The spacecraft produces more than 100 gigabytes of data daily, enough to fill the average smartphone's memory every single day. This will accumulate to some 32 petabytes throughout the mission, larger than the U.S. Library of Congress's entire digital collection. The mother lode presents a significant challenge in terms of data storage, processing, information extraction, and dissemination to the scientific community.

Astronomers even need computers to find the galaxies in the survey images. "Nobody will look at a million galaxies by eye," Jahnke says. Instead, Euclid scientists need to train algorithms to find and characterize these galaxies.

The galaxies won't stand out easily. "In the detector, a galaxy might be no more than 30 pixels across, with the brightest part occupying just three or four," Cropper adds.

This computer work started long before Euclid's launch. Scientists developed a large-scale cosmological simulation that could match the complexity and volume of the mission's real data, which they called the Flagship simulation. This "mock universe" served as a controlled testing ground, allowing researchers to refine their data analysis pipelines, identify potential biases, and optimize methods for measuring weak gravitational lensing and galaxy clustering. By comparing their analysis results with known parameters within this virtual universe, scientists verified the reliability of their methods before applying them to real data.

Flagship is the largest simulation of its type ever made, following the interactions of 4 trillion particles. "If you have a few particles, solving gravity between those few particles is easy," says Francisco Javier Castander (Institute of Space Sciences, Spain), who led Flagship's development. "The problem is solving it when you have trillions of particles."

In the simulation, each of these particles represents a mass of about 1 billion solar masses; about 100 of them are required to represent a galaxy like the Milky Way. "It's a universe within the computer."

Computer work will also be necessary to derive the cosmological implications. Scientists will use custom-built software to compare Euclid's real observations with the predictions of multiple cosmological models to determine which one provides the best match.

This level of computing complexity comes with risks. "There is a danger of people putting their expectations [about cosmology] into code," Jahnke says. Software engineers could inadvertently tweak the code they're using to fit what they think the data should contain. "A lot of these later steps of cosmology extraction are 'blinded,' so people that code

DEEP FIELD SOUTH The third deep field covers 28.1 square degrees in the constellation of Horologium, the Clock. Astronomers have identified more than 11 million galaxies in the field, after only one observation. No deep surveys have covered this patch of sky before.

ESA / EUCLID / EUCLID CONSORTIUM / NASA, IMAGE PROCESSING BY J.-C. CUILLANDRE, E. BERTIN, G. ANSELMI

and people that do tests do not see the result." Such blind analyses are a common approach for protecting results from scientists' preconceptions.

Other efforts aim to cross-correlate Euclid's data with other surveys, for instance with Planck's measurements of the *cosmic microwave background* (CMB), the relic radiation of the Big Bang era. The CMB acts like a giant lamp whose light is passing through the structures Euclid is observing, says Baccigalupi. The ultimate goal of comparing the different data sets is to measure the abundance of dark energy when the universe started accelerating, roughly halfway through cosmic history.

Euclid's arrival in the midst of significant advances in machine learning and artificial intelligence (AI) also seems serendipitous, Cropper says. "When I started, I was worried as to how we were going to deal with all these data," Cropper says. Now, he explains, it increasingly looks like AI "will just eat its way" through the massive data sets.

Petabyte-Deep Answers

In March 2025, ESA released the first scientific data from the mission, based on just the first pass over the three Euclid deep fields (*S&T:* Aug 2025, p. 10). These data come from only one week of observations and represent less than 3% of the total survey. Yet they revealed 26 million galaxies, the farthest of which we see as they were some 10 billion years ago.

Of these millions of galaxies, scientists have already sorted 380,000 galaxies based on their features, such as spiral arms, central bars, and tidal tails. This catalog represents just 0.4% of the total number of galaxies of similar resolution that Euclid will image over its lifetime. Researchers also found 500 strong-gravitational-lens candidates, most of them previously unknown. This work was accomplished thanks to a combination of AI and citizen-science efforts.

"Astronomers have been at the front of developing AI algorithms for the last decade or so, because astronomy in many ways is a 'computer vision' problem," says Euclid Consortium scientist Mike Walmsley (University of Toronto), referring to astronomers' need to automatically make sense of very large images. These systems are similar to face-recognition software on your smartphone, in which humans first tag training data sets that the machine then learns from to characterize objects of interest. "Once they are trained with enough data, the models become technically superhuman," Walmsley says, in the sense that they can become more accurate than humans and "measure the whole survey almost instantly."

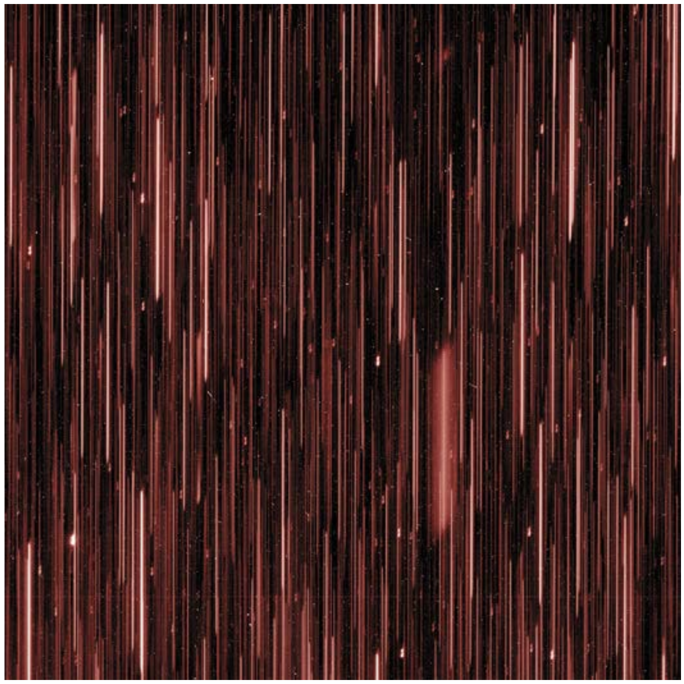
Having said that, Euclid is "a very human endeavor," Cropper notes. "This is something that is made by people, ordinary people, people who get tired and frustrated, people that don't get paid well enough, people who clash culturally without meaning to. . . . It's a wonderful example of cooperation amongst different cultures and different ways of thinking."

That cooperation will soon bring important insights into how the universe works. In late 2026, the collaboration plans to release Euclid's initial cosmology findings, based on a full year's worth of observations. "It's going to be really revolutionary," Pettorino says.

"The beautiful measurements of the cosmic expansion will come with the next releases in a couple of years," Baccigalupi explains. Scientists will then be able to compare the results with those from large ground-based surveys, which have recently hinted that dark energy might be weakening over time (*S&T:* Aug. 2025, p. 8).

Ultimately, Euclid is expected to help cosmologists either validate our standard picture of cosmic evolution on a universal scale or confirm the dynamic nature of dark energy, which would suggest that there are unknown forces at play and require us to revamp our framework. Whatever the result, it will likely stimulate theoretical research and push it in a definite direction, Jahnke says. "There's a lot to be learned, and by 2030 or 2031 we will be able to retire some of these theoretical approaches."

If Euclid achieves what it is specified to do, "it should distinguish between the various models," Cropper says, as he knocks on the wood of his desk. "So far, all the indications are that it will."



▲ **QUICK SPECTRA** This test image from Euclid's commissioning phase shows the light from a patch of sky passed through its spectrometer, which splits light from every star and galaxy by wavelength. Each streak is a source. Astronomers use these spectra to estimate galaxies' approximate redshifts.

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Beyond Cosmology

Euclid will collaterally provide unparalleled coverage of a large portion of the sky for researchers in other disciplines. "It's going to be the best near-infrared database that exists, and it's going to be an almost Hubble-like database of images of the whole sky that I simply can go to and get my favorite objects, or my favorite 100,000 objects," Jahnke says.

The list of Euclid's expected non-cosmological discoveries is long. These include the characterization of more than 100,000 solar system objects, ranging from asteroids and comets to objects beyond Neptune. Euclid will also detect thousands of Type Ia supernovae in far-off galaxies, which astronomers use to calculate galaxies' redshifts and pinpoint the universe's expansion rate. Euclid also has the ability to find free-floating "rogue" planets down to four times the mass of Jupiter and detect exoplanets through *microlensing*, a phenomenon where their passage in front of a distant star causes a brief brightening.

A Deep Dive with *the Dolphin*

There are plenty of visual treasures to explore in the waters of Delphinus.

On late summer evenings, the small but distinctive constellation of Delphinus, the Dolphin, never fails to capture my attention. Located about 12° northeast of Altair, Alpha (α) Aquilae, Delphinus is often overlooked, yet it contains enticing planetary nebulae, globular clusters, and double stars. Looking for a challenge? You can track down the faint, diminutive galaxies scattered across its star-studded field.

The 4th-magnitude stars marking the Dolphin's outline serve as handy navigational anchors to explore the constellation. In order of brightness (and moving counterclockwise), the cetacean's diamond-shaped head includes Beta (β) Delphini in the southwestern corner, Alpha (α), Gamma (γ), and Delta (δ). The tail arcs from Delta through 5th-magnitude Eta (η) and ends at 4th-magnitude Epsilon (ε). When it's near the meridian, the Dolphin appears to be leaping out of the water. But travel to the Southern Hemisphere, and you'll catch a diving Dolphin performing a backflip!

Gamma Delphini, which marks the tip of the snout, is an attractive 8.8″ double for small telescopes. It features a golden primary of magnitude 4.4 paired with a yellow-white companion of magnitude 5.0. However, perceived colors of close pairs often vary, and some observers report the secondary as light blue or blue-green. What do you see?

Gamma has an orbital period of 3,250 years. It forms a wide double-double with **Struve 2725** (Σ2725), a fainter

▲ **SPLASHING AROUND** Delphinus, the Dolphin, is depicted leaping playfully from star-filled waters in Alexander Jamieson's 1822 *Celestial Atlas*. Antinous, to its lower right, is an obsolete constellation that is now considered part of Aquila, the Eagle.

CHART: ALEXANDER JAMIESON / *CELESTIAL ATLAS* (1822) / UNITED STATES NAVAL OBSERVATORY LIBRARY / PUBLIC DOMAIN; WAVE TEXTURE: TAYYAB900 / SHUTTERSTOCK.COM binary 14′ to the south-southwest. Its 7.5- and 8.2-magnitude components are 6.2″ apart and take some 2,100 years to complete an orbit. Gamma and Σ2725 are neighbors in space, separated by only 5 to 10 light-years.

The long-period Mira variable **V Delphini** lies 3.2° due north of Gamma. Every 530 days, V Delphini reaches a peak brightness of magnitude 8 or 9, but in some cycles, it struggles to hit magnitude 11. At minimum brightness, this pulsating red variable plunges below 15th magnitude. On July 20, 1900, Yerkes Observatory astronomer John Parkhurst reported that it had slipped from view in the 40-inch refractor. George Ellery Hale, then the observatory director, estimated the star to be fainter than 17th magnitude — a dip of nearly 10 magnitudes (a factor of 10,000) from its previous maximum.

Last year, I caught V Delphini on the downswing at magnitude 12.7 in early July. Its next maximum should occur this year in early September. But V Del's cycle isn't regular, and its peak may occur a few weeks late. If you'd like to follow its erratic behavior, create a star chart with reference magnitudes of nearby stars from the American Association of Variable Star Observers at **aavso.org/vsp**. Just enter V Del for the variable's name and choose from a selection of predefined charts or customize one to your liking.

Let's shift our gaze 3.6° east of Gamma to the 10.6-magnitude globular cluster **NGC 7006**. This remote outpost, which resides in the Milky Way's halo, follows a highly eccentric orbit that swings between 7,600 light-years and 165,000 light-years from our galaxy's center. NGC 7006 is currently 42,000 light-years below the galactic plane and traveling inbound toward the galactic center. At its far-flung location, the globular is compact and challenging to resolve (its brightest members are nearly 16th magnitude), but it's still easily seen with a small aperture from a dark sky.

Viewing through a friend's 85-mm refractor at 43×, NGC 7006 appears as a fuzzy spot against a starry vista. Sharing the field is an orange 7th-magnitude *M*-type star 23′ southeast. Increasing to 75×, the globular exhibits a vivid core surrounded by a fainter halo. At 565× in my 18-inch reflector, I can resolve a few stars steadily and up to a dozen intermittently, sparkling in the halo.

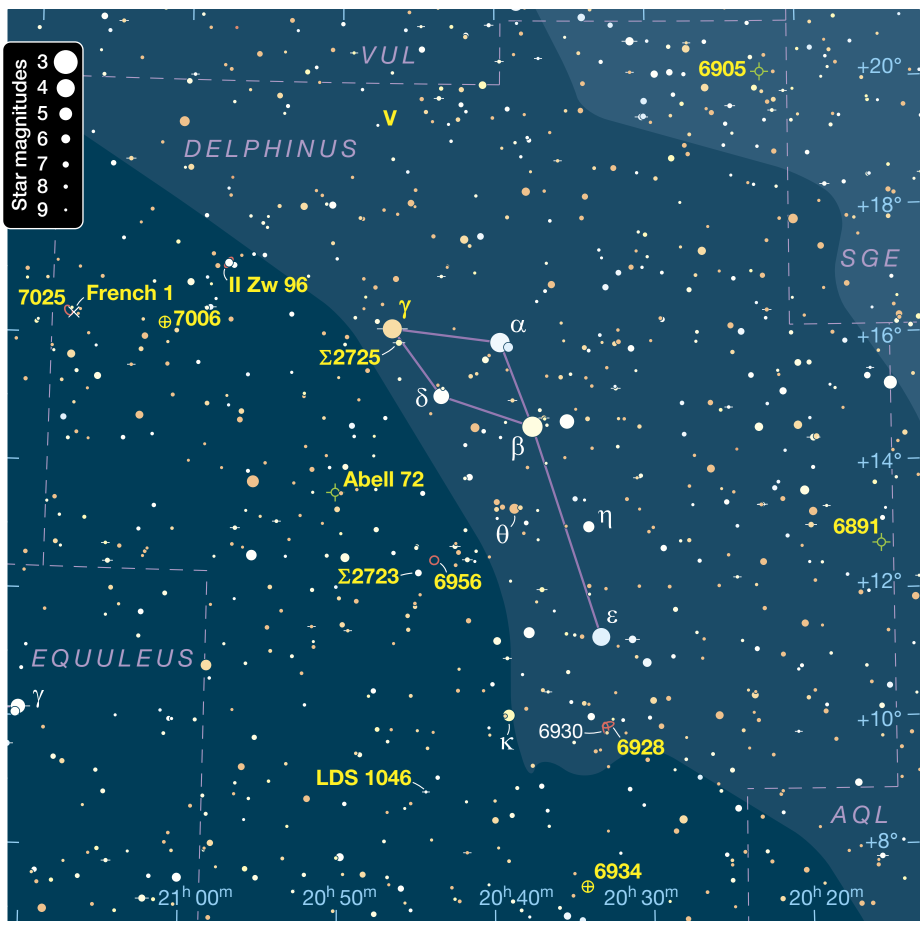
One of NGC 7006's brightest neighbors is PGC 65893, a 14th-magnitude elliptical galaxy just 12′ northwest. At 281×, my 18-inch shows a 20″ glow of moderate surface brightness. A wide pair of 11.5-magnitude stars 2.5′ to the galaxy's northwest point the way.

Even closer is the galaxy PGC 65907, just 3.5′ southwest of the globular's center. With averted vision, I see a 10″ gossamer smudge forming a small triangle with two 11.5-magnitude stars to its northeast. If these distant objects pique your interest, Contributing Editor Ken Hewitt-White featured 10 faint fuzzies less than 1° from NGC 7006 in his article, "Small Globular, Tiny Galaxies" (*S&T:* Oct. 2015, p. 57).

More Faint Fuzzies

Despite the Dolphin's proximity to the obscuring dust and gas clouds of the Milky Way, the constellation is rich in dim galaxies, as shown by the region surrounding NGC 7006.

Another example is **II Zw 96**, also designated PGC 65779, a spectacular mid-stage merger of two gas-rich spirals. This galactic mash-up is situated 1.4° northwest of NGC 7006, at a distance of 500 million light-years. With prodigious infrared emission equivalent to about 870 billion suns, the system



▶ **AQUATIC TARGETS** The relatively small but distinctive constellation of Delphinus is often ignored by observers, yet it offers delightful planetary nebulae, globular clusters, double stars, and galaxies. Use this finder chart to plan your angling strategy — the Dolphin's brighter stars can serve as jumping-off points, and you can refer to the text for detailed star-hopping instructions.

▲ **INTRICATE STRUCTURES** This Hubble Space Telescope image of the 10.4-magnitude planetary nebula NGC 6891 reveals a wealth of structures, including a spherical outer halo and ellipsoidal shells surrounding the central white dwarf star, as well as filaments and knots in the nebula's interior. North is up in all images unless otherwise stated.

▲ **BLUE FLASH NEBULA** Despite its fanciful moniker, discerning color visually in the 10.9-magnitude planetary nebula NGC 6905 can be a challenge. Sergei Komarov used Astro-Physics StarFire EDT 180mm f/9 and PlaneWave Instruments CDK12.5 f/8 telescopes as well as nitrogen II and RGB filters to record this view. North is to the upper left.

is classified a Luminous Infrared Galaxy, or LIRG (for more examples, see *S&T:* June 2022, p. 36). The nucleus of II Zw 96's southeastern spiral is undergoing a surge of star formation, but a powerful, dust-obscured starburst — either in its northeastern halo or the nucleus of a separate, third galaxy — emits up to 80% of the system's far-infrared luminosity. The entire chaotic interaction squeezes into a 30″ circle in the telescope.

Viewed at 281× in my 18-inch, the merged pair is a small oval extending 25″ by 10″ and slanting northwest. A distinct stellar brightening — the nucleus of the smaller spiral — is at the southeastern tip. A 7th-magnitude star shares the telescope field 6′ west-southwest.

Nudge your scope 1.4° east of NGC 7006 and you'll run into the 13′-wide triangular asterism **French 1**. Containing a dozen 9th- to 11th-magnitude stars, author Phil Harrington dubbed this delightful group the "Dolphin's Diamonds." Former *S&T* Contributing Editor Sue French formed a Toadstool outline using its brighter stars.

A close look shows 12.8-magnitude **NGC 7025** just east of the 10th-magnitude star marking French 1's northeastern end. Using my 8-inch reflector at 109×, I see a soft, round glow less than 1′ across. Through my 14.5-inch at 226×, the galaxy sports a small, bright core and has a halo that tilts northeast to southwest.

With no nearby neighbors, astronomers classify NGC 7025 as an isolated galaxy. But deep images show tidal features (telltale signs of a past interaction), and a recent spectroscopic study found that a spike in star formation occurred around 4 billion years ago. The most likely explanation for these anomalies is that NGC 7025 experienced a minor merger with a smaller companion that disrupted its outer disk and triggered a starburst.

Star-Hopping from Theta

Now, let's start at 5.7-magnitude Theta (θ) Delphini, an orange-colored supergiant just east of the Dolphin's tail. **NGC 6956**, a 12.3-magnitude barred spiral galaxy, is a 1.5° hop to the southeast. My 8-inch reflector displays a pale, roundish glow hampered somewhat by an 11th-magnitude star at its eastern edge.

Through my 18-inch, NGC 6956's halo grows slightly brighter to a quasi-stellar nucleus. But my 24-inch at 375× reveals its central bar sloping north to south. A spiral arm attached to the bar's south end curls to the east. The surrounding rich Milky Way field provides a lovely backdrop to this galaxy.

NGC 6956 has two fainter companions: UGC 11620 just 7′ southeast and UGC 11623 about 8′ east-southeast. The triplet forms KTG 71, at a distance of 200 million light-years (for more examples of KTG trios, see *S&T:* May 2015, p. 59). I can spot these small, 14th-magnitude galaxies in my 14.5-inch reflector, but they lack detail other than oval-shaped halos and weakly brighter centers.

Double star **Σ2723** is a close pair of stars of magnitudes 7.0 and 8.3 lying 19′ southeast of NGC 6956. With a period of roughly 800 years, this binary has tightened from 1.5″ in 1831 to its current separation of 1.0″. When the seeing is steady, the components split cleanly in my 14.5-inch at 226×.

From NGC 6956, a star-hop of 1.8° northeast leads to **Abell 72** (PK 059–18.1). This low-surface-brightness planetary

NGC 6891: NASA / ESA / A. HAJIAN (UNIVERSITY OF WATERLOO) / H. BOND (PENNSYLVANIA STATE UNIVERSITY) / B. BALICK (UNIVERSITY OF WASHINGTON), PROCESSING: GLADYS KOBER (NASA / CATHOLIC UNIVERSITY OF AMERICA) nebula lies just east of an 8th-magnitude star. A narrowband (O III) filter helps subdue the star's glow and enhances the planetary's visibility. My 8-inch at 73× shows a subtle gray stain between the bright star and two fainter ones off the eastern and southeastern sides. With my 24-inch at 125×, Abell 72 spans 100″ (larger than M57, the Ring Nebula, in Lyra), and its eastern and western rims contain slightly brighter arcs. Using 375× unfiltered, I can see Abell 72's 16th-magnitude central star, along with a few other superposed faint stars.

Epsilon Environs

Epsilon Delphini is a convenient jumping-off point for several worthwhile targets. Drop 1.4° due south and you'll hit 12.2-magnitude **NGC 6928**, the brightest of a small galaxy group 180 million light-years away. In my 8-inch at 109×, NGC 6928 is a hazy glow trending east to west with a small, bright nucleus. Through my 18-inch at 281×, its slender form stretches 1.2′ by 0.3′ to the east-northeast and exhibits a conspicuous core. A 13.5-magnitude star hugs the northern flank, and several fainter galaxies lie southwest and southeast.

With my 8-inch, I can spot the pale, elongated glow of NGC 6930 just 4′ southeast of NGC 6928. My 18-inch shows it as a weakly concentrated sliver running north-south for 50″. Using 328×, I see a very faint star just off NGC 6930's southern tip, and I can glimpse PGC 200365 as a tiny knot pinned against its northern end. This teensy galaxy hosts an active Seyfert 2 nucleus, with a supermassive central black hole estimated to weigh in at 23 million solar masses.

▲ **SOFTLY GLOWING BALL** Swimming 4° south from Epsilon (ε) Delphini, you'll encounter the 8.8-magnitude globular cluster NGC 6934. Stefan Binnewies and Josef Pöpsel captured this view from Much, Germany, using a remotely controlled Ganymed 60-cm Hypergraph and SBIG STX-16803 camera based on the Greek island of Crete.

NGC 6927, a 14.5-magnitude lenticular galaxy, lies 3′ west-southwest of NGC 6930. I missed it in my 8-inch, but the 18-inch displays a faint, oval smudge extending 20″ along

The Dolphin's Realm

Object	Type	Mag	Size/Sep	RA	Dec.
γ Delphini	Double star	4.4, 5.0	8.8″	20^h 46.7^m	+16° 07′
Σ2725	Double star	7.5, 8.2	6.2″	20^h 46.2^m	+15° 54′
V Delphini	Variable star	8.1 – 17	—	20^h 47.8^m	+19° 20′
NGC 7006	Globular cluster	10.6	2.8′	21^h 01.5^m	+16° 11′
II Zw 96	Galaxy pair	11.5	0.6′ × 0.3′	20^h 57.4^m	+17° 08′
French 1	Asterism	7.1	13′	21^h 07.4^m	+16° 18′
NGC 7025	Galaxy	12.8	1.9′ × 1.3′	21^h 07.8^m	+16° 20′
NGC 6956	Galaxy	12.3	1.9′ × 1.9′	20^h 43.9^m	+12° 31′
Σ2723	Double star	7.0, 8.3	1.0″	20^h 44.9^m	+12° 19′
Abell 72	Planetary nebula	12.7	134″ × 118″	20^h 50.0^m	+13° 33′
NGC 6928	Galaxy	12.2	2.0′ × 0.6′	20^h 32.8^m	+09° 56′
NGC 6934	Globular cluster	8.8	7′	20^h 34.2^m	+07° 24′
LDS 1046	Double star	11.1, 12.1	15″	20^h 44.5^m	+08° 54′
NGC 6891	Planetary nebula	10.4	15″	20^h 15.2^m	+12° 42′
NGC 6905	Planetary nebula	10.9	47″ × 37″	20^h 22.4^m	+20° 06′

Angular sizes and separations are from recent catalogs. Visually, an object's size is often smaller than the cataloged value and varies according to the aperture and magnification of the viewing instrument. Right ascension and declination are for equinox 2000.0. Magnitudes are visual.

its north-south axis. NGC 6927A, just 2′ to its south, is a challenging minute spot of haze.

Next, we'll head to **NGC 6934**, a small 9th-magnitude globular 4° south of Epsilon (or 2.5° south of NGC 6928). In 1830, John Herschel described the cluster as beautiful, very compressed, and well resolved into faint stars. That same year, renowned German Russian astronomer Friedrich Georg Wilhelm von Struve (who is identified in double-star catalogs with the designation Σ) paid him a visit. Herschel treated his guest with a view of the planetary nebula NGC 6572 (a Struve discovery in Ophiuchus) in his large reflector, as well as NGC 6934.

In an 85-mm refractor at 75×, the globular has a high surface brightness and a shiny 1′ core. A 9.3-magnitude star sits near the western edge of the halo, 2′ from the center. Larger apertures resolve the brightest (14th-magnitude) members at high power. A couple of dozen stars scintillate in the halo through my 14.5-inch at 304×, and several more flash into view over the mottled core. With my 18-inch at 538×, the halo swells to 4′ in diameter (elongated north-south) and numerous sparklers are also visible.

Hyades Exodus Stars

For a change of pace, head back to Epsilon and slide 1.9° southeast to 5th-magnitude Kappa (κ) Delphini. If you extend that line the same distance farther southeast, you'll arrive at **LDS 1046**, a high-proper-motion pair. The components are 11.1- and 12.1-magnitude *M*-type dwarfs separated by 15″. An unrelated 13th-magnitude star sits a similar distance south-west, and my 14.5-inch at 66× easily resolves the trio.

▲ **THE TOADSTOOL** Sailing 1.4° west of the spiral galaxy NGC 7025, visible at left, you'll reach the shores of French 1, an inverted toadstool-shaped asterism of more than a dozen 9th- to 12th-magnitude stars scattered over an area 13′ wide.

POSS-II / STSCII / CALTECH / PALOMAR OBSERVATORY

With plenty of star pairs to choose from in Delphinus, why bother with LDS 1046? In this case, it's not what they look like — it's where they originated that's remarkable. As open clusters age, they experience internal stellar interactions, encounters with massive molecular clouds in the galactic disk, and tidal forces from the Milky Way. As a result, a cluster slowly disperses, but lost members might stay in co-moving tidal tails that lead (in the sense of galactic rotation) and trail the cluster. Astronomers have discovered large-scale tails from globular clusters and captured dwarf galaxies. Still, clear-cut evidence of these traits for open clusters has been elusive because of contaminating field stars. However, in 2019 a pair of studies independently discovered two well-defined tidal tails emerging from the Hyades cluster in Taurus. High-precision Gaia positions, proper motions, and 3-dimensional velocity measurements of stars were key to identifying these tails. The structures stretch more than 700 light-years and contain hundreds of former Hyades members.

The LDS 1046 duo are two of these escaped stars. They're at the front of the leading tail in Delphinus, an astounding 112° from the Hyades cluster! Over time, they've both drifted closer to the Sun and are currently 80 light-years away, about half the distance of the Hyades. Using data from the study led by Siegfried Röser (Heidelberg University), German observer Peter Surma created a map of the tidal tails at **https://is.gd/Hyades_tidal_tails**. You'll find LDS 1046 at the head of the Hyades exodus, near the map's lower-right corner.

Up next is **NGC 6891**, a 10.4-magnitude, compact planetary nebula at the western border of Delphinus, 4.6° east-northeast of Epsilon. English astronomer Ralph Copeland discovered NGC 6891 in 1884 using a 6.1-inch refractor with an objective prism designed by stellar spectroscopist Angelo Secchi (*S&T:* Feb. 2025, p. 26). Scanning the Milky Way, Copeland identified the planetary by its telltale monochromatic light (O III emission lines) among the continuous spectra of surrounding field stars.

Through my 80-mm finder at 13×, NGC 6891 is indistinguishable from a faint star, but it gains a significant contrast boost if I insert an O III filter. At 127×, my 8-inch shows a blue, high-surface-brightness disk with a diameter of 10″ at most. My 14.5-inch at 226× exposes its central star as well as a faint, secondary shell that nearly doubles the planetary's size. Through my 18-inch at 700×, the inner shell appears oval with tapered ends, like a lens.

According to researchers, besides the two visible shells, NGC 6891 also has a detached outer halo 80″ in diameter, but it's more than 1,000 times fainter than the inner portion. This delicate structure was formed from mass loss during the progenitor star's late evolutionary phase, called the *asymptotic giant branch*, some 28,000 years ago.

The planetary nebula **NGC 6905** — nicknamed the Blue Flash Nebula — is tucked in the northwestern corner of Delphinus, about 6° northwest of Alpha Delphini. William Herschel discovered the object in 1784, stating,"I do not doubt

▲ **EXQUISITE BARRED SPIRAL** The Hubble captured this portrait of 12.3-magnitude NGC 6956, which lies about 214 million light-years away.

NASA / ESA / D. JONES (UNIVERSITY OF CALIFORNIA – SANTA CRUZ), PROCESSING: GLADYS KOBER (NASA / CATHOLIC UNIVERSITY OF AMERICA)

but it consists of very much compressed stars."

Herschel based his comment on his success in resolving many Messier clusters and nebulae. As a result, he believed all nebulous objects were distant clusters of stars, though he later changed his view. In 1831, William's son John described NGC 6905 as a "fine planetary nebula" and reported that four nearby stars appeared "like satellites." In fact, he checked their configuration over three nights in the hope that they could be a new planetary system!

With my 8-inch at 127×, NGC 6905 is a 10.9-magnitude oval glow spanning at least 30″ from north to south. Under dark, steady skies, my 18-inch provides an impressive view at 565× — the planetary's 15.7-magnitude central star is visible continuously, and the nebula's interior appears irregular. Slightly darker patches lie north and south of the central star, and a brighter triangular wedge fans to its east. John Herschel's "satellites" include a 12.4-magnitude star 0.6′ south-southeast, a 10.4-magnitude star 0.8′ north, and an 11.7-magnitude star 1′ east.

Roughly 10% of planetary nebulae central stars are hydrogen-poor, with strong, broad emission lines in their spectra from helium, carbon, nitrogen, and oxygen. These spectral features resemble those of a rare class of extremely luminous and massive Wolf-Rayet stars. NGC 6905's central star is a scorching, [*WO*]-type Wolf-Rayet with high-excitation oxygen lines and a temperature of 140,000 kelvin.

As you can see, Delphinus has many visual attractions to offer despite its relatively small size, so it's definitely worth a visit the next clear night.

Happy diving!

■ Contributing Editor **STEVE GOTTLIEB** enjoys viewing deep-sky objects of all sizes from northern California. For more of his favorite observing projects, see **adventuresindeepspace.com**.

 by Douglas MacDougal

"TAIL STAR" ABOVE ALKMAAR Dutch landscape artist Lambert Doomer created this January 1681 depiction of the Great Comet of 1680 after it passed perihelion. His dramatic painting includes several astonished onlookers witnessing the comet rising high over a field in Alkmaar. The Great Comet's appearance was key to understanding how these mysterious objects moved about the Sun.

Newton, Halley, and the Great Comet of 1680

How one celestial visitor changed the course of astronomy.

An unexpected celestial event can have a surprising ripple effect on the progress of science. It can compel a reexamination of old paradigms, inspire new lines of investigation, or help confirm a new theory. A dazzling comet that appeared in the autumn of 1680 triggered every one of those effects.

Gottfried Kirch was a 17th-century German astronomer who made his living by publishing calendars and ephemerides. Despite having 14 children (or perhaps because of it), he still found time to view the night sky with his telescope. On the morning of November 14, 1680, Kirch had been observing a waning crescent Moon and Mars, then shifted his gaze slightly westward from the Red Planet. That's when he swept up a "sort of nebulous spot, of an uncommon appearance" in the constellation of Leo, the Lion. Two nights later, the "spot" had changed position and now sported a short tail — telltale signs that Kirch had chanced upon a comet. Not only was it the first comet discovered with a telescope, it was also destined to have an important and inspiring impact on the history of science.

And what a sight it was! One of the great comets of the 17th century, Kirch's comet became known (unfortunately for his shot at fame) as the Great Comet of 1680, and later, Newton's Comet. It put on a spectacular show around the world, becoming one of the rare comets visible even in daylight. It remained a morning showpiece with a 20°- to 30°-long tail as it brightened through November. By early December, however, it disappeared into the solar glare. For the purposes of our story, we'll refer to this remarkable morning visitor as Comet 1.

On December 20th, skywatchers were amazed by another glorious comet, this time adorning the western evening sky. Early Dutch settlers in New York stated that "there appeared an extraordinary comet, it caused very great consternation throughout the province." Some attributed a golden hue to its tail, rendering it all the more beautiful. The comet was a stunning sight on December evenings with a tail said to have reached 70° in length, or even 90° by some reports from Europe. It remained visible to the naked eye until February, and Isaac Newton followed it telescopically until mid-March 1681. We'll call this evening object Comet 2.

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One Comet or Two?

This double celestial spectacle afforded the opportunity for a historic and fruitful mathematical collaboration between Isaac Newton and Edmund Halley. Newton, the brilliant loner famous for his prickly defensiveness, would not be at the top of anyone's list of desirable collaborators. Yet with Halley he was different; their mutual respect ran deep, resulting in a relationship that was "long and happy," according to science historian Robert E. Schofield. Indeed, the greatly gifted Halley would soon devote three years of his life to editing Newton's 1687 masterwork, *Philosophiæ Naturalis Principia Mathematica* (*The Mathematical Principles of Natural Philosophy*, or simply *Principia*), and helping to get it published.

The main challenge for Newton was to apply his newly minted laws of motion to ascertain the orbital parameters of these remarkable comets. But were they two separate bodies, or one and the same? Initially, it seemed doubtful they could be a single object. After all, Comet 1, though beautiful, was less dramatic than showstopper Comet 2. In his book *Comets*, research scientist Donald K. Yeomans (NASA Jet Propulsion Laboratory) wrote that, "The November comet was a morning object with a relatively modest tail, while the one in December was a bright evening object with an enormous tail. Not only did they appear physically dissimilar, but their apparent motions, when taken together, could not be represented with any figure resembling a circle or a straight line."

To understand the uncertainty, it helps to remember that even though Johannes Kepler had published his three laws of planetary motion early in the 17th century, even he wasn't confident that comets behaved at all like planets. According to Halley in his 1705 *A Synopsis of the Astronomy of Comets*, Kepler had observed the parallax of two comets and concluded that they "moved freely through the Planetary Orbs, with a Motion not much different from a Rectilinear one; but of what Kind, he could not then precisely determine."

Polish astronomer Johannes Hevelius, following Kepler, also thought comets moved rectilinearly (that is, in a straight line) or nearly so, though his calculations didn't quite square with that assumption. That's why Newton and others had little reason to doubt that these bodies traveled through the solar system on straight-line paths as they approached or passed by the Sun. They were thought to be purely transient objects without the possibility of a reappearance. Once seen, a comet would fly out of the solar system as fast as it arrived, never to return. In any event, when Comet 1 appeared in the morning sky heading *toward* the Sun, followed by Comet 2 sailing *away*, Newton assumed he had observed two different objects.

◀ **COMET COLLABORATORS** *Top:* Astronomer and mathematician Gottfried Kirch discovered one of the most famous comets in history, the first ever found with a telescope. *Middle:* The great English mathematician Isaac Newton, shown here at age 47, found that number-crunching the orbital path of the Comet of 1680 was "a problem of very great difficulty." *Bottom:* Polymath Edmund Halley is best remembered for the comet that bears his name but was also instrumental in coaxing Newton's *Principia* to publication — a feat often said to be Halley's greatest contribution to the history of science.

KIRCH: ART COLLECTION / ALAMY STOCK PHOTO; NEWTON: GODFREY KNELLER / WIKIMEDIA COMMONS / PUBLIC DOMAIN; HALLEY: PICTORIAL PRESS LTD / ALAMY STOCK PHOTO

Not everyone agreed. John Flamsteed, the first Astronomer Royal, thought they were a single object seen twice. Flamsteed, however, was an observer not a theorist. In one of the first of many disputes with Newton that would later grow to epic proportions, Flamsteed argued in letters that some kind of "magnetic attraction" moved the body around the Sun, returning it in the same direction that it had appeared. Newton summarily dismissed Flamsteed's argument, noting for example that heat will extinguish magnetism, and asserting that the documented motions didn't appear to fit a single body.

While Newton was trying to work out the orbital path of the Great Comet of 1680, yet another remarkable visitor appeared in 1682. Newton's observations of this comet, together with data from American astronomer Arthur Storer, a childhood friend who resided in Maryland (then a British colony), helped convince him that a rectilinear path simply could not work as a mathematical template for cometary motion. Indeed, unpublished manuscripts from that time show Newton trying to compute a trajectory for the 1680 comet from four sets of positions. But it wasn't until September 1685 that he confessed in a letter to Flamsteed that the Astronomer Royal was correct, writing, "taking that [comet] of 1680 into fresh consideration, it seems very probable that those of November and December were ye same comet."

Cometary Conundrum

The arrival of these comets coincided with Newton's work on the laws of motion, as documented later in *Book III* (*On the system of the world*) of the *Principia*, which includes pages of recorded observations, data, analyses, and drawings. Indeed, one of the unresolved outliers in *Principia* and his theory of gravitation was what to do about comets. This section, which

Newton described as "the most difficult of the whole book," recounts his struggles in applying his laws of gravitation — so brilliantly demonstrated with the moons and planets of the solar system — to the motion of comets. Part of the trouble lay with overcoming the long-standing assumption of how comets moved rectilinearly through space. Another had to do with the extreme nature of comet orbits. The most dramatic examples enter the solar system at breakneck speeds diving toward the Sun as they briefly become glorious, long-tailed spectacles before vanishing into the void as quickly as they came.

Both Newton and Halley recognized that the well-observed Comet of 1680 would be a good test of Newton's laws of motion. As Halley wrote in *A Synopsis of the Astronomy of Comets* some years later:

> *At length, came that prodigious Comet of the Year 1680, which descending (as it were) from an infinite Distance Perpendicularly towards the Sun, arose from him again with as great a Velocity. This Comet, (which was seen for Four Months continually) by the very remarkable and peculiar Curvity of its Orbit (above all others) gave the fittest Occasion for investigating the Theory of the Motion.*

Using a subset of observations gathered by himself, Flamsteed, and others, Newton, "partly by arithmetical operations, and partly by scale and compass" plotted the path of the comet. He then assessed his findings against other observations to see if his orbit fit, which it only roughly did. Then Halley, in Newton's words, "determined the orbit to a greater accuracy by an arithmetical calculus than could be done by graphic operations," and significantly reduced the fitting errors. The question now was whether the Comet of 1680 was a one-time visitor on a parabolic track, or if it had been steered by the Sun's gravity into a closed, elliptical orbit and therefore was destined to return. It was a question of mathematical fine-tuning that even today requires exceptionally accurate observations.

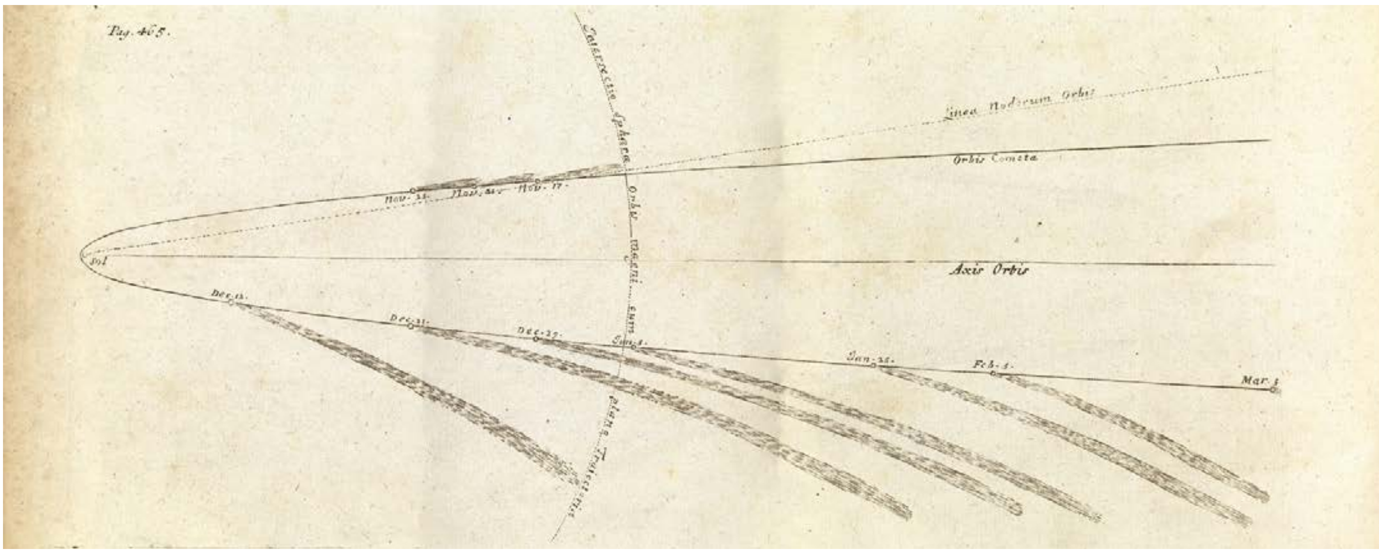
A New Path Forward

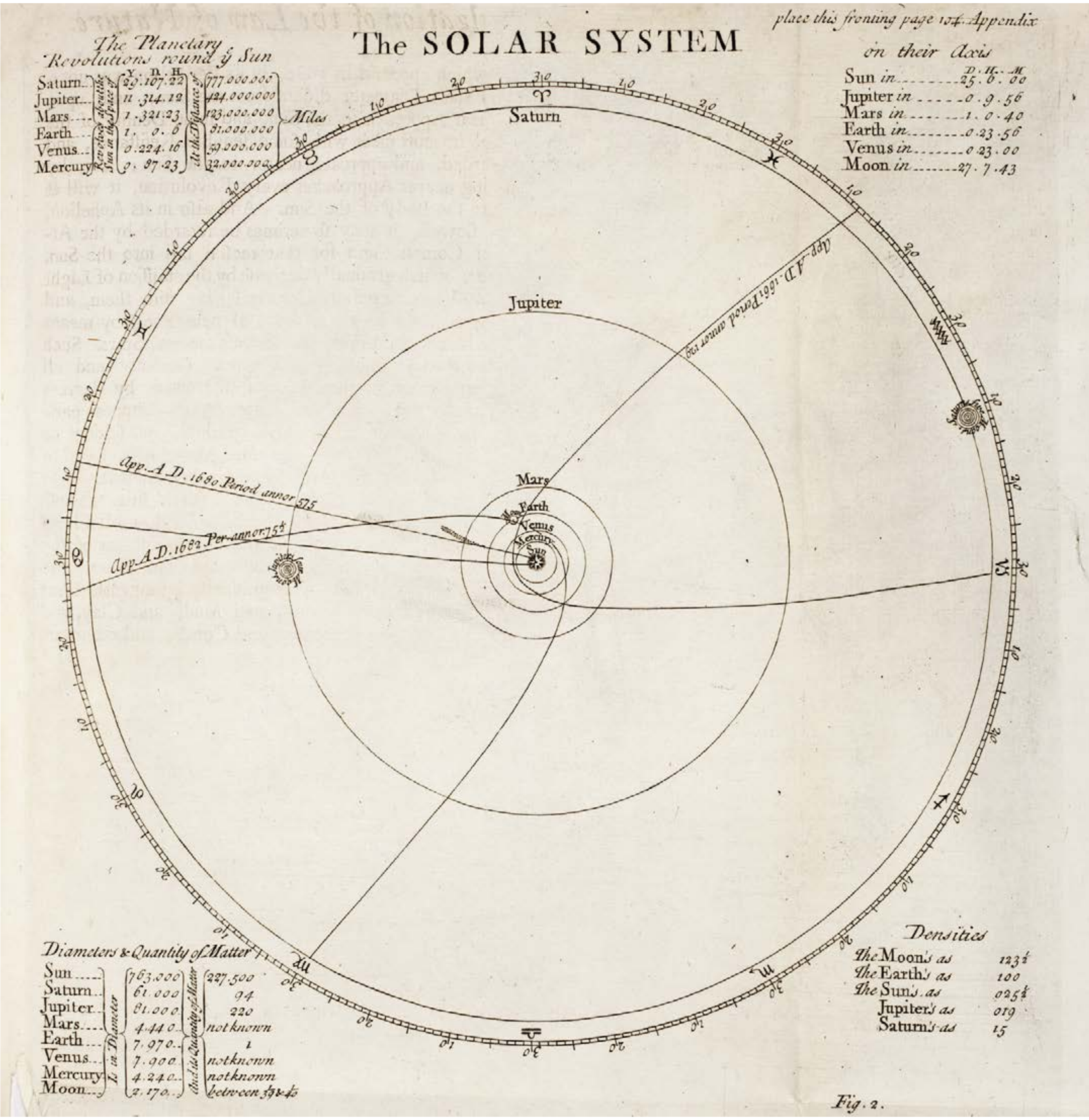
Halley put forth an argument from historical records that the Comet of 1680 was the same object that had been observed at least twice before, with repeat visits every 575 years. Here is how Newton described Halley's insight in his *Book III*:

> *Moreover, Dr. Halley, observing that a remarkable comet had appeared four times at equal intervals of 575 years (that is, in the month of September after Julius Caesar was killed; An. Chr. 531, in the consulate of Lampadius and Orestes; An. Chr. 1106, in the month of February; and at the end of the year 1680; and that with a long and remarkable tail, except when it was seen at Caesar's death, at which time, by reason of the inconvenient situation of the earth, the tail was not so conspicuous), set himself to find out an elliptic orbit whose greater [semimajor] axis should be 1382957 parts, the mean distance of the earth from the sun containing 10000 such [i.e., about 138.3 au]; in this orbit a comet might revolve in 575 years . . . [and with] the equal time of perihelion Dec. 7d. 23h. 9m. . . and its conjugate [semiminor] axis 18481.2 [or about 1.8 au], he computed the motions of the comet in this elliptic orbit.*

Combining this information with his calculations, Newton concluded that the orbit of the Comet of 1680 was not parabolic but instead was a highly eccentric ellipse. His sketch in *Book III* is the first in history showing a comet rounding the Sun. Halley's efforts appeared to be the key to Newton's elliptical-orbit solution. It was also a dramatic early demonstration of how difficult it can be to distinguish between elliptical, parabolic, and hyperbolic orbits, which

▼ **ORBITAL MECHANICS** Comets played an important role in the development of Newton's laws of motion and universal gravitation – his masterpiece, *Philosophiæ Naturalis Principia Mathematica* (*Mathematical Principles of Natural Philosophy*), devotes one third of *Book III* to them. This depiction of the Great Comet of 1680 rounding the Sun appeared in *Principia* and is based on Newton's observations and calculations.





▲ **A SOLAR SYSTEM DOMINATED BY COMETS** Richard Cumberland, an English bishop and philosopher, probably made this drawing when Newton was working on further editions of his *Principia*. It skillfully depicts the orbits of the Great Comet of 1680 and the comet of 1682, which would later be called Halley's Comet. Cumberland's drawing also includes a 1661 comet mistakenly thought to be the return of the spectacular comet of 1532.

exist in that fine zone just slightly this side or the other of an eccentricity of 1.0. If a comet is gravitationally bound into an elliptical orbit (when the eccentricity of the ellipse is less than 1.0, even if only *very* slightly so) it will return. However, if it's in a parabolic or hyperbolic trajectory (where the eccentricity is equal to or greater than 1.0, even if only *very* slightly so) it's a one-time-only visitor.

In truth, though, finding matching returns of 575 years in the historical records should not have led Halley and Newton to conclude that the comets of 531, 1106, and 1680 were one and the same. While the first two ancient visitors made dramatic shows, their full orbital parameters were unknown, so their common identity with the Comet of 1680 couldn't be confirmed. But at least the idea of returning comets was now in the air. When an object's orbital elements are known, it's indeed possible to make intelligent historical comparisons and predict future returns. This was an insight Halley was about to apply brilliantly to the comet of 1682.

Cracking the Comet Code

With Halley's help and much calculation, Newton cracked the comet code and completed his *Book III* — one of the most elegant treatises-within-a-treatise in scientific history. In his role as Newton's computer, Halley generated orbital ephemerides for the comets that appeared in 1664, 1682, 1683, and 1723 (in later editions). All closely matched the positions reported from observations. Toward the end of *Book III*, Newton summed up their mathematical triumph: "From these examples it is abundantly evident that the motions of comets are no less accurately represented by our theory than the motions of the planets commonly are by the theories of them."

By encompassing comets within his mathematical model of celestial motion, Newton demonstrated that they too are simply members of the solar system, subject to the same mathematical laws that govern the rest of the Sun's menagerie.

In 1687, Halley wrote the first review of the *Principia* in the *Philosophical Transactions of the Royal Society*. It was succinct and (perhaps unsurprisingly) glowing. About the mathematical conquest of the orbit of the Comet of 1680, he said:

> *Lastly the Theory of the Motion of Comets is attempted with such success, that in an Example of the great Comet which appeared in 1680/1681, the Motion thereof is computed as exactly as we can pretend to give the places of the primary Planets; and a general Method is here laid down to state and determine the Trajectory of Comets, by an easy Geometrical Construction; upon supposition that those Curves are Parabolic, or so near it that the Parabola may serve without sensible Error; tho' it be more probable, saith our Author, that these Orbs are Elliptical, and that after long periods Comets may return again.*

During this period too, Halley busied himself with many other scientific tasks, including compiling all known historical comets for which he could obtain data to compute their orbital elements. In his *A Synopsis of the Astronomy of Comets*, Halley showed, among other things, striking similarities within the orbital elements of the comets of 1531, 1607, and 1682. Halley concluded that all these sightings were actually of the same comet following an elliptical orbit. He boldly predicted it would be back: "Hence I dare venture to foretell that it will return again in the year 1758. And, if it should then return, we shall have no reason to doubt but the rest must return too."

Although Halley died in 1742 at age 85, his comet reappeared, almost miraculously it seemed, on Christmas Day in 1758. The return of Halley's Comet made an enormous impact. As MIT author Marcia Bartusiak wrote in her book *Archives of the Universe*, "The public was bedazzled and Newton's critics were instantly silenced. It was at that moment that Newton's controversial law of gravity was at last triumphant among both scientists and the public, and Halley's name became forever linked to the periodic celestial visitor."

▲ **SHOWY SUNGRAZER** This image of the glorious sungrazer Comet Lovejoy (C/2011 W3) was taken from the International Space Station a week after the icy visitor's perihelion. Like the Great Comet of 1680, Lovejoy managed to survive a terrifyingly close perihelion passage.

NASA / JSC / DAN BURBANK

A Certifiably Prodigious Comet

Halley's Comet returns reliably every 76 years because it plays it safe with low-risk trips around the Sun, never approaching closer than Mercury's orbit. The Great Comet of 1680, on the other hand, was a daredevil, trading safety for show by venturing scorchingly close (900,000 km) to the Sun's surface — nearly 100 times closer than Halley's Comet ever gets. Its perihelion resembles that of the famous Kreutz sungrazer family of comets, the showiest, most kamikaze-like visitors in history — including Comet Ikeya-Seki (C/1965 S1), and more recently, Comet Lovejoy (C/2011 W3).

In mid-December 1680, Gottfried Kirch's Great Comet skimmed close to the Sun at a pants-on-fire pace of 534 km per second (1.2 million miles per hour). Its remarkably close encounter with the Sun explains why it was so astonishingly brilliant when it reappeared a short time later to begin its outbound journey. Modern analyses reveal an even tighter eccentricity and a semimajor axis more than triple Newton's estimate, making its orbital period almost 9,400 years! Kirch would have been pleased to know his find was so exceptional, even if it never achieved the lasting fame of Halley's Comet.

■ **DOUGLAS MACDOUGAL** still treasures his sketchbook of Comet Halley's 1985–86 apparition, seen with his 6-inch telescope from his backyard in Hawai'i. He's the author of *Newton's Gravity: An Introductory Guide to the Mechanics of the Universe*. You can read his blog at **douglasmacdougal.com**.

ALMA's Face Lift

Extensive upgrades to the prolific observatory will propel its prowess back to the cutting edge.

Up on the desert plateau, as close to the arid skies as we could put it, one of humanity's finest telescopes is growing old. The Atacama Large Millimeter/submillimeter Array (ALMA) sits high in the Chilean Andes, eyeing the heavens day and night. It's been doing so for nearly a decade and a half.

This high stretch of the Atacama Desert is not a gentle place for a telescope. Sometimes, the observatory's 66 antennas have to turn away from the sky, tucking themselves east and downwards to huddle away from the wind.

ALMA was placed on this lofty, inhospitable land to avoid humidity. Its receivers catch a niche portion of the electromagnetic spectrum, right between short radio waves and far-infrared. These wavelengths are absorbed by water in the atmosphere. To catch the photons before the atmosphere does, astronomers built ALMA at an altitude above most water vapor — 5,000 meters (16,500 ft) above sea level, in the driest non-polar desert on Earth.

The antennas are designed to withstand the frigid wind that whips across the plateau, sometimes reaching speeds of 160 km/h (99 mph). Up here, the barometric pressure is about half that at sea level. The supercomputer, which correlates signals from the individual antennas so that they work together as one large telescope, receives special ventilation to compensate for the thin air.

But even a first-rate team of engineers can't stop the march of time. The observatory is now in its 14th year of operations. That might not sound so long, but ALMA was built with state-of-the-art electronics, the definition of which moves quickly these days: ALMA released its first images to the public the day before Apple announced the iPhone 4s. (We're now on 16.) While our own pocket lenses and data storage have multiplied, ALMA's still analyzing distant galaxies with the same old chips and cables that it began with in 2011.

REMOTE OUTPOST Perched on the Chajnantor Plateau in the Chilean Andes, ALMA uses 66 radio dishes to study the cosmos. It appears here as it was in December 2012, a few months before its inauguration in March 2013. (Science operations had begun in 2011, with a smaller number of antennas.)

ESO / BABAK TAFRESHI (TWANIGHT.ORG)

"Not even the computer in your house can survive 20 years," says Álvaro González, the observatory's deputy director of development. Critical pieces break down, and replacements stop being sold, especially for a supercomputer as custom-made as ALMA's.

None of this comes as a surprise. Modern observatories constitute such feats of scientific architecture that they resemble medieval cathedrals in manpower, funding, and timeline. Yet they're not meant to last nearly as long; astronomers and engineers design them with the knowledge that they will quickly be overshadowed.

Some telescopes have been deprioritized or shut down when they start to show their age. But ALMA is indispensable. It remains far and away the best eye on the sky in the millimeter- and submillimeter-wavelength range, perfect for studying cold, dusty pockets of the universe. The observatory receives roughly 1,700 proposals each year from astronomers around the world, the large majority of which must be denied due to scheduling constraints. It also has no direct successor on the horizon to cover these wavelengths.

▼ **MORE HOSPITABLE** Workers stay at the Operations Support Facility, at a lower elevation of 2,900 meters. The buildings include offices, labs, and a cafeteria.

And refurbishment makes sense after such a steep upfront cost: With a construction price tag of $1.4 billion (equivalent to $1.9 billion today), ALMA is one of the world's most expensive ground-based telescopes to date.

Ideas for a massive upgrade started stirring practically as soon as the observatory achieved first light. Planners drew up an official road map in 2018. Today, the ALMA 2030 Wideband Sensitivity Upgrade (WSU) is well under way.

The WSU will retrofit ALMA's entire nervous system, from the front-end receivers through every step of data transmission and processing, until observation results are handed neatly to researchers. It will usher the observatory back to the cutting edge, ensuring its relevance and priming it for continued collaboration with the James Webb Space Telescope and other new instruments.

It will take years to upgrade the observatory piece by piece. While the timeline isn't certain, the result is: ALMA will continue producing exceptional science for many years to come.

The Big Retrofit

From the Operations Support Facility (OSF), at a more hospitable altitude of 2,900 meters in the foothills, swaths of red and pink landscape stretch for miles until they hit tower-

ing Andean peaks. Wild donkeys walk around the compound, ambling among buildings holding laboratories, offices, and dormitories that stand stark against the desert. Distant mining operations light up at night, competing with the stars above.

It's here that the majority of non-maintenance operations take place. As the Sun sets, lights blink out everywhere across the observatory except the control room, where a lone astronomer stands guard through the early morning hours, directing observations and checking data as it streams in.

Workers typically travel to the remote outpost for eight days at a time, where they are fed and housed. There's even a gym and a soccer pitch. Every morning, the cafeteria fills with dozens of chattering engineers and technicians, and as the wide sky lightens, people flow into the medical rooms to have their vitals checked. They need daily clearance and oxygen tanks to head 2,000 meters higher to the Chajnantor Plateau, where ALMA's antennas squat in various configurations, sometimes spread up to 16 kilometers (9.9 miles) apart.

Many of the upgrades will unfold up here. It takes about 50 minutes to drive from the operations facility to the station housing the multi-room supercomputer, known as the correlator. If the antennas are the eyes of the observatory, then the correlator is the brain, and the kilometers of fiber-optic cables stretched from one to the other make up the nerves between them. Without the correlator, ALMA would be a disconnected collection of dishes (*S&T:* May 2025, p. 14). "Really, the correlator is the key link in all of this," says observatory scientist John Carpenter.

In the cold air outside the supercomputer's station, gloved technicians walk around, dwarfed by the assortment of 7-meter- and 12-meter-wide antennas. The larger ones weigh about 100 tons. When radio waves arrive from far-off galaxies and stars, they bounce off these dishes into the receivers.

The antennas were designed to house 10 receivers, each sensitive to a particular range (or "band") of wavelengths. Band 3, for instance, catches wavelengths of 2.6 to 3.6 mm, ideal for detecting molecules in interstellar gas clouds.

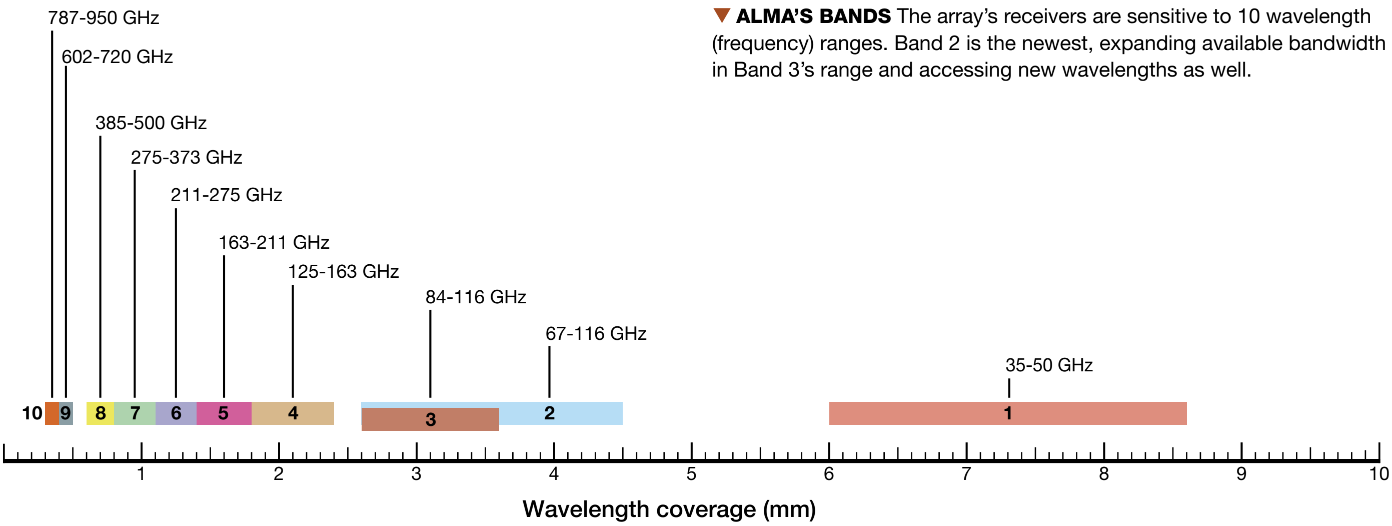
▲ **DEEP BREATH** A technician checks the ALMA correlator's electronics at the high-altitude site. Here, everyone needs supplemental oxygen.

Band 7 (0.8 to 1.1 mm) is better suited for studying the dust around newborn stars.

Astronomers have added the receivers in installments over the years, gradually broadening ALMA's vision to span from 0.3 to 8.6 millimeters. Band 2 (2.6 to 4.5 mm) will be the last of the 10 slotted in. It will also be the first with WSU capabilities, followed by an upgraded replacement of Band 6.

Although they're easy to switch between, only one band can be used at a time, limiting the wavelengths astronomers can record during an observing campaign. If, for example, researchers are looking for the redshift of a particular galaxy, they might have to try several bands before they hit on the spectral lines they need. This process takes time, a precious commodity on such a highly sought-after telescope.

The primary goal of the WSU is to double, and eventually quadruple, the span of frequencies that receivers detect at one time. That means that each antenna will be able to record



▼ **ALMA'S BANDS** The array's receivers are sensitive to 10 wavelength (frequency) ranges. Band 2 is the newest, expanding available bandwidth in Band 3's range and accessing new wavelengths as well.

OPERATIONS SUPPORT FACILITY: ESO; CORRELATOR: CARLOS PADILLA (NRAO / AUI / NSF); WAVELENGTH DIAGRAM: BEATRIZ INGLESSIS / S&T

data from a wider range of wavelengths simultaneously. What might today take several observations could be done in just one or two. The massive front-end improvements should also reduce noise and increase sensitivity.

But upgrading the hardware within the antennas is only the first step.

Having traveled from far-off stars and galaxies, entered Earth's atmosphere, and finally rained down on the Chajnantor Plateau, the millimeter- and submillimeter-wavelength photons that hit ALMA's parabolic dishes are not immediately useful to astronomers. First, they need to be fashioned into a comprehensible format. An automated system digitizes the signal, then transfers it via the fiber-optic cables to the correlator. From there, the raw data sets enter the archives. Usually within 30 days, specialists known as *science archive content managers* pull the data back out for calibration, formatting, and quality assurance, before delivering the data to the researchers who requested the observation.

The upgrade requires a revamp of every link of that chain. "Everything needs to be able to handle a lot more data," says Carpenter.

Carpenter chaired the committee that decided to pursue the WSU overhaul instead of other options, such as increasing the number of antennas, expanding the possible distances between them (which would improve resolution), or adding focal arrays to them. "We felt the WSU had the biggest bang for the buck," he says.

With current receiver bands and 3-bit digitizers, each antenna produces 96 Gbps of data. Improvements will multiply that rate by a factor of 10. New fiber optics laid under the road will stream the data all the way down to OSF, home of the new correlator, as well as a new digital spectrometer that will process data from a handful of single-dish antennas. New software will process everything after.

In Search of Our Cosmic Origins

Over the last 14 years, ALMA has captured light from galaxies up to 13.4 billion years in the past. It has consistently broken records — the farthest oxygen ever detected, the most distant rotating galaxy, the sharpest view yet of gas filaments threading the Milky Way's churning core.

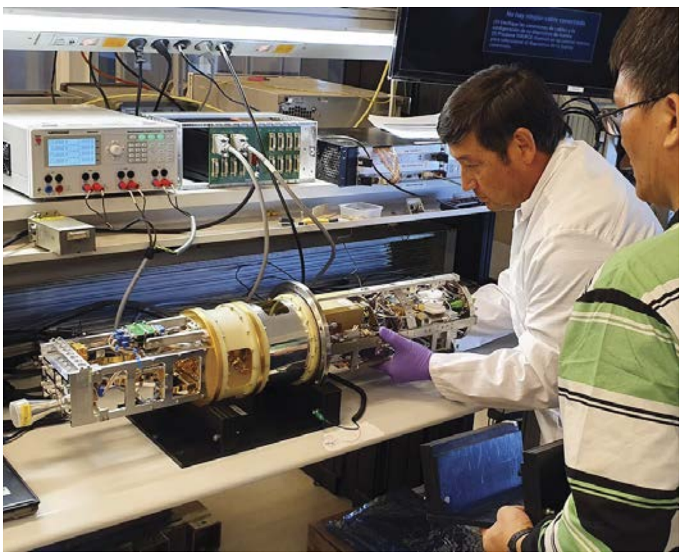
In 2014, the observatory took a groundbreaking image of HL Tauri, a young star surrounded by a disk of dust and gas, ringed with the gaps predicted to exist during the early stages of planet formation. In 2017, ALMA joined the Event Horizon Telescope, a global network of radio observatories, to detect the light-ringed silhouettes of two supermassive black holes, one at the center of the galaxy M87 and the other in the heart of the Milky Way (*S&T:* Sept. 2019, p. 18).

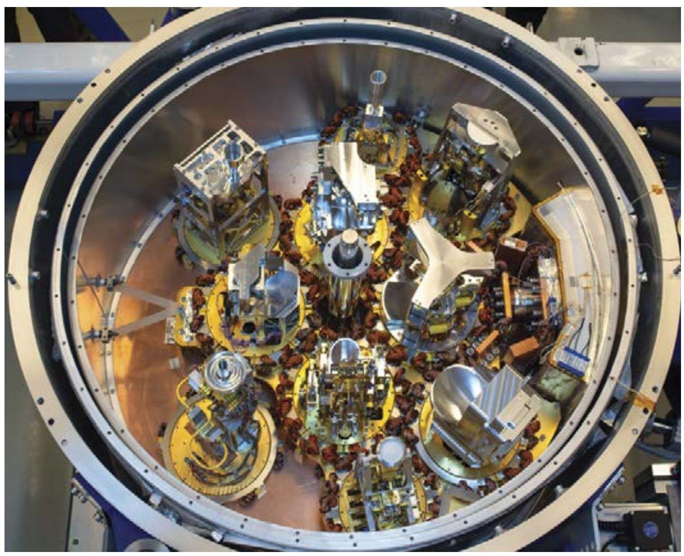
As a whole, the telescope has been incredibly productive. In fact, the ALMA International Visiting Committee decided in 2019 that the project's initial goals for studying distant galaxies and forming planetary systems had already been achieved.

Now, ALMA has its sights set even higher. On fainter, farther galaxies. On more precise, detailed images of protoplanetary disks.

The observatory's motto has always been "In Search of Our Cosmic Origins." The WSU's goals center around that mission, focusing on beginnings — of planets, galaxies, and chemical complexity.

ALMA has led in imaging protoplanetary disks since HL Tau. Its library of images displays many examples of the swirling, sometimes ring-laden gas and dust around young stars. The gaps in these disks suggest the presence of emerging giant planets. But we're only beginning to understand protoplanetary disks. For example, recent research suggests that disks around low-mass stars, which make up the majority of star systems, are far more compact than the brightest examples imaged before, and they generally don't have gaps



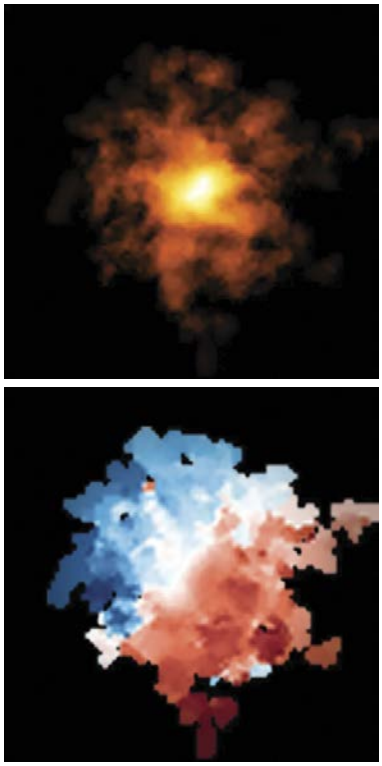


▲ **RECEIVERS** *Left:* Band 1 receiver being assembled at the OSF. *Right:* An ALMA antenna's cryostat with 10 receivers inside. The cryostat cools the receivers to only a few degrees above absolute zero.

BAND ASSEMBLY: G. SIRINGO / ALMA (ESO / NAOJ / NRAO); 10 RECEIVERS: S. OTAROLA / ALMA (ESO / NAOJ / NRAO)

(*S&T:* Aug. 2025, p. 11). Astronomers want to collect more examples, in as much detail as possible, to paint a clearer picture of the planet-formation process.

One important piece of evidence is the chemical composition of different parts of the disk. ALMA traces the properties of protoplanetary disks by tracking various molecules within them — in fact, it's been a world leader in this work. But doing so requires *high spectral resolution*, or the ability to distinguish between closely spaced wavelengths in an observing target's spectrum.



◀ **DISTANT GALAXY** ALMA's image of the early galaxy REBELS-25 *(top)* shows the distribution of cold gas inside the galaxy. When astronomers look at the gas's motion *(bottom)*, they see clear rotation: Blue is toward Earth, red away, with darker shades being faster. The motions reveal that REBELS-25, seen as it was only 700 million years after the Big Bang, has an orderly rotating disk. Astronomers expected more chaos.

Right now, ALMA can achieve the spectral resolution required to detect specific molecular transitions — such as when molecules switch rotation states, emitting photons in the process — but not across an entire band. The correlator simply can't handle it. Observers have to narrow their scope to achieve that level of detail, which means that teams have to choose a handful of molecular transitions to look for and ignore the forest of spectral lines belonging to other compounds.

"It's a shame," says Carpenter. "You might be spending 20 hours looking at various points in the disk, throwing away all this information because you can't collect it with the correlator."

The WSU will make it possible to scan for dozens of molecular transitions simultaneously, providing an order-of-magnitude increase in the number of spectral lines observed at high resolution. That change will enable more efficient mapping of chemical abundances, velocities, and gas kinematics.

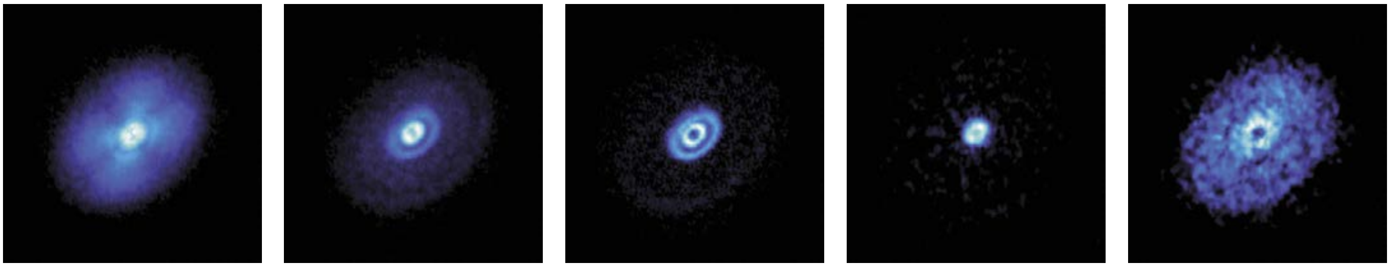
This improvement will help us pin down planets in the early stages of formation, which are difficult to image directly: They're too faint and puny compared to the bright disks they swim through. By capturing more detail on the internal motions and compositions of these disks, we can piece together where and how planets are being born. One day, that knowledge could help us fill in the details of our own planet's origin story.

Beyond protoplanetary disks, ALMA will use its revamped capacity for detecting molecules to explore all sorts of environments, from the interstellar medium to the envelopes of aging stars. Scanning the cosmos after WSU, it will capture a much more diverse chemical inventory.

Scientists will use ALMA to look for molecules previously undiscovered in space, in particular any biologically significant ones. They'll probe the clouds where stars are born and where organic molecules form, in an effort to understand the origins of chemical complexity — ultimately, how our universe became home to the building blocks of life, and then life itself (*S&T:* July 2025, p. 34).

▲ **REPAIR VEHICLE** Designed like an airline catering truck, a service vehicle rises into the air to access the receiver cabin on a 12-meter dish. The vehicle itself weighs 26 tons and has a cargo hold for storing receiver cryogenics.

REBELS-25: ALMA (ESO / NAOJ / NRAO) / L. ROWLAND ET AL. (2); ELEVATED TRUCK AMONG DISHES: C. PADILLA (NRAO / AUI / NSF)

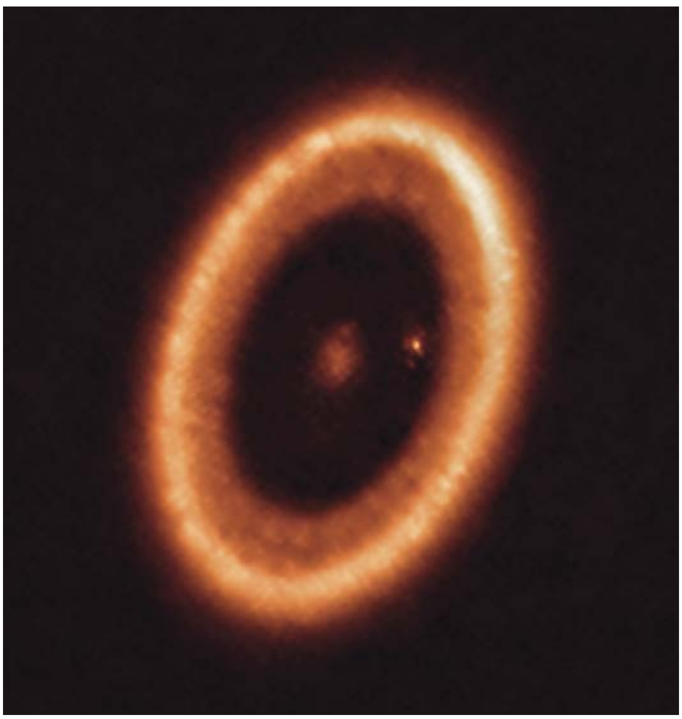


▲ **MOLECULES MATTER** These five ALMA images all show the same protoplanetary disk system, HD 163296, but looking at different molecular spectral lines. The disk's appearance changes dramatically depending on the observed line, due to the disk's properties.

ALMA's third steering goal is to chart the history of galaxies over cosmic time. Galactic evolution informs various lines of research, from testing cosmological theories to understanding the story of our own Milky Way.

The observatory has already unveiled galaxies from the cosmic dawn through to the recent universe. With the WSU capabilities in place, ALMA aims to reach back to the very first galaxies. It will also trace how galaxies' chemical compositions have evolved from cosmic dawn through cosmic noon, the latter being a period that lasted from roughly 7.5 to 11.5 billion years ago when the rate of star formation peaked across the universe.

And observations will be much faster, which is important for a telescope under such high demand. Right now, depending on the source, it could take multiple hours just to determine a single galaxy's redshift. With the WSU, spectral scans could be 50 times more efficient, enabling much larger surveys.



▲ **YOUNG PLANETS** The PDS 70 system, located some 400 light-years away, has at least two exoplanets: 70b (not visible) and 70c (dot at center right), which has its own disk. The planets occupy a cavity in the star's protoplanetary disk.

The exploration of galactic evolution, protoplanetary disks, starbirth, and organic molecules will keep ALMA busy in its third decade. But these aren't the only projects that will benefit from the upgrade. Improved sensitivity, efficiency, and *spectral tuning grasp* (which refers to the telescope's ability to detect a wide range of spectral lines at the same time) will impact every observing campaign ALMA undertakes.

"Slow and Steady" Wins the Race

That's why the WSU was selected in the first place. It certainly wasn't chosen for simplicity: The upgrade involves at least 10 subprojects, all in various stages of design that will take years to pan out.

But with a price tag likely exceeding $100 million, the WSU is still cheaper than other upgrades could have been, and it will be more universally impactful.

Much of the high-level planning has been done in Santiago, Chile's capital city, which sits about 1,600 km south of ALMA at a far more clement elevation of 520 meters above sea level. The observatory's administrative headquarters lie at the end of a wide road lined with coffee shops and boutiques. Surrounded by greenery and birdsong, the offices are the opposite of OSF's Martian-esque landscape.

Here, project manager Carla Crovari is working to schedule the upgrade as smoothly as possible. Every component needs to be designed, approved, assembled, integrated, and commissioned. A single delay could affect everything.

Most importantly, she says, they don't want the WSU to interfere with data taking. They'll do it bit by bit in parallel, old systems working with new until everything is launched, with the goal of minimizing technical downtime.

"We want to be mindful of the users," she says, "of the people doing research with the observatory."

Planners aim for initial WSU-enabled operations by the end of the decade. Users will feel the benefits immediately.

"There's always a question: Do you continue the same way, or do you try for the next big leap?" says González. ALMA has chosen the latter. "We're evolving for the science we want to do."

■ Science journalist **PAIGE CROMLEY** was very cold in the Atacama. She writes about astronomy and the environment.

HD 163296: K. I. ÖBERG ET AL. / *ASTROPHYSICAL JOURNAL SUPPLEMENT SERIES* 2021; PROTOPLANETARY DISK: ALMA (ESO / NAOJ / NRAO) / BENISTY ET AL.

SKY AT A GLANCE
September 2025

2 EVENING: Algol shines at minimum brightness for roughly two hours centered at 9:20 p.m. EDT (see page 50).

7 FULL MOON (2:09 P.M. EDT): A total lunar eclipse will be visible across easternmost Africa, most of the Middle East and Asia, and the western half of Australia. See page 50 for more.

8 EVENING: Face east to see the waning gibbous Moon rise in tandem with Saturn some 5½° to its right.

12 EVENING: The Moon, two days shy of last quarter, follows the Pleiades by about 3° as they rise above the east-northeastern horizon.

13 DUSK: Look very low in the west-southwest to see Spica and Mars a smidgen more than 2° apart. Binoculars will enhance the view, but you'll have to be quick to catch this sight before the star-planet duo sink out of view. Turn to page 46 for more on this and other events listed here.

16 MORNING: Turn toward the east-northeast to see the waning crescent Moon in Gemini where it forms a delightful, near-isosceles triangle with sides of around 4° long. Jupiter is to the Moon's lower right and Pollux to its lower left.

19 MORNING: The soft glow of the zodiacal light should be visible from dark locations at mid-northern latitudes beginning about two hours before sunrise. In the next two weeks, look toward the east for a tall, hazy pyramid of pale light stretching from Cancer through Gemini and into Taurus and beyond.

19 DAWN: A tight trio comprising the lunar crescent, Venus, and Leo's brightest light, Regulus, adorns the east-northeastern horizon.

19 EVENING: Algol shines at minimum brightness for roughly two hours centered at 11:12 p.m. PDT.

20–21 ALL NIGHT: Saturn arrives at opposition, where it shines in Pisces. The Ringed Planet glides into Aquarius at the very end of the month.

21 NEW MOON (3:54 P.M. EDT): A partial solar eclipse sweeps across New Zealand, the South Pacific Ocean, and Antarctica.

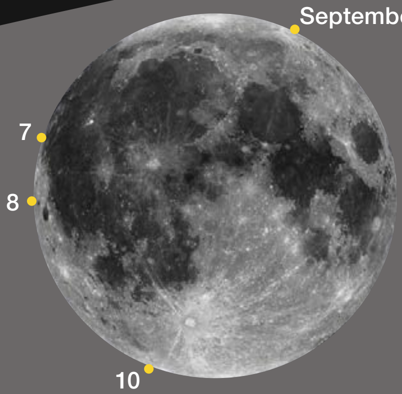
22 AUTUMN BEGINS in the Northern Hemisphere at the equinox, at 2:19 p.m. EDT (11:19 a.m. PDT).

22 EVENING: Algol shines at minimum brightness for roughly two hours centered at 11:01 p.m. EDT.

27 DUSK: Look toward the south-southwest to catch the sight of the waxing crescent Moon 3° left of Antares, the celestial Scorpion's heart.
—DIANA HANNIKAINEN

▲ Saturn arrives at opposition this month. This image shows one of the Cassini mission's last views of the planet taken on October 28, 2016, seen from a perspective impossible from Earth. NASA / JPL-CALTECH / SPACE SCIENCE INSTITUTE

SEPTEMBER 2025 OBSERVING
Lunar Almanac
Northern Hemisphere Sky Chart



Yellow dots indicate which part of the Moon's limb is tipped the most toward Earth by libration.

NASA / LRO

MOON PHASES

SUN	MON	TUE	WED	THU	FRI	SAT
	1	2	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				

FULL MOON
September 7
18:09 UT

LAST QUARTER
September 14
10:33 UT

NEW MOON
September 21
19:54 UT

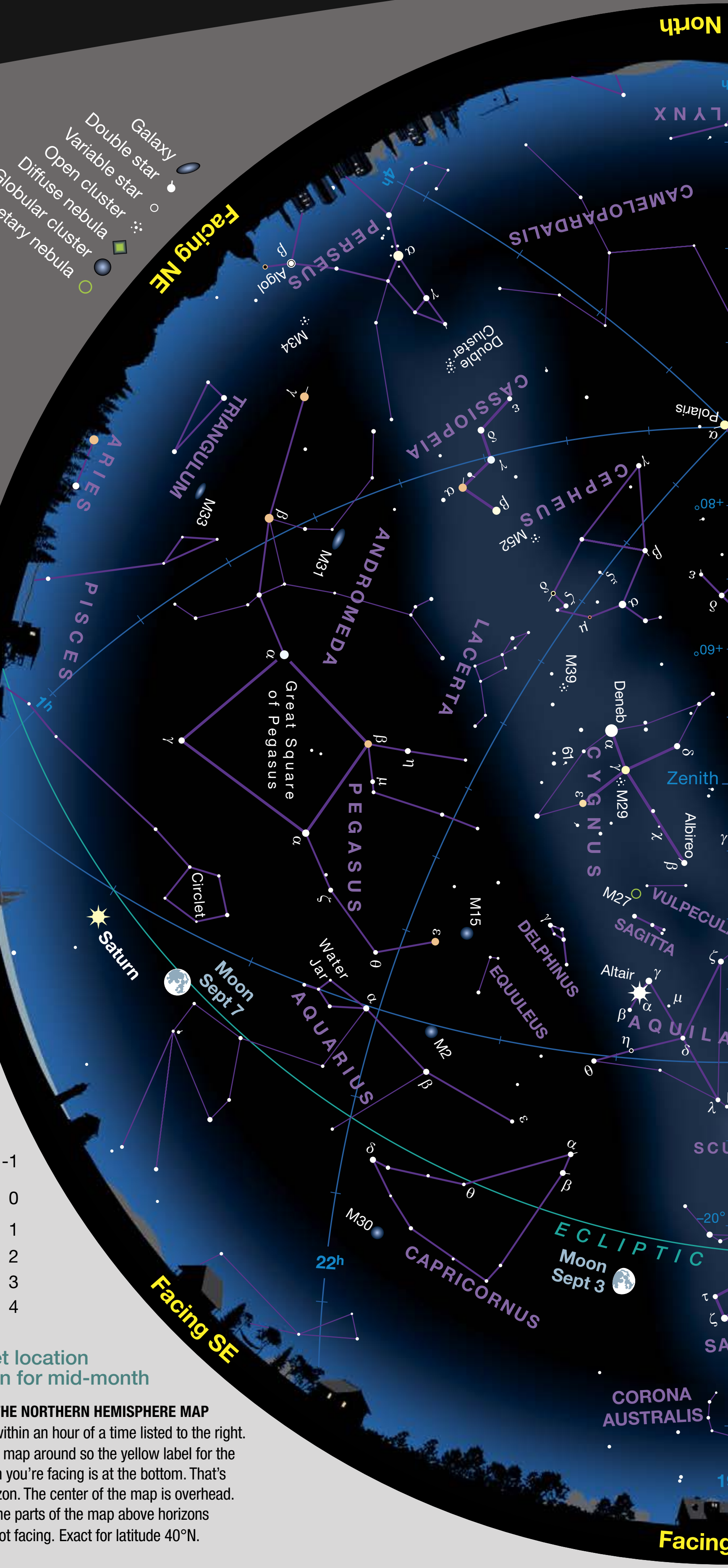
FIRST QUARTER
September 29
23:54 UT

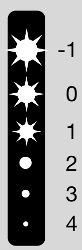
DISTANCES

Perigee	September 10, 12^{h} UT
364,779 km	Diameter 32′ 46″
Apogee	September 26, 10^{h} UT
405,547 km	Diameter 29′ 28″

FAVORABLE LIBRATIONS

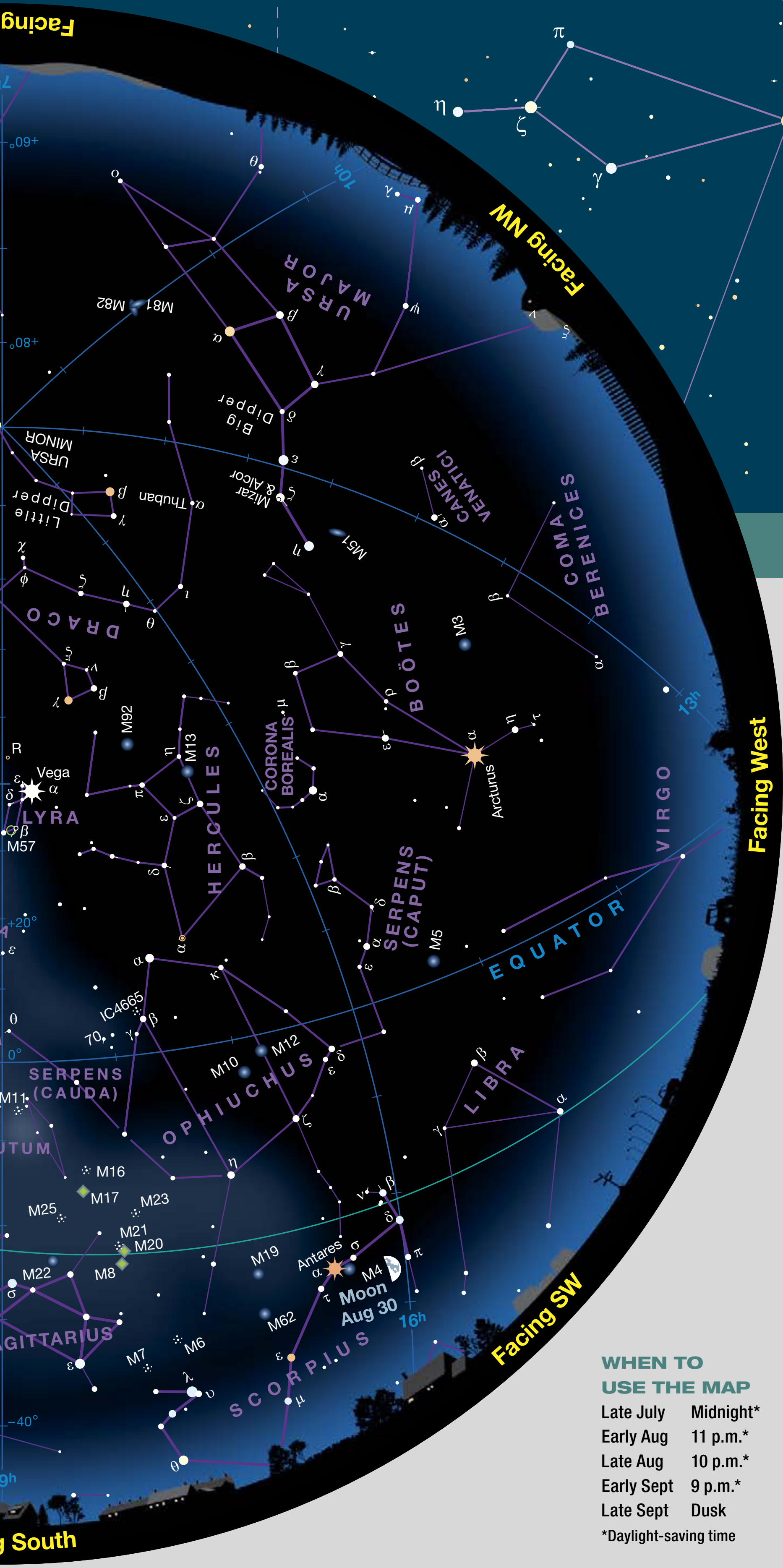
- Krafft Crater — September 7
- Riccioli Crater — September 8
- Hausen Crater — September 10
- Hayn Crater — September 24





Planet location shown for mid-month

USING THE NORTHERN HEMISPHERE MAP
Go out within an hour of a time listed to the right. Turn the map around so the yellow label for the direction you're facing is at the bottom. That's the horizon. The center of the map is overhead. Ignore the parts of the map above horizons you're not facing. Exact for latitude 40°N.



Binocular Highlight by Mathew Wedel

Ancient Light in Aquarius

Late summer and early autumn are among the most enjoyable seasons for stargazing. Nights are getting longer, temperatures are usually not too bad, and there's a lot up there to choose from. Our target this month is one of my favorites: globular cluster **M2** in Aquarius, the Water Bearer.

Compared to the cluster-packed constellations along the summer Milky Way, the waters of Aquarius seem downright sparse. Fortunately, M2 has a couple of bright signposts. The cluster lies about 5° north of Beta (β) Aquarii, and 8° west-southwest of Alpha (α) Aquarii, creating a right triangle with the two stars. Glowing at magnitude 6.6, M2 is naked-eye visible under ideal conditions, and an easy catch in binoculars of any size. At best, you'll make out a round, slightly hazy patch of brightness, but this not-so-faint fuzzy has tales to tell.

Astronomers estimate that M2 is around 12.5 billion years old, making it one of the oldest globular clusters in the Milky Way. But it hasn't been part of our galaxy that entire time. Along with a handful of other globulars, M2 is thought to have belonged to a dwarf galaxy that merged with the Milky Way sometime between 8 and 11 billion years ago. Keep in mind that our Sun and the solar system formed much later — *only* 4.6 billion years ago. That means M2 is a survivor from the staggeringly distant past. It's a cosmic wanderer that swapped galaxies at least once and whose oldest stars aren't much younger than the universe itself.

I joke about being interested in everything big and ancient, but even among celestial old-timers M2 is something of a standout. Go see it for yourself.

■ Given the time of year and his proclivities, **MATT WEDEL** is probably out in the dark right now, bathing his retinas in ancient starlight.

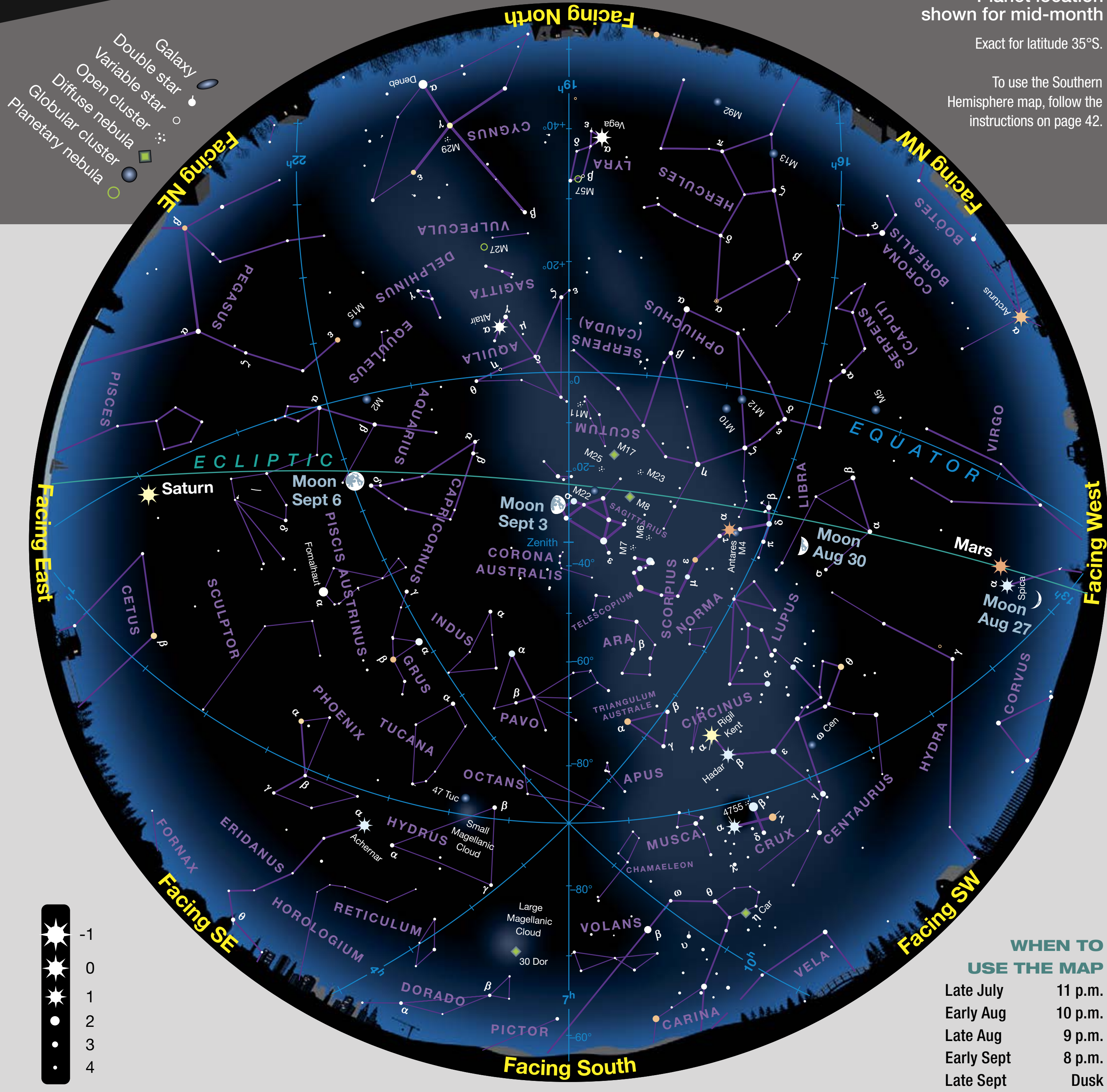
WHEN TO USE THE MAP

Late July	Midnight*
Early Aug	11 p.m.*
Late Aug	10 p.m.*
Early Sept	9 p.m.*
Late Sept	Dusk

*Daylight-saving time

Southern Hemisphere Sky Chart

by Jonathan Nally



Planet location shown for mid-month

Exact for latitude 35°S.

To use the Southern Hemisphere map, follow the instructions on page 42.

WHEN TO USE THE MAP

Late July	11 p.m.
Early Aug	10 p.m.
Late Aug	9 p.m.
Early Sept	8 p.m.
Late Sept	Dusk

THE CONSTELLATION Octans, named after the *octant* navigational device, is a rather dim and undistinguished figure that takes in the region surrounding the south celestial pole. Its brightest star is 3.7-magnitude Nu (ν) Octantis, while the second brightest is Beta (β), at magnitude 4.1. Along with 4.3-magnitude Delta (δ), they form the isosceles triangle plotted on the chart above.

The constellation is perhaps best known for the star Sigma (σ) Octantis. While Northern Hemisphere stargazers have the luxury of using 2nd-magnitude Polaris for polar aligning their scopes, southern observers have to make do with Sigma. It's the brightest star closest to the south celestial pole, though at magnitude 5.4 it's barely visible to the naked eye and sits a little more than a full degree from the pole. ■

Job's Coffin: A Stellar Mystery

Could this coffin be afloat in a bowl of tears?

▲The obverse side of a medal given to Samuel Plimsoll (1824–1898) showing a Coffin Ship. Plimsoll appealed for years to get legislation passed to improve safety and maintenance of these overinsured and overloaded vessels. With some imagination, the diamond of Delphinus can be seen as one of these Coffin Ships.

Delphinus is one of the night sky's smallest constellations but also one of the most endearing. As with most small constellations, its brightest stars lie close together, drawing attention to them. In *The Phenomena and Diosemeia of Aratus*, Greek poet Aratus (circa 315–240 BC) notes that the "Dolphin was considered by the ancients as the most remarkable of fishes." So it's not surprising that this playful cetacean was placed among the stars.

The main star pattern of Delphinus is a crisp and conspicuous diamond of four moderately bright stars packed into an area of sky that you can easily cover with two fingers held at arm's length. You'll find the diamond of Delphinus on this month's all-sky chart on pages 42–43, just east and slightly north of brilliant Altair in Aquila, the Eagle. The Dolphin lies in the celestial sea and surmounts other water constellations, such as Capricornus, the Sea Goat; Aquarius, the Water Bearer; and even Pegasus, the Winged Horse. (Turn to page 22 for more on Delphinus.)

In the past, stargazers have also seen the Dolphin's diamond as the shape of a coffin — Job's Coffin, in particular. This curious title has been liberally introduced for centuries, though its origins remain a mystery. As Garrett P. Serviss states in his 1910 book, *Round the Year with Stars*, "the 'Dolphin,' often called 'Job's Coffin,' [is] a name for which I have never been able to find any explanation." Nor could Elijah Burritt (1794–1838), who, in his 1836 *Geography of the Heavens and Class-Book of Astronomy*, writes, "To many, [Delphinus] is known by the name of *Job's Coffin*; but from whom, or from what fancy, it first obtained this appellation, is not known."

Despite its veil of mystery, in his 1911 *Star Lore of All Ages*, astronomy popularizer William Tyler Olcott (1873–1936) notes that "'Job's Coffin,' has a wider vogue than the great majority of the constellation names." But Martha Evans Martin almost seems surprised at the moniker's popularity. In her 1907 book, *The Friendly Stars*, she writes, "Why the figure should suggest a coffin rather than a dolphin, it is not easy to see. It can hardly be said to much resemble either object."

Some Thoughts

Job's Coffin is not mentioned in classical mythologies or detailed by later celestial cartographers. One possibility is that it could represent the protective hedge that Satan accuses God of placing around Job; or it could be a metaphor for Job's return to the womb upon his death. Alternatively, it may be a misprint for "Jonah's Coffin," as in the biblical Jonah, a sailor swallowed by a "great fish," often represented by a whale (a cetacean), in whose belly he was entombed for three days. In ancient times, the shapes of whales and dolphins were not well known. Some imagined them as leviathans, which may have been a metaphor for Satan, revealing the ancients' fear of the fathomless depths of the sea.

Job's Coffin may also have another maritime connection, one that likely dates to before 1835. The association was brought to mind during a recent trip to Boston. In April 2025, my wife, Deborah, and I visited a memorial to the nearly two million starving Irish who, during the Great Famine of the mid-1800s, made a frantic attempt to outwit death. According to one of the inscriptions, "In 1847 alone, 37,000 Irish refugees landed in Boston, on the edge of death and despair, impoverished and sick." They boarded vessels so unseaworthy they were called Coffin Ships. "So many passengers died at sea," the memorial states, "that poet John Boyle O'Reilly called the Atlantic Ocean upon which they journeyed 'a bowl of tears.'"

One does not need to know the exact meaning of Job's Coffin to recognize the courage it took to make this voyage on ships so poorly maintained and overburdened that they had only a slim chance of making their destination, or to honor the brave souls who made the ultimate sacrifice with a diamond in the bowl of the sky.

■ Contributing Editor **STEPHEN JAMES O'MEARA** has been studying the stars and their lore for more than 50 years.

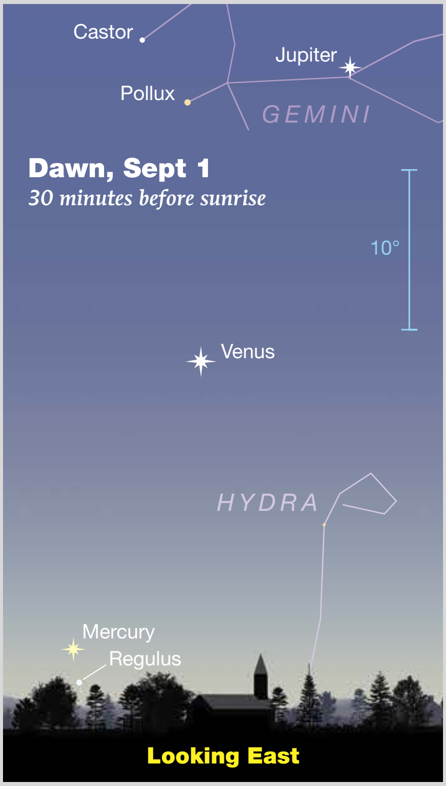
To find out what's visible in the sky from your location, go to skyandtelescope.org.

Venus Dazzles at Dawn

The Morning Star shares the sky with the Beehive Cluster, the Moon, and Regulus.

MONDAY, SEPTEMBER 1

The morning sky is a hive of activity this month. So, it's fitting that on the very first day of September we find the brightest planet of all positioned near M44 in Cancer, better known as the **Beehive Cluster.** You can catch this lovely sight by setting an early alarm and heading out around 5 a.m. local daylight time — just before the start of morning twilight. Face the east-northeastern horizon and you can't miss **Venus**, the Morning Star gleaming at magnitude –3.9. However, seeing the cluster likely means getting out your binoculars as the individual bees in the stellar hive aren't very bright. Look for the cluster about 1° upper left of the planet.



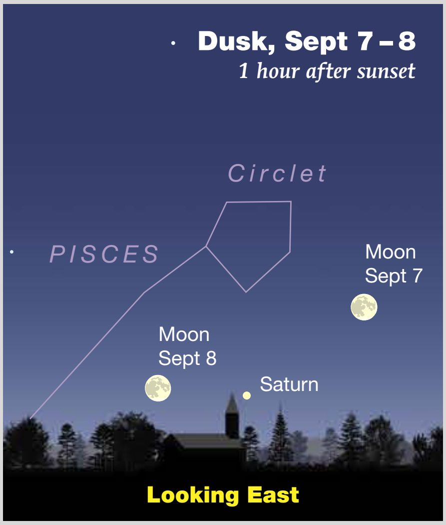
Venus is roughly midway through its current morning reign and has begun its slow drift sunward. This motion becomes obvious if you tune in again on the following morning, September 2nd. Not only is Venus farther from M44 — roughly 2° below the cluster — but it's now very close to the 4th-magnitude star, **Delta (δ) Cancri**. Indeed, the planet looks almost as if it's acquired a temporary new moon, positioned about ¼° to its upper right. Of course, Venus is one of only two worlds that lacks a natural satellite, the other being Mercury. By the morning of the 3rd, the gap between Venus and Delta is great enough to shatter the faux moon illusion.

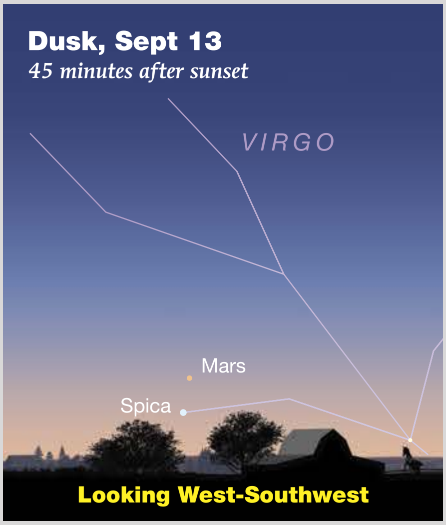
Another eye-catching sight awaiting early risers on the 1st is a neatly spaced array of three bright planets: **Mercury**, **Venus**, and **Jupiter**. To see this you'll have to wait until a bit after 5:30 a.m. — that's when Mercury rises to complete the trio. The innermost little world shines at magnitude –1.2 and is nearing the tail end of its current apparition. You can pick it out about 20° lower left of Venus, while Jupiter, at magnitude –2.0, shines brightly about 20° upper right of Venus. Mercury has one last notable event on its calendar before it disappears into the Sun's glare. On the morning of the 2nd, it's about 1¼° upper right of 1st-magnitude **Regulus**, the brightest star in Leo, the Lion. Brightening twilight means you'll need your binoculars to catch this pairing.

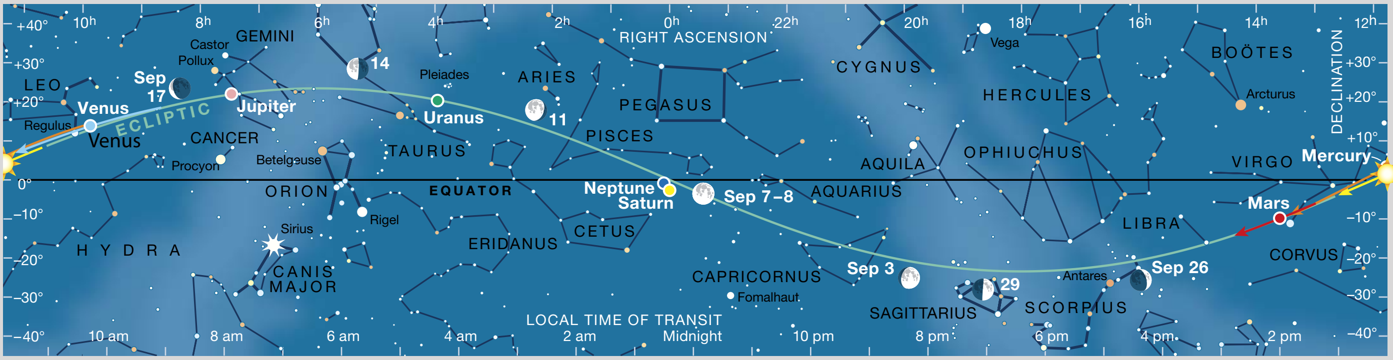
SATURDAY, SEPTEMBER 13

Over the past few weeks, the dusk sky's lone planet, **Mars**, has been slowly creeping up on **Spica**, Alpha (α) Virginis. This evening the two are at their closest, with only a touch more than 2° separating them. That said, the

◀▼▶ These scenes are drawn for near the middle of North America (latitude 40° north, longitude 90° west). European observers should move each Moon symbol a quarter of the way toward the one for the previous date; in the Far East, move the Moon halfway.

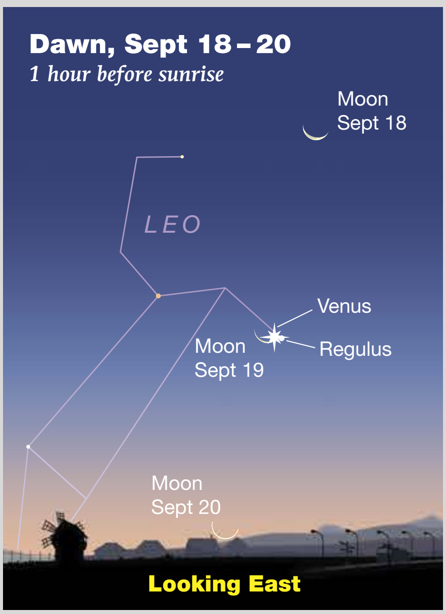






▲ The Sun and planets are positioned for mid-September; the colored arrows show the motion of each during the month. The Moon is plotted for evening dates in the Americas when it's waxing (right side illuminated) or full, and for morning dates when it's waning (left side illuminated). "Local time of transit" tells when (in Local Mean Time) objects cross the meridian — that is, when they appear due south and at their highest — at mid-month. Transits occur an hour later on the 1st and an hour earlier at month's end.

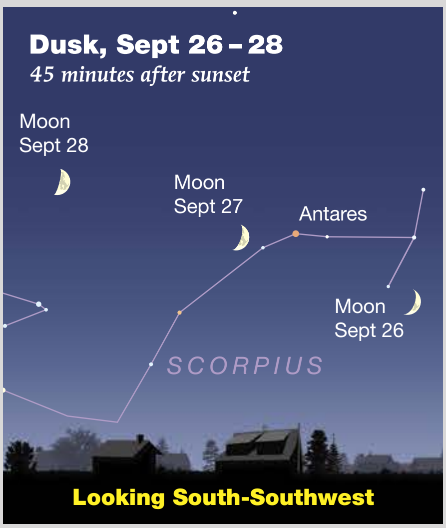
gap between the two is very nearly the same on the 12th and the 14th, giving you alternate dates if clouds intervene on the 13th. They're found low in the west-southwest, so you'll want to look as early as possible. Binoculars will help you spot the duo in fading twilight and also enhance the striking color contrast between icy-blue Spica and the Red Planet. This might prove to be one of the last times you view Mars this apparition. Its steady eastward movement has prevented it from being swallowed up by bright twilight, but inevitably it will lose that battle. Indeed, when it comes to being visible to the unaided eye, Mars will be a goner by month's end, well before it has its conjunction with the Sun on January 9, 2026.



SUNDAY, SEPTEMBER 14

This morning the **Moon** has its closest encounter with a bright star when it cozies up to **Beta (β) Tauri**. If you don't recall that star being mentioned before in this context, don't worry — your memory is fine. The Moon's path along the ecliptic doesn't normally carry it so far north. That's the lunar standstill at work again — a phenomenon described in detail in the April issue (page 49).

This morning, the Moon's declination is slightly greater than +28°. And to be fair, calling Beta "bright" might be overselling it a bit. Beta is classed as a 2nd-magnitude star, though at magnitude 1.7, it's only a tiny bit fainter than 1.4-magnitude Regulus — a star whose lunar encounters get mentioned here regularly. As for how close is *close*, it depends. As described on page 49, the lunar disk actually covers Beta from some locations in the southern U.S. and Mexico. But for most of us, it'll simply be a pleasing close call with the Moon passing just south of the star.



FRIDAY, SEPTEMBER 19

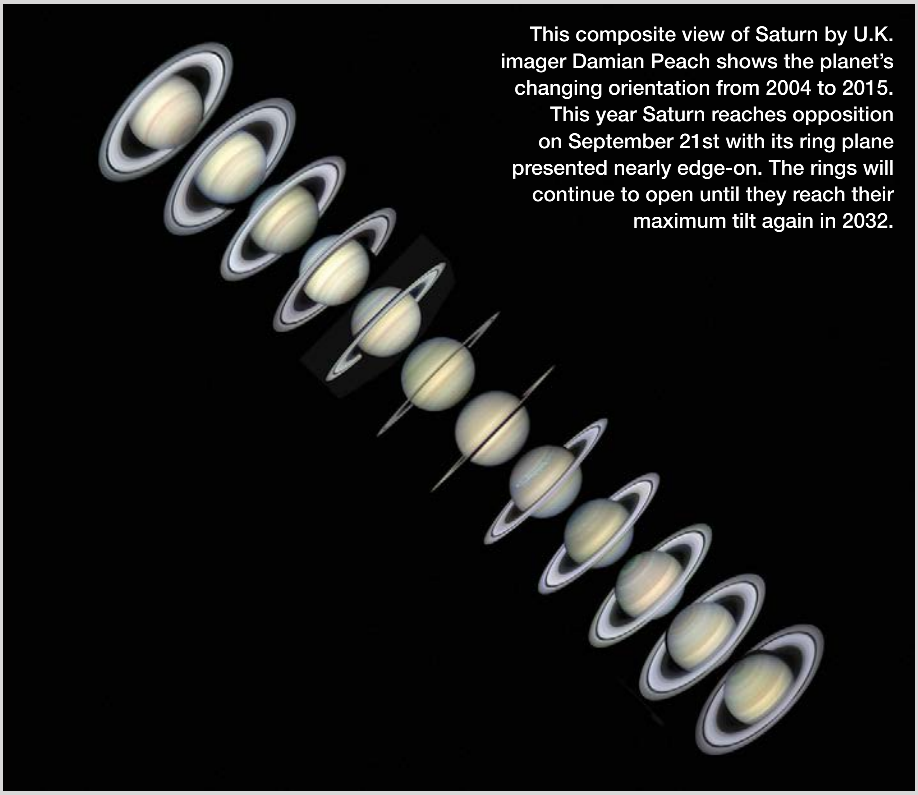
In what is one of the most striking conjunctions of the year, this morning the **Moon**, **Venus**, and **Regulus** are clumped together in a tight, flattened triangle. The thin, waning lunar crescent (5% illuminated) is adorned with ghostly earthshine. Nearby is gleaming Venus, positioned just ¼° upper right of the Moon. Any time the Moon and Venus get together, it's a noteworthy sight, but this time it's doubly so. Not only are they the closest they'll be all year, we also have the added attraction of 1st-magnitude Regulus twinkling gamely ½° lower right of Venus. However, the silvery planet is 100 times brighter than the star.

For some observers in northern Canada and Greenland, the meeting between the Moon and Venus actually produces an occultation. Churchill, Manitoba, and Yellowknife, Northwest Territories, are among the favored locations, though much of northern Alberta, Saskatchewan, and Manitoba are also in the occultation zone. And though residents of Edmonton, Alberta, miss seeing the Moon cover Venus, they do get to enjoy a very close conjunction.

■ Consulting Editor **GARY SERONIK** is a big fan of close conjunctions that include the Moon and Venus.

Two Planet Oppositions

Saturn and Neptune are visible from dusk to dawn.



This composite view of Saturn by U.K. imager Damian Peach shows the planet's changing orientation from 2004 to 2015. This year Saturn reaches opposition on September 21st with its ring plane presented nearly edge-on. The rings will continue to open until they reach their maximum tilt again in 2032.

You'll have no problem remembering the opposition dates for two planets this month. Saturn's occurs on September 21st — one day before the autumn equinox — and Neptune's on the 23rd, one day after. Since they happen just two days apart, you'd be correct if you guessed that the two planets are also close together in the sky. On the 21st, they're just 2.6° apart in Pisces, southeast of the Circlet asterism. Saturn shines at magnitude +0.7, while Neptune is at 7.8, which means the most distant major planet is accessible in 50-mm binoculars and an easy catch in small telescopes.

Both planets are currently moving westward in retrograde motion, though at different rates. Saturn, being much closer to Earth than Neptune, covers ground more rapidly than its distant sibling. The gap between the duo increases for much of the rest of the year.

Saturn is famously known as the Ringed Planet for obvious reasons. However, this year's opposition is notable for the unusual appearance of the planet's signature feature. Because Saturn's orbit is inclined 2.5° to the plane of Earth's orbit, the rings seesaw several degrees north and south during each apparition as Earth travels around the Sun. Saturn's rings were presented edgewise last March when the planet was near solar conjunction and out of view. Around opposition, however, the rings are still vanishingly thin. After reaching a tilt of –3.6° in early July (the minus sign indicating the south face is visible), the rings have narrowed again. At the beginning of September, the ring plane is tipped at –2.5°, then flattens to –1.5° by the 30th. Finally, the rings reach a minimum inclination of –0.3° in late November, after which they'll continue to open until 2032 when the cycle begins again.

Narrow rings mean we get a square-on view of both Saturnian hemispheres and their associated belts and zones. Much like Jupiter, the most prominent are the gray-toned North and South Equatorial Belts, though Saturn's are less contrasty and more diffuse. The belts border either side of the pale-yellow Equatorial Zone. The ring plane bisects the Equatorial Zone and the rings mostly overlap their own shadow this month. After opposition, the shadow slowly shifts northward and becomes more apparent.

This season also offer interesting viewing prospects for Saturn's major moons as they shuttle back and forth on either side of the planet like beads on an abacus. On the 18th at around 11:30 p.m. EDT, seven moons line up on either side of Saturn, with an eighth moon, Iapetus, a short distance southeast of the planet. An exceptionally compact gathering of Tethys, Dione, Enceladus, and Mimas takes place on the 20th just 10″ east of the ring plane starting around 11:35 p.m. EDT. In just 30 minutes the bunch morphs from a parallelogram into a trapezoid. Mimas, which glimmers at magnitude 12.9 and is known as the "Death Star" moon, is one of the most difficult to observe despite its relative brightness because it orbits within the glare of Saturn and its rings. Another great moon-watching opportunity arises on the 14th, when Rhea, Tethys, and Dione form a tiny triangle just west of Saturn's rings between about 1 and 2 a.m. EDT. Additional striking linear satellite arrangements occur on the nights of September 1st, 7th, 21st, and 29th.

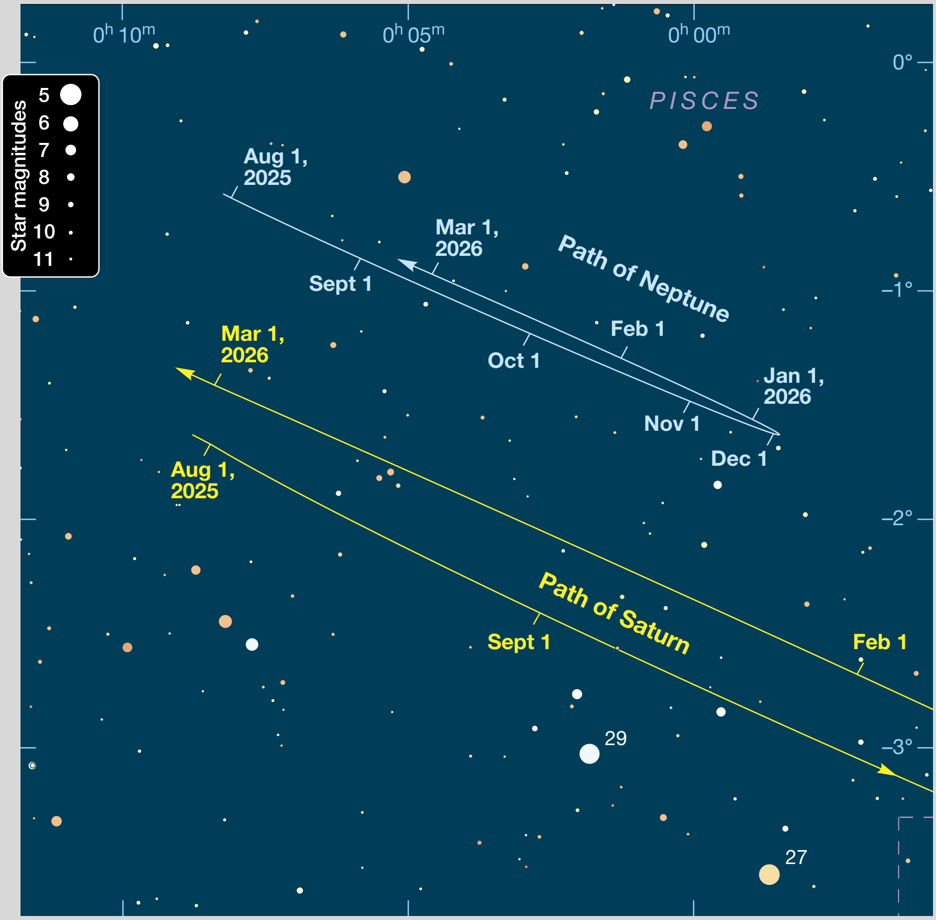
And let's not forget Saturn's Jekyll-and-Hyde moon, Iapetus. Dark dust coats its leading hemisphere while its opposite side is covered in ice. During its 79-day orbit we alternately view its bright face at western elongation, and coal-black hemisphere at eastern elongation, causing its magnitude to vary from 10.1 to 11.9. Western elongations occur on August 25th and November 12th.

To find the positions of the planet's brightest satellites, use our interactive Saturn's moons calculator found on the Tools page at **skyandtelescope.org**.

Given its proximity to Saturn, locating Neptune is rarely easier than it is this opposition. Through a telescope magnifying around 150×, it looks like a tiny blue dot just 2.4″ across. Its distinctive color is caused by a small percentage of methane in its hydrogen- and helium-rich atmosphere, which absorbs red light and reflects blue.

Neptune's polar axis is tipped 28.3°, so it experiences seasonal effects even 4.5 billion kilometers (2.8 billion miles) from the Sun. Hubble imagery has revealed an increase in brightness and cloud cover over the southern hemisphere at the start of Neptunian summer. It takes the planet 165 years to complete an orbit, so each season lasts about 40 years. It's now mid-winter in Neptune's northern hemisphere, with spring just 20 years off.

Of Neptune's 16 known moons, only 13.4-magnitude Triton is bright enough to see in amateur telescopes. It orbits the planet every 5.9 days in *retrograde motion* (opposite Neptune's direction of rotation) tilted 157° to the planet's equator. An 8-inch scope will show Triton well, especially if you observe it when it's at greatest elongation. That's when it's positioned about 16″ away from Neptune's tiny disk. Due to Triton's extreme orbital tilt, elongations occur when the satellite appears to the northeast and southwest of the planet. Northeasterly elongations for the Americas occur on the nights of August 31st, September 6th, 12th, 17th, 24th, 29th, October 5th, and 11th. Southwesterly elongations take place on September 3rd, 9th, 15th, 21st, 26th, October 2nd, 8th, and 14th. To keep tabs on the big moon, consult the Triton tracker app on the Tools page at **skyandtelescope.org**.



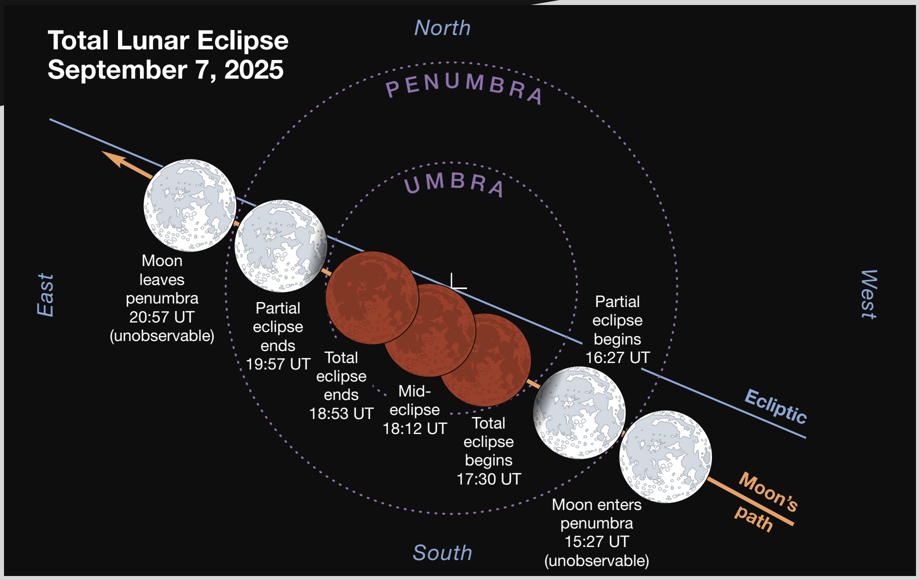
A Half-Moon Occults Elnath

EARLY-RISERS IN THE southwestern U.S. and Mexico can watch the last-quarter Moon occult 1.7-magnitude Beta (β) Tauri on September 14th. The star, also known as Elnath, disappears at the Moon's leading bright limb and reappears in a dramatic flash on the dark limb a few moments to more than an hour later, depending on your location.

Texas and Oklahoma are located at the eastern end of the visibility zone, where the occultation takes place at dawn, with Elnath reappearing around the time of local sunrise. From just south of Wichita, Kansas, the star briefly grazes the Moon's northern limb, flickering in and out of view as rugged lunar terrain intermittently covers and uncovers it. While the close shave happens shortly after sunrise, it may still be possible to view it in a telescope by using high magnification to darken the background sky.

Farther west, observers near Carlsbad, California, witness a grazing occultation in a dark sky. Elnath's reemergence should be plainly visible in binoculars. Elsewhere in the U.S. and Canada, the Moon simply passes south of the star.

For a detailed listing of cities and times for the star's disappearance and reappearance, visit the International Occultation Timing Association's web site at **https://is.gd/betatau**.



A Pair of Eclipses

SEPTEMBER FEATURES two eclipses: one solar and one lunar. Unfortunately, neither is visible from the Americas.

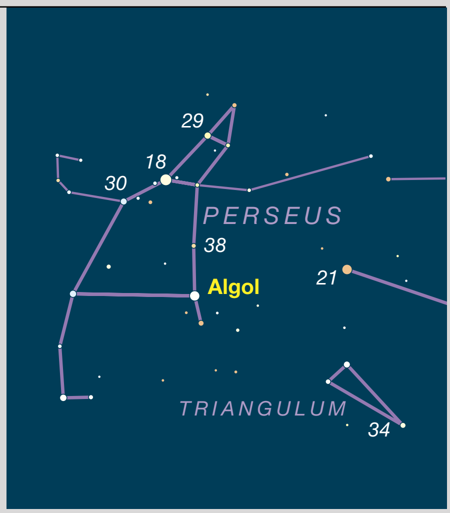
The year's second total lunar eclipse occurs on September 7th and favors observers in Europe, Africa, Asia, Australia, and New Zealand. Observers there get to enjoy spectacular views of the Moon's changing light and color as it crosses the southern half of Earth's inner shadow, the *umbra*. For a good chunk of western Europe, the Moon rises during totality and exits the umbra during (or shortly after) the end of evening twilight.

The year's final eclipse is the partial solar eclipse on September 21st. It happens on the morning of the 22nd for observers in New Zealand, a narrow fringe of Australia's east coast, Tasmania, several Pacific Islands, and parts of Antarctica. Maximum obscuration — when the Moon covers 80% of the Sun — happens over the South Pacific Ocean.

Minima of Algol

Aug.	UT	Sept.	UT
2	12:25	3	1:20
5	9:14	5	22:09
8	6:03	8	18:57
11	2:51	11	15:46
13	23:40	14	12:35
16	20:28	17	9:23
19	17:17	20	6:12
22	14:06	23	3:01
25	10:54	25	23:49
28	7:43	28	20:38
31	4:31		

These geocentric predictions are from the recent heliocentric elements Min. = JD 2457360.307 + 2.867351E, where E is any integer. They were derived by Roger W. Sinnott from 15 photoelectric series in the AAVSO database acquired during 2015–2020 by Wolfgang Vollmann, Gerard Samolyk, and Ivan Sergey. For a comparison-star chart and more info, see **skyandtelescope.org/algol**.



▲ Perseus reaches the zenith during predawn hours in September. Every 2.87 days, Algol (Beta Persei) dips from its usual magnitude 2.1 to 3.4 and back. Use this chart to estimate its brightness in respect to comparison stars of magnitude 2.1 (Gamma Andromedae) and 3.4 (Alpha Trianguli).

Action at Jupiter

SEPTEMBER REPRESENTS the first truly favorable month for Jupiter observers this apparition. By mid-month the planet rises around 1:30 a.m. local daylight time and climbs to an altitude of 40° just as morning astronomical twilight begins. On the 15th it shines from Gemini at magnitude –2.1 and presents a disk spanning 35.5″. Jupiter continues to brighten slightly and grow in apparent size until it reaches opposition on January 10, 2026. (Unusually, the planet doesn't reach opposition this year.)

Any telescope reveals the four big Galilean moons, and binoculars usually show at least two or three. The moons orbit Jupiter at different rates, changing positions along an almost straight line from our point of view on Earth. Use the diagram on the facing page to identify them by their relative positions on any given date and time. All the observable interactions between Jupiter and its satellites and their shadows are tabulated on the facing page.

Features on Jupiter appear closer to the central meridian than to the limb for 50 minutes before and after transiting. Here are the times, in Universal Time, when the Great Red Spot should cross Jupiter's central meridian. The dates, also in UT, are in bold. (Eastern Daylight Time is UT minus 4 hours.)

August 1: 8:20, 18:15; **2:** 4:11, 14:07; **3:** 0:03, 9:59, 19:54; **4:** 5:50, 15:46; **5:** 1:42, 11:38, 21:33; **6:** 7:29, 17:25; **7:** 3:21, 13:16, 23:12; **8:** 9:08, 19:04; **9:** 5:00, 14:55; **10**: 0:51, 10:47, 20:43; **11**: 6:39, 16:34; **12**: 2:30, 12:26, 22:22; **13**: 8:18, 18:13; **14**: 4:09, 14:05; **15**: 0:01, 9:56, 19:52; **16**: 5:48, 15:44; **17**: 1:40, 11:35, 21:31; **18**: 7:27, 17:23; **19**: 3:18, 13:14, 23:10; **20**: 9:06, 19:02; **21**: 4:57, 14:53; **22**: 0:49, 10:45, 20:40; **23**: 6:36, 16:32; **24**: 2:28, 12:24, 22:19; **25**: 8:15, 18:11; **26**: 4:07, 14:02, 23:58; **27**: 9:54, 19:50; **28**: 5:45, 15:41; **29**: 1:37, 11:33, 21:29; **30**: 7:24, 17:20; **31**: 3:16, 13:12, 23:07

September 1: 9:05, 19:00; **2:** 4:56, 14:52; **3:** 0:48, 10:44, 20:39; **4:** 6:35, 16:31; **5:** 2:27, 12:22, 22:18; **6:** 8:14, 18:10; **7:** 4:05, 14:01, 23:57; **8:** 9:53,

BEATRIZ INGLESSIS / *S&T*, SOURCE: FRED ESPENAK

19:48; **9:** 5:44, 15:40; **10:** 1:36, 11:31, 21:27; **11:** 7:23, 17:19; **12:** 3:14, 13:10, 23:06; **13:** 9:01, 18:57; **14:** 4:53, 14:49; **15:** 0:44, 10:40, 20:36; **16:** 6:32, 16:27; **17:** 2:23, 12:19, 22:15; **18:** 8:10, 18:06; **19:** 4:02, 13:58, 23:53; **20:** 9:49, 19:45; **21:** 5:40, 15:36; **22:** 1:32, 11:28, 21:23; **23:** 7:19, 17:15; **24:** 3:10, 13:06, 23:02; **25:** 8:58, 18:53; **26:** 4:49, 14:45; **27:** 0:41, 10:36, 20:32; **28:** 6:28, 16:23; **29:** 2:19, 12:15, 22:11; **30:** 8:06, 18:02

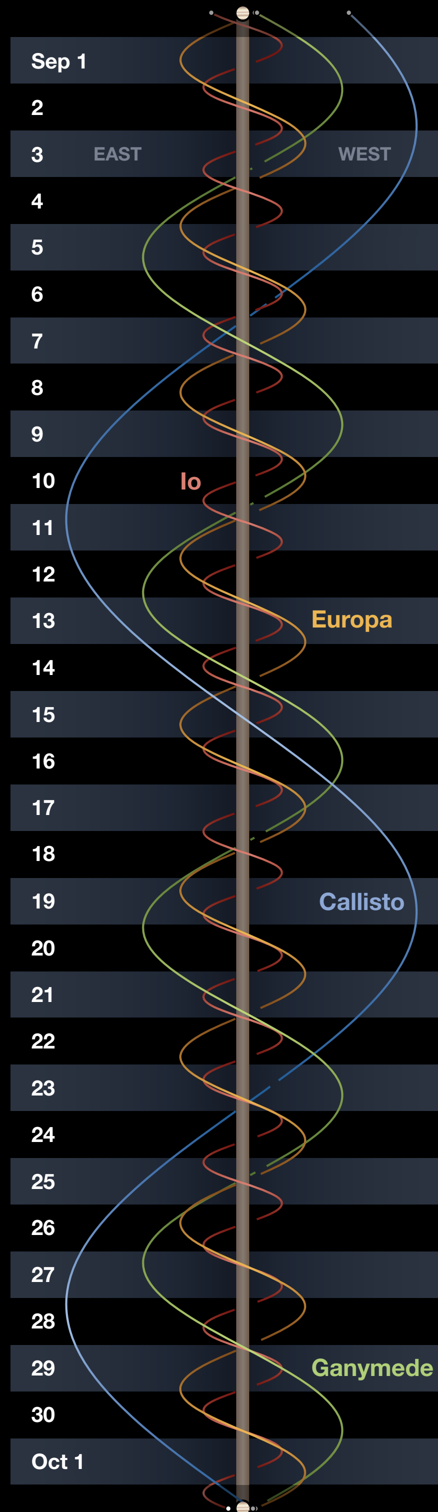
These times assume that the spot will be centered at System II longitude 81° on September 1st. If the Red Spot has moved elsewhere, it will transit $1\frac{2}{3}$ minutes earlier for each degree less than 81° and $1\frac{2}{3}$ minutes later for each degree more than 81°.

Phenomena of Jupiter's Moons, September 2025

Date	Time	Event
Sept. 1	13:00	I.Ec.D
	16:18	I.Oc.R
Sept. 2	5:45	II.Sh.I
	7:51	II.Tr.I
	8:32	II.Sh.E
	10:19	I.Sh.I
	10:40	II.Tr.E
	11:20	I.Tr.I
	12:33	I.Sh.E
	13:35	I.Tr.E
Sept. 3	7:28	I.Ec.D
	10:48	I.Oc.R
	16:20	III.Ec.D
	19:20	III.Ec.R
	20:34	III.Oc.D
	23:43	III.Oc.R
Sept. 4	0:40	II.Ec.D
	4:47	I.Sh.I
	5:33	II.Oc.R
	5:50	I.Tr.I
	7:01	I.Sh.E
	8:04	I.Tr.E
Sept. 5	1:57	I.Ec.D
	5:18	I.Oc.R
	19:04	II.Sh.I
	21:14	II.Tr.I
	21:50	II.Sh.E
	23:16	I.Sh.I
Sept. 6	0:03	II.Tr.E
	0:19	I.Tr.I
	1:30	I.Sh.E
	2:34	I.Tr.E
	14:18	IV.Ec.D
	17:05	IV.Ec.R
	20:25	I.Ec.D
	23:47	I.Oc.R
Sept. 7	0:23	IV.Oc.D
	3:45	IV.Oc.R
	6:35	III.Sh.I
	9:33	III.Sh.E
	10:55	III.Tr.I
	13:57	II.Ec.D
	14:02	III.Tr.E
	17:44	I.Sh.I
	18:49	I.Tr.I
	18:55	II.Oc.R
	19:58	I.Sh.E
	21:03	I.Tr.E
Sept. 8	14:54	I.Ec.D
	18:17	I.Oc.R
Sept. 9	8:21	II.Sh.I
	10:36	II.Tr.I
	11:08	II.Sh.E
	12:13	I.Sh.I
	13:18	I.Tr.I
	13:25	II.Tr.E
	14:26	I.Sh.E
	15:32	I.Tr.E
Sept. 10	9:22	I.Ec.D
	12:46	I.Oc.R
	20:18	III.Ec.D
	23:20	III.Ec.R
Sept. 11	0:51	III.Oc.D
	3:14	II.Ec.D
	4:01	III.Oc.R
	6:41	I.Sh.I
	7:47	I.Tr.I
	8:16	II.Oc.R
	8:55	I.Sh.E
	10:02	I.Tr.E
Sept. 12	3:50	I.Ec.D
	7:16	I.Oc.R
	21:40	II.Sh.I
	23:59	II.Tr.I
Sept. 13	0:27	II.Sh.E
	1:09	I.Sh.I
	2:17	I.Tr.I
	2:48	II.Tr.E
	3:23	I.Sh.E
	4:31	I.Tr.E
	22:19	I.Ec.D
Sept. 14	1:45	I.Oc.R
	10:33	III.Sh.I
	13:32	III.Sh.E
	15:09	III.Tr.I
	16:31	II.Ec.D
	18:17	III.Tr.E
	19:38	I.Sh.I
	20:46	I.Tr.I
	21:36	II.Oc.R
	21:51	I.Sh.E
	23:00	I.Tr.E
Sept. 15	1:10	IV.Sh.I
	3:59	IV.Sh.E
	11:56	IV.Tr.I
	15:22	IV.Tr.E
	16:47	I.Ec.D
	20:15	I.Oc.R
Sept. 16	10:58	II.Sh.I
	13:20	II.Tr.I
	13:45	II.Sh.E
	14:06	I.Sh.I
	15:15	I.Tr.I
	16:10	II.Tr.E
	16:20	I.Sh.E
	17:29	I.Tr.E
Sept. 17	11:16	I.Ec.D
	14:44	I.Oc.R
Sept. 18	0:18	III.Ec.D
	3:20	III.Ec.R
	5:05	III.Oc.D
	5:48	II.Ec.D
	8:17	III.Oc.R
	8:34	I.Sh.I
	9:44	I.Tr.I
	10:48	I.Sh.E
	10:56	II.Oc.R
	11:58	I.Tr.E
Sept. 19	5:44	I.Ec.D
	9:13	I.Oc.R
Sept. 20	0:16	II.Sh.I
	2:42	II.Tr.I
	3:03	I.Sh.I
	3:03	II.Sh.E
	4:13	I.Tr.I
	5:16	I.Sh.E
	5:32	II.Tr.E
	6:28	I.Tr.E
Sept. 21	0:13	I.Ec.D
	3:43	I.Oc.R
	14:31	III.Sh.I
	17:31	III.Sh.E
	19:04	II.Ec.D
	19:20	III.Tr.I
	21:31	I.Sh.I
	22:30	III.Tr.E
	22:42	I.Tr.I
	23:45	I.Sh.E
Sept. 22	0:16	II.Oc.R
	0:57	I.Tr.E
	18:41	I.Ec.D
	22:12	I.Oc.R
Sept. 23	8:16	IV.Ec.D
	11:14	IV.Ec.R
	13:34	II.Sh.I
	15:59	I.Sh.I
	16:03	II.Tr.I
	16:21	II.Sh.E
	17:11	I.Tr.I
	18:13	I.Sh.E
	18:52	II.Tr.E
	19:26	I.Tr.E
	19:41	IV.Oc.D
	23:15	IV.Oc.R
Sept. 24	13:10	I.Ec.D
	16:41	I.Oc.R
Sept. 25	4:16	III.Ec.D
	7:20	III.Ec.R
	8:21	II.Ec.D
	9:15	III.Oc.D
	10:28	I.Sh.I
	11:40	I.Tr.I
	12:28	III.Oc.R
	12:41	I.Sh.E
	13:36	II.Oc.R
	13:54	I.Tr.E
Sept. 26	7:38	I.Ec.D
	11:10	I.Oc.R
Sept. 27	2:53	II.Sh.I
	4:56	I.Sh.I
	5:24	II.Tr.I
	5:40	II.Sh.E
	6:09	I.Tr.I
	7:10	I.Sh.E
	8:14	II.Tr.E
	8:23	I.Tr.E
Sept. 28	2:07	I.Ec.D
	5:39	I.Oc.R
	18:29	III.Sh.I
	21:30	III.Sh.E
	21:38	II.Ec.D
	23:24	I.Sh.I
	23:29	III.Tr.I
Sept. 29	0:38	I.Tr.I
	1:38	I.Sh.E
	2:40	III.Tr.E
	2:52	I.Tr.E
	2:55	II.Oc.R
	20:35	I.Ec.D
Sept. 30	0:08	I.Oc.R
	16:10	II.Sh.I
	17:53	I.Sh.I
	18:44	II.Tr.I
	18:58	II.Sh.E
	19:07	I.Tr.I
	20:06	I.Sh.E
	21:21	I.Tr.E
	21:34	II.Tr.E

Every day, interesting events happen between Jupiter's satellites and the planet's disk or shadow. The first columns give the date and mid-time of the event, in Universal Time (which is 5 hours ahead of Eastern Standard Time). Next is the satellite involved: **I** for Io, **II** Europa, **III** Ganymede, or **IV** Callisto. Next is the type of event: **Oc** for an occultation of the satellite behind Jupiter's limb, **Ec** for an eclipse by Jupiter's shadow, **Tr** for a transit across the planet's face, or **Sh** for the satellite casting its own shadow onto Jupiter. An occultation or eclipse begins when the satellite disappears **(D)** and ends when it reappears **(R)**. A transit or shadow passage begins at ingress **(I)** and ends at egress **(E)**. Each event is gradual, taking up to several minutes. Predictions courtesy IMCCE / Paris Observatory.

Jupiter's Moons



The wavy lines represent Jupiter's four big satellites. The central vertical band is Jupiter itself. Each gray or black horizontal band is one day, from 0^h (upper edge of band) to 24^h UT (GMT). UT dates are at left. Slide a paper's edge down to your date and time, and read across to see the satellites' positions east or west of Jupiter.

A Lunar Eye Chart

Use the Moon's features to test your vision.

A little more than a century ago, Harvard astronomer William Henry Pickering (1858–1938) devised a test of visual acuity based on the ability to discern detail on the face of the Moon with the naked eye. In order of increasing difficulty, his lunar "eye chart" consists of 12 features:

1. The bright ray system surrounding the crater Copernicus. Spanning some 1,100 kilometers (680 miles), these rays are draped across the contrasting dusky surfaces of Mare Imbrium to the north and Mare Cognitum to the south.
2. The dark basalt expanse of Mare Nectaris on the Moon's southeastern quadrant. Measuring 340 kilometers in diameter, the mare is part of the best-preserved impact basin on the Earth-facing lunar hemisphere.
3. The 420-kilometer-diameter Mare Humorum, surrounded on three sides by lighter highlands that sharply delineate its shoreline.
4. The rays that encircle the crater Kepler and stand out boldly against the uncluttered plains of Oceanus Procellarum.
5. The lighter region on the northern shore of Mare Humorum that terminates between the lava-flooded floors of the craters Gassendi and Letronne.
6. A patch of bright terrain near the prominent crater Plinius bordering Mare Serenitatis to the north and Mare Tranquillitatis to the south.
7. Mare Vaporum, the smallest of the classical maria. It's bordered by Montes Apenninus (the Apennine mountains) to the northwest and by the Haemus mountains and the brilliant impact crater Manilius to the northeast.
8. A bright region on the northwestern shore of Mare Nubium north of the lava-flooded crater Lubiniezky.
9. Sinus Medii, the 350-kilometer-wide region that appears like a southern extension of Mare Vaporum. This feature is located very close to the center of the lunar nearside.
10. A faint, dull shading near the crater Sacrobosco in the rugged southern highlands.
11. A small, dark patch of mare basalt bordering the northwestern flanks of the Apennine Mountains.
12. Montes Riphaeus, an irregular range of peaks that lies along the southeastern edge of Oceanus Procellarum.

▲ William Henry Pickering was a skilled observer from Boston, Massachusetts, and an early pioneer of astrophotography.

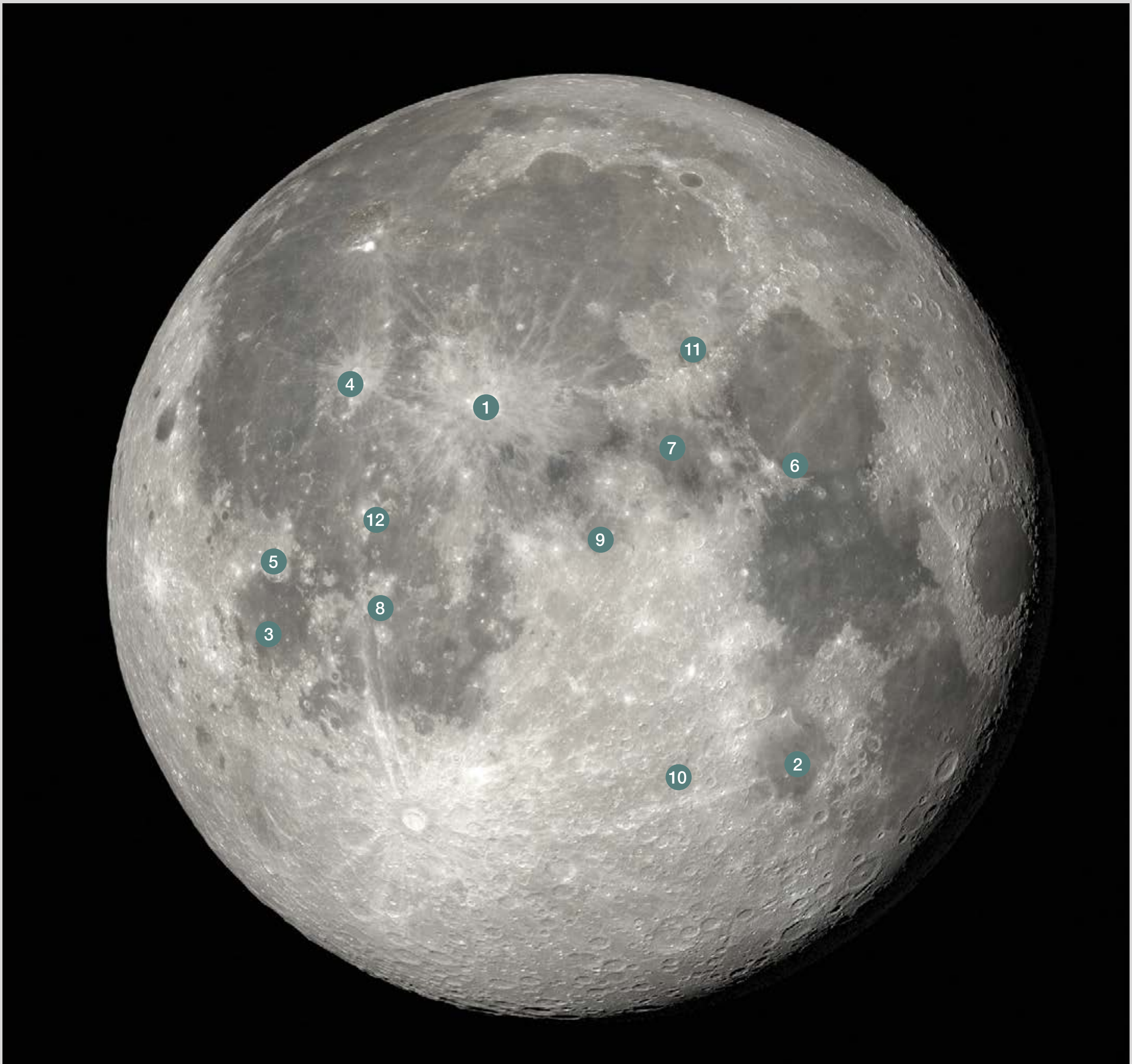
According to Pickering, an observer with average eyes is able to see the first seven features. Keen eyesight is needed to make out features 8, 9, and 10. Exceptionally acute vision is required to glimpse 11, while 12 may be beyond the grasp of even the finest naked-eye vision. In his classic 1955 guide *Amateur Astronomer's Handbook*, J. B. Sidgwick recommended using binoculars to identify the features before attempting to pick them out with the naked eye.

You might imagine that the best time to conduct this test is when a full Moon is riding high in the sky on a winter night, but that isn't actually the case. At full phase, when our satellite is illuminated from directly behind an earthbound observer, every point on the lunar surface shines some 40% brighter than just one day earlier or later. At very narrow angles of incidence, reflected light is enhanced when it strikes a microscopically rough surface covered with minuscule grains comparable in size to the light's wavelength. Provided that the distance between the particles is greater than one wavelength, light rays tend to multiply the scatter in a backward direction and combine by constructive interference with incoming rays to produce an amplified reflection. Known as *coherent backscattering*, this phenomenon results in enhanced glare when observing the full Moon.

Another Harvard astronomer, Joseph Ashbrook (*Sky & Telescope* editor in chief, who authored the Astronomical Scrapbook column in these pages from 1954 to 1980), repeatedly tested his vision using Pickering's method. He reported:

> *The best results, I have found, are obtained by viewing the waning gibbous Moon during the latter part of morning twilight. Much less is visible by night, when glare hampers, or in full daylight, when contrasts are diluted. Thus seen against the deep blue sky of a cool dawn, the pale lunar disk is richly dappled with recognizable markings.*

Ashbrook's experience echoes a recommendation by the Russian astronomer Vsevolod Sharonov, who



This lunar simulation shows the Moon as it appears on the morning of September 9th, labeled with Pickering's 12 tests of visual acuity.

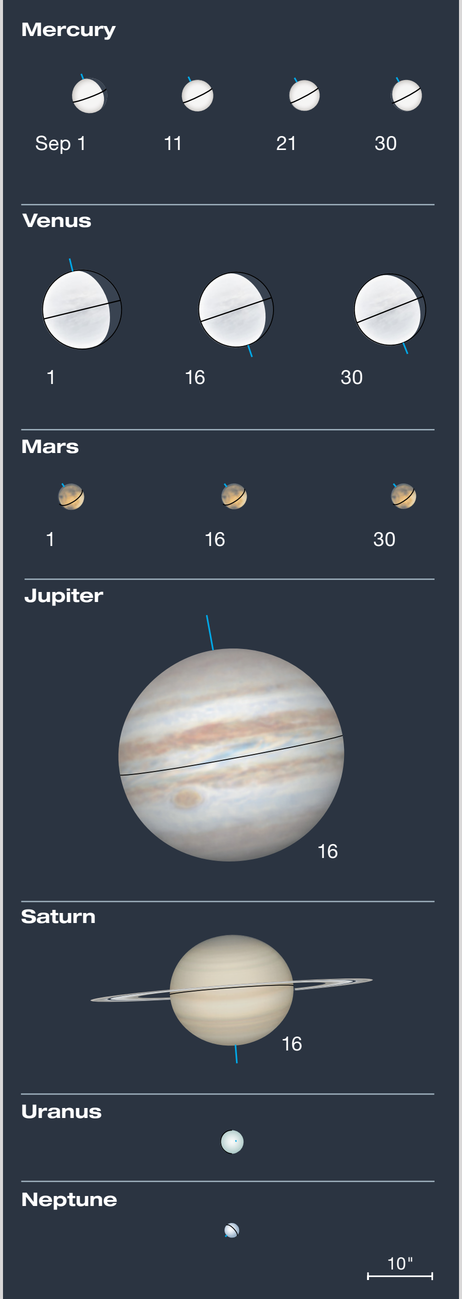
NASA'S SCIENTIFIC VISUALIZATION STUDIO

pointed out that reducing the difference in brightness between the disk of a planet or a satellite and the background against which it is viewed significantly improves the threshold contrast sensitivity of the eye. That's why surface markings on Jupiter's Galilean satellites are much easier to see during transits, when they are silhouetted against the backdrop of Jupiter's cloud tops rather than against a dark sky.

My vision doesn't fare too well when subjected to Pickering's test even though my eyeglasses do a decent job of correcting my nearsightedness and astigmatism. I take great comfort in the example of the 19th-century English observer William Rutter Dawes, who discovered a host of double stars and several delicate planetary features using surprisingly modest telescopes. Dawes also famously determined the limit of a telescope's resolving power, known today as Dawe's Limit. Although widely referred to as "the eagle-eyed Dawes" for his many telescopic revelations, Dawes was so nearsighted that he could pass his wife on the street without recognizing her.

■ Contributing Editor **TOM DOBBINS** is coauthor of *Epic Moon, A History of Lunar Exploration in the Age of the Telescope*, available at **shopatsky.com**.

PLANET VISIBILITY (40°N, naked-eye, approximate) **Mercury** visible at dawn until the 4th • **Venus** visible at dawn all month • **Mars** visible low in the west at dusk until the 24th • **Jupiter** rises in the predawn and visible to dawn • **Saturn** rises at sunset and visible all night.

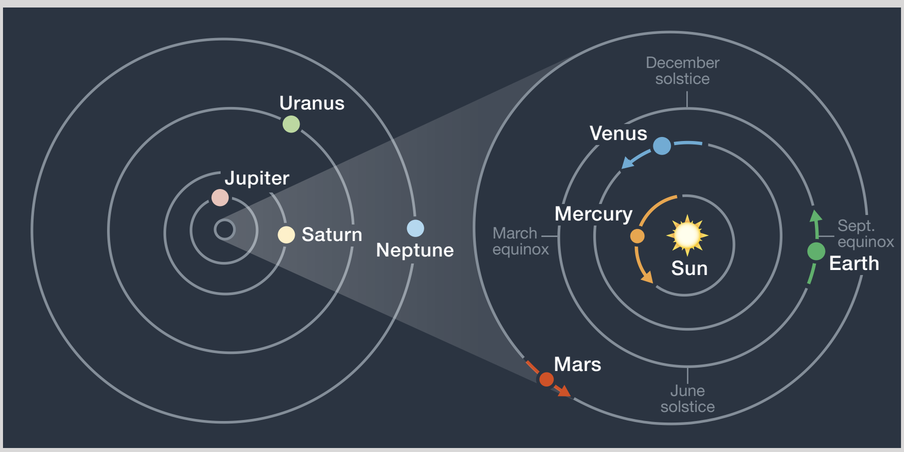


▲ **PLANET DISKS** are presented north up and with celestial west to the right. Blue ticks indicate the pole currently tilted toward Earth.

September Sun & Planets

	Date	Right Ascension	Declination	Elongation	Magnitude	Diameter	Illumination	Distance
Sun	1	$10^h\ 40.4^m$	+8° 23′	—	–26.8	31′ 42″	—	1.009
	30	$12^h\ 24.8^m$	–2° 41′	—	–26.8	31′ 56″	—	1.002
Mercury	1	$9^h\ 57.8^m$	+14° 02′	12° Mo	–1.2	5.5″	88%	1.223
	11	$11^h\ 10.9^m$	+7° 08′	3° Mo	–1.8	4.9″	100%	1.363
	21	$12^h\ 17.0^m$	–0° 45′	6° Ev	–1.1	4.8″	98%	1.399
	30	$13^h\ 11.0^m$	–7° 31′	13° Ev	–0.5	4.9″	94%	1.374
Venus	1	$8^h\ 38.5^m$	+18° 35′	31° Mo	–3.9	12.3″	84%	1.357
	11	$9^h\ 27.5^m$	+15° 37′	29° Mo	–3.9	11.8″	87%	1.411
	21	$10^h\ 15.3^m$	+11° 53′	26° Mo	–3.9	11.4″	89%	1.461
	30	$10^h\ 57.3^m$	+8° 02′	24° Mo	–3.9	11.1″	91%	1.502
Mars	1	$12^h\ 57.7^m$	–5° 54′	37° Ev	+1.6	4.1″	96%	2.263
	16	$13^h\ 34.3^m$	–9° 45′	32° Ev	+1.6	4.0″	97%	2.315
	30	$14^h\ 10.1^m$	–13° 12′	28° Ev	+1.6	4.0″	98%	2.354
Jupiter	1	$7^h\ 15.9^m$	+22° 15′	51° Mo	–2.0	34.3″	99%	5.743
	30	$7^h\ 35.0^m$	+21° 40′	75° Mo	–2.1	36.8″	99%	5.350
Saturn	1	$0^h\ 02.7^m$	–2° 25′	159° Mo	+0.7	19.3″	100%	8.609
	30	$23^h\ 54.7^m$	–3° 19′	170° Ev	+0.7	19.4″	100%	8.558
Uranus	16	$3^h\ 55.9^m$	+20° 10′	112° Mo	+5.7	3.7″	100%	19.110
Neptune	16	$0^h\ 04.4^m$	–1° 01′	172° Mo	+7.8	2.4″	100%	28.891

The table above gives each object's right ascension and declination (equinox 2000.0) at 0h Universal Time on selected dates, and its elongation from the Sun in the morning (Mo) or evening (Ev) sky. Next are the visual magnitude and equatorial diameter. (Saturn's ring extent is 2.27 times its equatorial diameter.) Last are the percentage of a planet's disk illuminated by the Sun and the distance from Earth in astronomical units. (Based on the mean Earth–Sun distance, 1 a.u. equals 149,597,871 kilometers, or 92,955,807 international miles.) For other timely information about the planets, visit **skyandtelescope.org**.



▶ **ORBITS OF THE PLANETS** The curved arrows show each planet's movement during September. The outer planets don't change position enough in a month to notice at this scale.

by Ken Hewitt-White

Night of the Lizard

Lacerta may be a small constellation, but it offers big rewards for deep-sky treasure seekers.

Big, it ain't. Covering an area of some 200 square degrees, Lacerta is ranked 68th in size among the sky's 88 official constellations. The Lizard was brought to life in 1687 by Polish astronomer Johannes Hevelius, who shoehorned the wee critter into an inconspicuous star field surrounded by several much larger constellations symbolizing people and animals. It's a wonder the little guy hasn't been stepped on.

Lacerta's slender pattern fits inside a rectangular region 20° by 10° in extent. The main stick figure is essentially a north-south zigzag of eight faint stars plus one additional marker to flesh out the body. Atop the zigzag are blue-white 3.8-magnitude Alpha (α) and yellowy 4.4-magnitude Beta (β) Lacertae. The six other zigzag markers, five of them identified by Flamsteed numbers, are magnitudes 4.1 to 4.6. For suburban observers, it's a marginal pattern.

Ten years ago, when my city nights weren't quite as light-polluted as they are now, I could occasionally trace Lacerta's zigzag high up alongside the pale band of the Milky Way. It was those unexpected sightings that prompted me to explore the constellation in 2015 with my 4¼-inch f/6 Newtonian reflector. Because Lacerta's northern border nearly touches the galactic equator, I was pretty sure the telescopic fields would be pleasing.

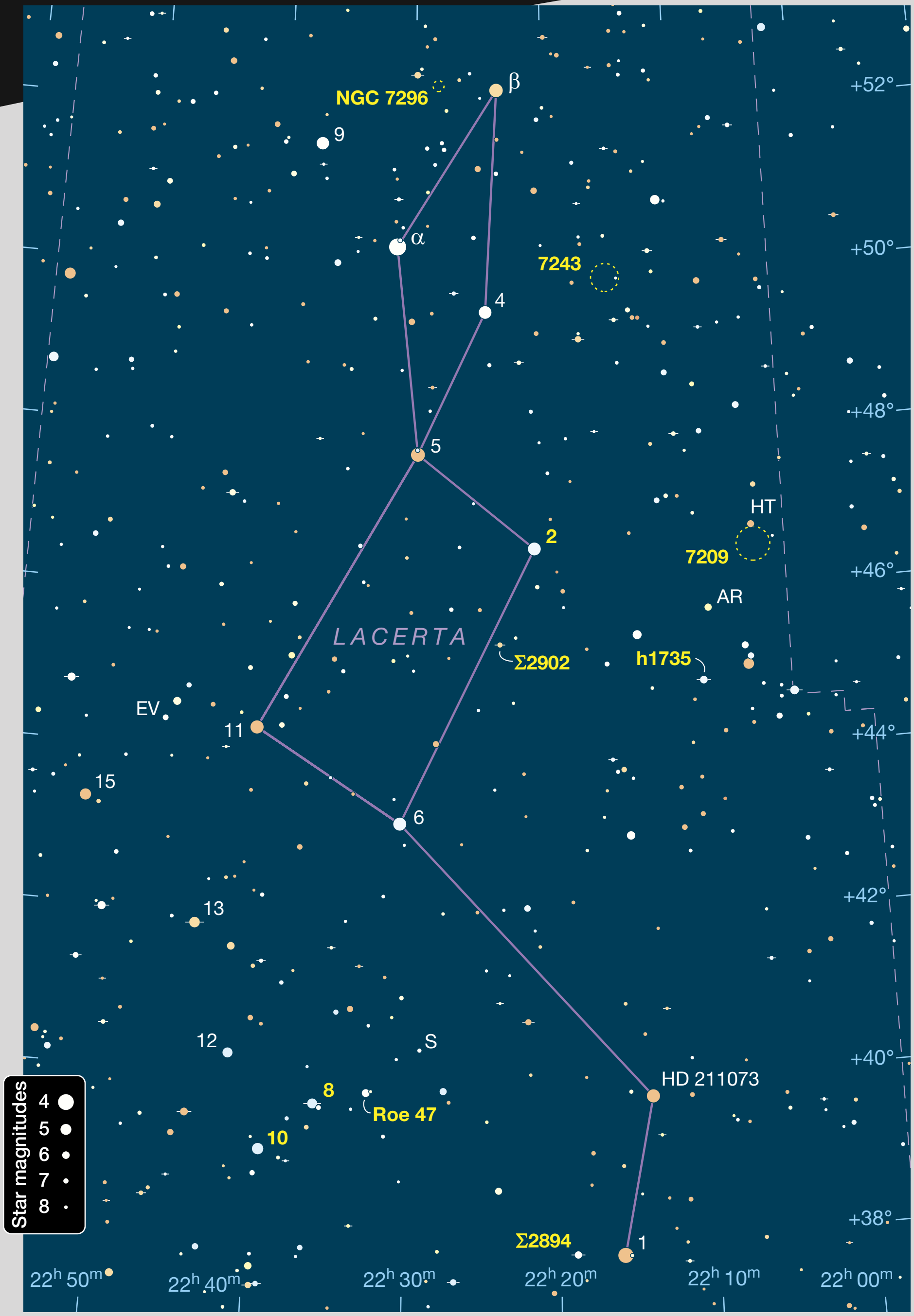
ALAN DYER

▲ **NO RESPECT** Small and faint, the constellation Lacerta, the Lizard, doesn't attract much attention from stargazers. Most of the lizard's body is submerged in a rich Milky Way star field northeast of Cygnus, the Swan. This image depicts the constellation's northern half, where many of the objects described in this article reside. Beta (β) Lacertae is the bright white star at upper right. Use the chart on page 56 to identify the rest of the stars and the trio of open clusters shown in the photo.

Dissecting the Lizard

My hit list included three open clusters. Two of them fall conveniently south-southwestward from Beta Lacertae, while our first and toughest target, 9.7-magnitude **NGC 7296**, glows just 40′ east of the star. A triangular landmark of 7th- and 8th-magnitude stars, 6′ wide, lies helpfully ¼° northeast of NGC 7296. The cluster materialized at 27× in my little reflector as a mere smudge that would fit comfortably inside the triangle. A 9.8-magnitude yellow-orange star guards the meagre specimen immediately northwest. Bumping up to 72× produced a compact mist of exceedingly faint pinpoints, none of them brighter than 11th magnitude.

After hopping back through Beta to Alpha, I made a right-angle turn southwestward to 4.6-magnitude 4 Lacertae, then jumped westward 1½° to find 6.4-magnitude **NGC 7243**. This modest glitter is slightly elongated east-west, measuring about 30′ across. At 27×, I observed a coarse smattering of stars, the brightest around magnitude 8.5. Increasing to 72× yielded additional members down to magni-



▲ **LIZARD LINES** The main stick-figure outline of Lacerta is a zigzag of eight stars. A few fainter stars help flesh out the body and head of the celestial lizard. Note that 2° north of 4.1-magnitude 1 Lacertae is a star of similar brightness, 4.5-magnitude HD 211073. The star is part of the zigzag star pattern yet lacks a Flamsteed number, demonstrating the imperfection of early sky surveys.

tude 11. Inside NGC 7243, a petite pairing named **Struve 2890** (Σ2890) displayed 9.4- and 9.7-magnitude elements 9.4″ apart. On the cluster's southwestern periphery, a broader tandem, **CLL 20**, exhibited 9.1- and 9.4-magnitude stars separated by a relatively generous 38.9″.

I retreated back to 4 Lacertae, dropped south-southeastward to 4.4-magnitude 5 Lacertae (an attractive deeply orange star), then southwestward for nearly 2° to bluish 4.5-magnitude **2 Lacertae**. The latter is a challenging double of dramatically unequal brightness. Increasing to 186× enabled me to glimpse the 11.5-magnitude attendant 47.6″ north of bright blue 2.

The final cluster on my list is nearby to the west — but first I made a short detour. Reducing the magnification to 72×, I shifted 1¼° south-southeast of 2 Lacertae to admire **Σ2902**, a superb binary. Its 7.6- and 8.2-magnitude components are 6.5″ apart. Nice! Returning to 2 Lacertae, I headed westward 2.7° to 7.7-magnitude **NGC 7209**. Viewed at 72×, NGC 7209 was a 15′-wide splash of 9th-magnitude (and fainter) stars, just south of the 6.1-magnitude reddish-orange variable HT Lacertae. The middle of NGC 7209 was oddly hollow, with the cluster registering as a doughnut of dim sparks.

Doubling Down

Nailing the three open clusters satisfied my urge to explore a span of seemingly nondescript celestial terrain I'd always overlooked. Next, I used my scope's 6×30 finderscope to star-hop carefully to a few multiple stars scattered across southern Lacerta.

Throttling down to 27×, I hopped from NGC 7209 southward about 1½° to arrive at the southern end of a 14′-long bent line of three stars, oriented north-south. The top two are 6th-magnitude and blue; the bottom one is 5th-magnitude and deeply orange. At the orange light, I turned eastward for a tad more than ½° to a multiple system designated **h1735**. Eyed at 27×, h1735 gave me only two stars, magnitudes 6.7 and 6.8 (the A and D components), separated by 110″, slanted to the east-southeast. But increased magnification netted a 9.7-magnitude sibling (B component) 27.2″ farther southeast.

I returned to the Lizard's zigzag backbone and slipped down to its southern terminus, anchored by 4.2-magnitude 1 Lacertae. Approximately ½° east of the yellow-orange star is a splendid double called **Σ2894**, whose 6.2- and 8.9-magnitude elements, 15.8″ apart, split at 27×. After a brief moment appreciating Σ2894, I veered east-northeast 4.1° to 4.8-magnitude **10 Lacertae**. Upping to 72× revealed that 10 Lacertae holds a

10.3-magnitude companion 62.6″ northeast. The strongly uneven duo of 10 Lacertae occupies the southeastern end of a shallow curve of 5th- and 6th-magnitude stars. Inside the crescent, less than 1° northwest of 10 Lacertae, is **8 Lacertae**, which resolves easily into a splendid north-south set featuring 5.7- and 6.3-magnitude stars 22.5″ apart (A and B components). But wait: 48.8″ south-southeast of the brighter star is a 10.4-magnitude fleck (C), while 32.8″ farther southeast is one of magnitude 9.1 (D). I captured all four members of this quadruple system at just under 100×.

Another 40″ west-northwestward along the crescent is 5.9-magnitude HD 213660, which centers a tough triple dubbed **Roe 47**. Flanking the primary are a 11.5-magnitude secondary (B component) 43.0″ to the south-southeast and a 12.4-magnitude tertiary (C) 33.4″ to the north-northwest. I needed almost 200× to pull in those incredibly faint flankers, but it was a satisfying sight. The feeble dots on either side of a healthy central sun gave Roe 47 the appearance of a mini solar system!

A Second Look

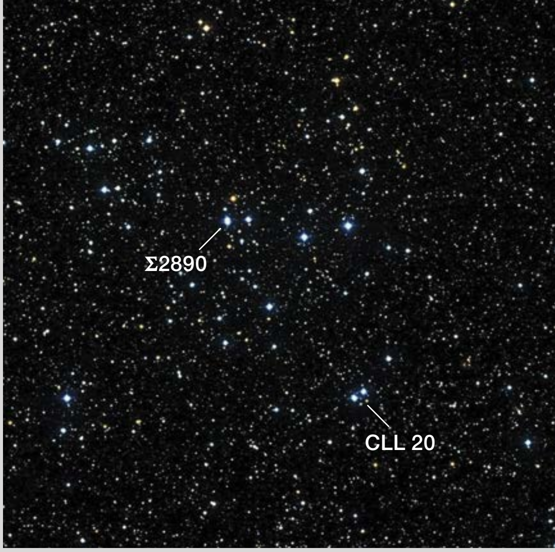
Fast forward to January 2025. As Lacerta stood halfway up the northwestern sky at nightfall, I returned to the three NGC clusters, this time deploying my 8-inch f/6 Dobsonian reflector. Thanks to a decade's worth of deterioration to my backyard sky, the views were only marginally superior to those obtained via my 4¼-inch scope. Your agent's suburban sky had become the color of thick soup (usually cream of mushroom).

I started off using a wide-angle 30-mm eyepiece generating 41× on the 8-inch Dob. All three clusters were visible, although diminutive NGC 7296 near Beta Lacertae was still a hard sell. The unconcentrated cluster resolved into a sparkly patch not truly detached from the surrounding Milky Way. Upping to 76× lifted the delicate sparkle; indeed, that magnification produced maybe two dozen exceedingly dim pinpoints. The best view was at 135×, though the cluster remained tiny.

NGC 7243 was reasonably prominent even at 41×. That said, the cluster looked thinly populated in the middle, whereas its eastern and western sides were defined by fairly bright curves of stars. The result was a heart-like structure, the pointy end facing south. In total, I counted more than a dozen 9th- and 10th-magnitude stars. Many fainter ones flickered near the threshold of my vision. The binaries noted earlier were a delight to behold — especially Σ2890.

NGC 7209 again struck me with the sparseness of its central region. However, working with the larger reflector at 76×, I learned that the loose assembly wasn't quite the doughnut I'd perceived previously. Instead, NGC 7209 was a glittery horseshoe opening to the west. I noticed a few orangey suns, but most of the several dozen cluster members, 10th-magnitude and lower, glowed blue-white. The fiery hue of 6th-magnitude HT Lacertae supercharged the scene.

Johannes Hevelius's reptilian constellation stands high in the northeast in mid-September. With the Moon rising after midnight, it's a perfect time to enjoy these subtle Milky Way treasures. Even if you dislike lizards, ya gotta love Lacerta!



▲ **BEST IN SHOW** The most prominent open cluster in Lacerta is NGC 7243. Although populated with perhaps only 40 stars, NGC 7243 stands out against the Milky Way background in small suburban telescopes. The cluster resides at a distance of almost 2,500 light-years.

SLOAN DIGITAL SKY SURVEY

■ Apart from Lacerta, Contributing Editor **KEN HEWITT-WHITE** has never encountered a lizard in the wild. But he did get to know one pet lizard that lived for many years at a friend's house.

Lizard Treasures

Object	Type	Mag	Size/Sep	RA	Dec.
NGC 7296	Open cluster	9.7	4′	$22^h\ 28.0^m$	+51° 17′
NGC 7243	Open cluster	6.4	30′	$22^h\ 15.1^m$	+49° 54′
Σ2890	Double star	9.4, 9.7	9.4″	$22^h\ 15.2^m$	+49° 53′
CLL 20	Double star	9.1, 9.4	38.9″	$22^h\ 14.4^m$	+49° 42′
2 Lacertae	Double star	4.5, 11.5	47.6″	$22^h\ 21.0^m$	+46° 32′
Σ2902	Double star	7.6, 8.2	6.5″	$22^h\ 23.6^m$	+45° 21′
NGC 7209	Open cluster	7.7	15′	$22^h\ 05.1^m$	+46° 29′
h1735 AD	Double star	6.7, 6.8	110″	$22^h\ 09.3^m$	+44° 51′
h1735 AB	Double star	6.7, 9.7	27.2″	$22^h\ 09.3^m$	+44° 51′
Σ2894	Double star	6.2, 8.9	15.8″	$22^h\ 18.9^m$	+37° 46′
10 Lacertae	Double star	4.8, 10.3	62.6″	$22^h\ 39.3^m$	+39° 03′
8 Lacertae AB	Double star	5.7, 6.3	22.5″	$22^h\ 35.9^m$	+39° 38′
8 Lacertae AC	Double star	5.7, 10.4	48.8″	$22^h\ 35.9^m$	+39° 38′
8 Lacertae AD	Double star	5.7, 9.1	81.6″	$22^h\ 35.9^m$	+39° 38′
Roe 47 AB	Double star	5.9, 11.5	43.0″	$22^h\ 32.4^m$	+39° 47′
Roe 47 AC	Double star	5.9, 12.4	33.4″	$22^h\ 32.4^m$	+39° 47′

Angular sizes and separations are from recent catalogs. Visually, an object's size is often smaller than the cataloged value and varies according to the aperture and magnification of the viewing instrument. Right ascension and declination are for equinox 2000.0. Magnitudes are visual.

New Perspectives on the Cosmos

THE DAWN OF MODERN COSMOLOGY: *From Copernicus to Newton*

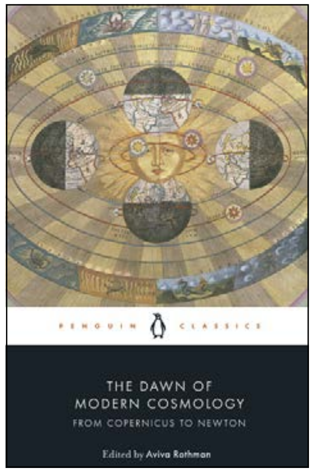
Aviva Rothman
Penguin Classics, 2024
672 pages, ISBN 9780241360637
$22.00, paperback

"AS YOU READ THIS BOOK, you will see how our world slowly transformed from one in which we stood motionless at the very centre of creation to one in which we found ourselves moving around one small sun among a near infinitude of others." From the outset in *The Dawn of Modern Cosmology: From Copernicus to Newton*, editor Aviva Rothman promises a sweeping tale. In a grand historical retelling, Rothman has expertly compiled 70 letters, dialogues, treatises, and illustrations that unfold the Copernican revolution. The book is not for the faint of heart, spanning 672 pages as it takes readers through the discoveries and postulates of great scientific thinkers such as Copernicus, Kepler, Galileo, and Newton.

An Associate Professor of History at Case Western University (Ohio), Rothman is a historian of science focusing on the early modern period. Her work curates more than 250 years of this scientific story, with a comprehensive introduction that outlines the book's progression and her approach. Translating many excerpts herself, Rothman aims for clarity and straightforward language throughout, offering short comments to the beginning of each section.

The book traces the evolution of astronomy from a branch of natural philosophy to an empirical way of thinking about the world. The very form of science and means by which it was pursued, discussed, and advanced were constantly evolving, progressing from local universities and monasteries to a widespread network of scholars communicating discoveries across geopolitical boundaries.

As *The Dawn of Modern Cosmology* outlines the first challenges to geocentric thinking and on to our modern understanding of cosmology, Rothman provides context for each transition. First, she discusses Ptolemy's model, which placed Earth at the center of an ordered, spherical cosmos where the Sun, Moon, and planets revolved on stationary, crystalline spheres. Then, Rothman turns to Copernicus, quoting excerpts from his works, *Little Commentary* and *On the Revolutions of the Heavenly Spheres*. Although imperfect, his heliocentric models represented a revolutionary step forward. Copernicus's work inspired astronomer Johannes Kepler to develop his laws of planetary motion for elliptical orbits around the Sun.



The course of astronomy was forever altered with the 17th-century invention of the telescope and Galileo's stunning observations of planets, Jupiter's moons, and other phenomena, all described in *Starry Messenger*. Rothman also adds nuance to the infamous clash between Galileo and the Catholic Church, describing how the Church initially supported Galileo's endeavors — until, in a letter to a colleague, he suggested reinterpreting biblical passages to align with a heliocentric view, which eventually led to a trial and house arrest.

However, the revolution was already underway, and soon a new physicist came along who synthesized the work of his predecessors. Enter Isaac Newton and his theories of gravity, acceleration, and other physical laws published in *Philosophiæ Naturalis Principia Mathematica*.

"Newton, then, is often where this story ends," Rothman writes. He had finally achieved a universal theory of nature, developing laws that explained heliocentrism, uniting celestial motions to terrestrial physics. "But this story is not only about ideas, but also about the forms that those ideas take," Rothman adds. Alongside letters and dialogues between fictional characters, Rothman includes images, expertly demonstrating their various pedagogical uses as visual companions to scientific theories. Pictures illustrate an author's argument, simplify technical concepts, and are even used to attract a broader audience.

To this mixture, Rothman adds short stories, poems, and novel excerpts, such as a passage from John Milton's *Paradise Lost* where Adam and the angel Raphael debate geocentric versus heliocentric theory. These interdisciplinary texts flesh out the arc of the Copernican revolution, reflecting the influence of astronomy on broader society as it ignited the imagination of scientists and non-scientists alike.

The Dawn of Modern Cosmology weaves together a complete picture of the Copernican revolution, drawing the story from history and illustrating the evolution of the content and form of astronomy and scientific inquiry.

■ **ARIELLE FROMMER** is a recent graduate of Harvard University, where she received a bachelor's degree in astrophysics and physics.

How to Build a Spectroheliograph

This project lets you record full-disk images of the Sun at any wavelength.

The Sun is at solar maximum with plenty of activity. So how can you take advantage of the show? These days, there are many solar filters and specialized telescopes available that permit safe views of the Sun. The problem is that beyond the photosphere, it can be costly to view the specific, narrow regions of the solar spectrum where much of the excitement occurs. Hydrogen-alpha (Hα) or calcium-K (CaK) solar filters typically each cost thousands of dollars or more. If only there were a single device that grants you access to these regions of the solar spectrum where prominences, plages, filaments, and flares are seen that won't break the bank. Well, there is. It's called a spectroheliograph — and it isn't that hard to build.

Building your own spectroheliograph connects you to a historic solar imaging technique updated for the digital age.

You may have heard of a spectroheliograph but perhaps remember it as a large observatory instrument. Both George Ellery Hale and Henri-Alexandre Deslandres are credited with independently inventing the device in 1890 and 1894, respectively. A spectroheliograph was first put to practical use at Hale's personal observatory, the Kenwood Astrophysical Observatory, in Chicago, Illinois.

These devices aren't visual instruments but, rather, were developed for photography of the Sun. Typically a meter long or more with moving parts, the instrument focuses sunlight from a refracting telescope through a narrow slit. The light then passes through collimating optics onto a prism or diffraction grating, where the sunlight is dispersed into its spectral components. Another set of optics focuses the spectrum onto a photographic plate, where a second slit isolates a particular spectral line of interest. As the telescope is slewed across the face of the Sun, the photographic plate is simultaneously moved at a corresponding speed to build a solar image. This clever technique produces a full-disk image of the Sun in extremely narrow regions of the spectrum. Unfortunately, such a complex process was beyond the realm of all but the most advanced amateurs, so it never caught on.

A Modern Take

Fast-forward to 2025, when modern technology comes to the rescue. Today's spectroheliographs incorporate some important advancements that reduce much of the complexity (and size) of the device. The concept remains the same as ever, but instead of a moving photographic plate, the device uses a fixed CMOS video camera to record the solar spectra. The second slit that isolates the spectral line of interest is replaced by a long and narrow region-of-interest (ROI) box in the camera-control software — effectively a virtual slit. The telescope slews across the face of the Sun at a preset speed as a high-speed video of the ROI selection containing the spectral line of interest is recorded. The resulting video is then processed with specialized software to assemble the frames into a recognizable image of the Sun, which is then sharpened like any other solar or planetary image.

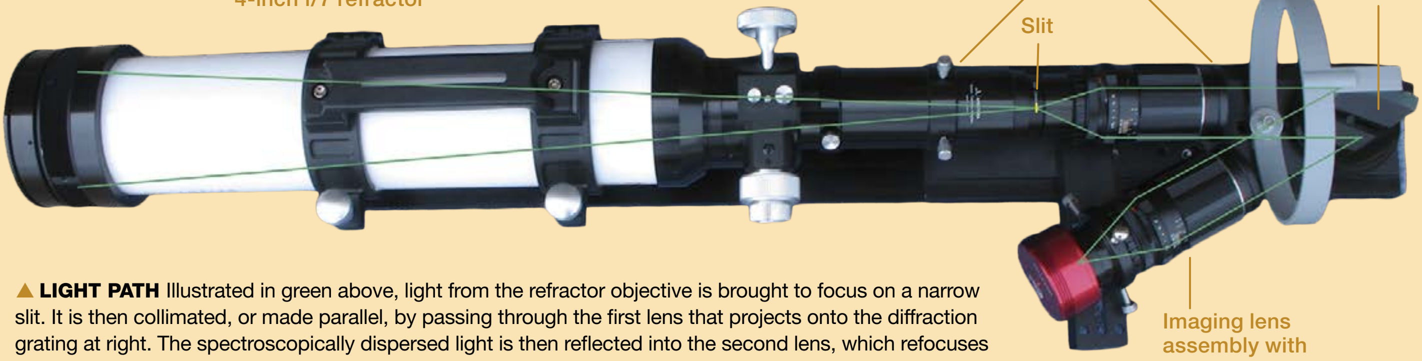
The good news is that you can acquire your own spectroheliograph with all these modern improvements. Commercially available units are available, as well as 3D-printed kits with optics that require some assembly.

French amateur Christian Buil developed a basic spectroheliograph design called Sol'Ex, the latest version is available at **https://is.gd/solex2**. Another option offered by MLAstro is constructed from aluminum and includes the internal optics, sold at **mlastro.com/mlastro-shg**.

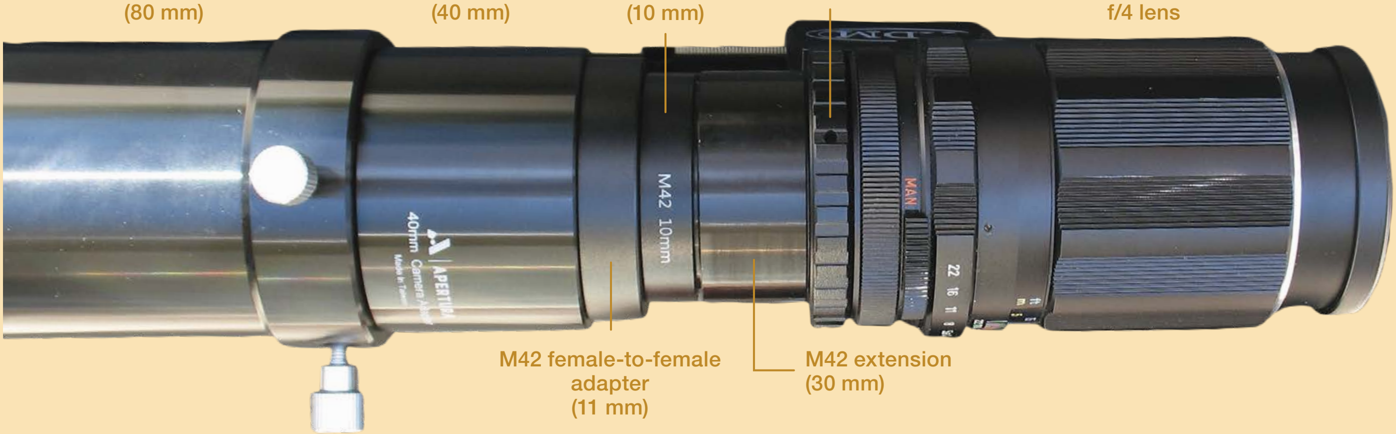
You can build your own spectroheliograph using mostly off-the-shelf components. The images made with this version can be surprisingly detailed with excellent contrast at any visible wavelength. Most amazingly, a spectroheliograph offers an effective bandpass that's much narrower than that of the etalon filters used in most commercial solar telescopes — and it comes at a fraction of the cost. Images showing the calcium-H or calcium-K line are a revelation when captured with an effective bandpass of only 0.02 nanometer. This is

◀ **SIMPLE ELEGANCE** The author's do-it-yourself spectroheliograph is shown here without its light-tight shroud. The assembly rides atop an Astro-Physics 900QMD German equatorial mount.

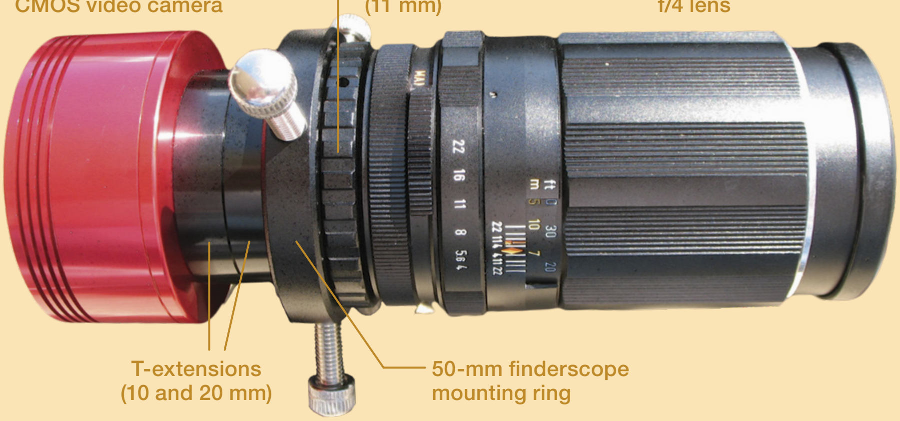
Main Components The author's spectroheliograph is designed around an Explore Scientific ED102 triplet refractor, a narrow slit, a pair of used Asahi Super-Takumar 150-mm f/4 camera lenses, and a 50-mm square, 2,400-lines-per-millimeter holographic reflective diffraction grating.



▲ **LIGHT PATH** Illustrated in green above, light from the refractor objective is brought to focus on a narrow slit. It is then collimated, or made parallel, by passing through the first lens that projects onto the diffraction grating at right. The spectroscopically dispersed light is then reflected into the second lens, which refocuses the beam onto the CMOS sensor at lower right.



▲ **SLIT FOCUS AND STRAIGHTEN** The collimation assembly consists of several adapters, a UV/IR-blocking filter, a slit aperture, and a 150-mm lens. Note the slit is installed near the telescope's focus point within an M42 spacer.



▲ **REFOCUSING** After reflecting off the diffraction grating, the solar spectrum passes through the second 150-mm camera lens with the imaging camera positioned at the focal plane.

▲ **HEAT RESISTANT SLIT** One of the most critical parts in the spectroheliograph is a slit that controls the amount of light reaching the camera. The author uses a custom-generated 9-micron-wide, 12-mm-long slit printed in chrome on a quartz substrate which is mounted in a 1¼-inch filter cell.

SLIT: DOUG SMITH

10 to 20 times narrower than typical commercially available filters, and the resulting image is almost unrecognizable compared to those recorded through an etalon.

Assembling the Components

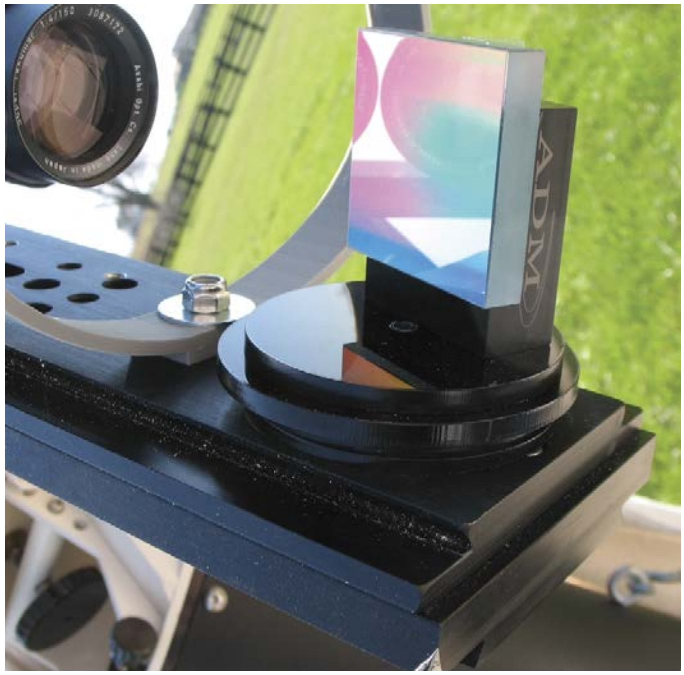
If you decide to build your own spectroheliograph, you'll first need a sturdy equatorial mount that can be slewed at specific, consistent speeds. One that is capable of a solar tracking rate is particularly desirable, as you'll see later.

The main optic is a refractor that's permanently mated to the device. Once assembled and adjusted, you won't want to take the unit apart again. My spectroheliograph is designed around a 4-inch Explore Scientific ED102 f/7 refractor with a 2-inch focuser. Scopes in this range are available from many suppliers. And since you're targeting a fraction of a single wavelength of light, an expensive apochromatic model isn't necessary, though you may need to refocus when targeting different spectral regions.

Next are the main mounting plates that everything is bolted to. I use a 31-inch ADM DUP31- D Series Universal Dovetail Bar, sold at **admaccessories.com**. This is the perfect length for my entire assembly, and it slides onto the Losmandy D-style saddle plate on my equatorial mount. An additional, small mounting bar is needed to hold the collimating optics and camera. The 7-inch ADM VDUP7- V-Series Universal Dovetail Bar works perfectly for the job.

The first section of the spectroheliograph consists of a mounted slit and a camera lens that functions as a beam collimator. By placing the lens backwards in the light path exiting the telescope's focuser, it converts the converging light cone into parallel rays. The focal length of this lens is related to both the size of the slit and that of your camera's detector. However, a lens with a focal length too short, say, 50 mm, produces too much field curvature, projecting an image of the slit that is only in focus in the central region. I used an old Pentax Asahi Super-Takumar 150-mm f/4 manual-focus camera lens (made in the 1960s), which, when combined with the refractor, produces an image of the Sun that spans 6.4 mm at focus. As a bonus, the lens uses an M42 mounting thread (42-mm aperture with a 1-mm thread pitch), a common format for astrophotography adapters. I also added an L1 Astronomik UV/IR-blocking filter at this point to block the Sun's intense infrared emission, which can damage components in the light path, but still pass the near-ultraviolet calcium-H and calcium-K spectral lines. A stronger neutral-density filter is recommended to attenuate the light to a less damaging level if your slit isn't made of a heat-resistant glass such as quartz.

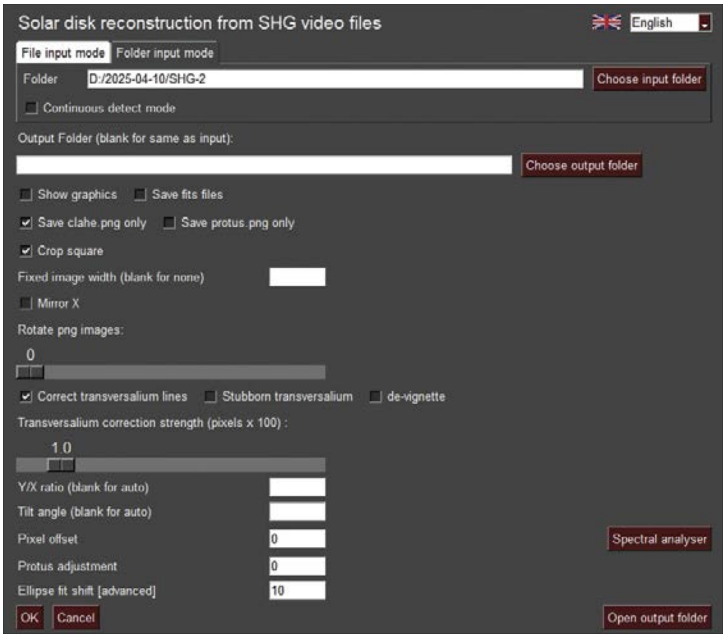
A narrow slit is positioned at the lens's focal plane. This is perhaps the most difficult part to acquire. An unmounted version is available through a Chinese retailer at **https://is.gd/shgslit**. I sourced mine from English amateur and fellow spectroheliograph enthusiast Doug Smith (who provided invaluable advice in the design and building of this project). He produces custom slits in batches using the photolithographic process described at **https://is.gd/lithoslits**.



▲ **ROTATING GRATING** The 2,400-lines-per-millimeter reflective holographic diffraction grating is attached to part of a repurposed ADM V-Series dovetail adapter mounted on a series of acrylic disks used to center the grating in the optical path. The front surface of the grating must be aligned with the rotational axis of its mounting screw.

▲ **LIGHT-TIGHT** The spectroheliograph needs to be sealed from extraneous light while in use. The author uses three nested black plastic bags secured by twist ties, which are then covered with a thick towel.

I purchased a 12-mm-long, 9-micron-wide unit from him printed in chrome on quartz glass and mounted in a 1¼-inch filter cell. I needed several threaded adapters and spacers to position the slit just inside the focal plane of the lens, which lies approximately 45.5 mm beyond the flange of the lens mount. Additionally, a T-to-2-inch eyepiece adapter and a 2-inch-format extension tube are required to connect the collimating assembly to the scope. The focus of this collimating lens is adjusted after the parts are assembled.



◀ **CONVERTOR** The videos produced through the spectrograph are converted into images using custom software *SHG*. The results are then stacked and sharpened like solar images recorded with other equipment.

The next component of the device is a rotatable diffraction grating assembly. It consists of a 50-mm, 2,400-line-per-millimeter reflective holographic diffraction grating available through Thorlabs (**thorlabs.com**) or Edmund Optics (**edmundoptics.com**). This is mounted on an ADM V-Series dovetail adapter, which is connected to a few black acrylic disks I picked up on eBay that are used to position the grating in the light path. Rotating this assembly pans the grating through the solar spectrum and allows me to image any spectral line I desire — all from one device.

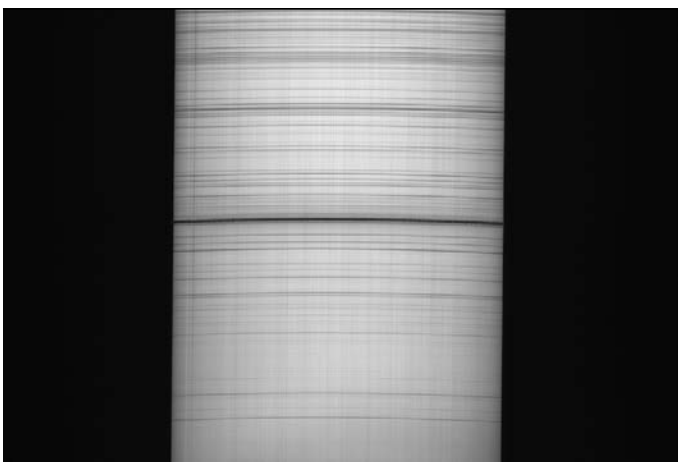
Light bouncing off the diffraction grating is redirected into the imaging lens assembly consisting of a second Super-Takumar 150-mm f/4 lens, with its front facing the grating, as shown in the photo on page 63. A few more adapters and spacers are needed to focus the lens with the camera. I use a ZWO ASI183MM camera that includes a T-thread interface. This is all held in place with a 50-mm inner-diameter finderscope mounting ring.

My choice of camera was determined based on the physical size of the detector (13.2 mm wide) and its 2.4-micron photosites. Since the slit I use is 12 mm wide, the spectrum it produces fits comfortably on the detector with room to spare. The pixel size is related to the slewing rate when scanning the Sun. Slightly larger pixels, say 3 microns, would be ideal for my setup, but there weren't any sensors available that met these specifications when I was designing my spectroheliograph. So I oversample with this combination, which produces a pixel scale of 0.67 arcseconds per pixel.

Finally, the entire spectroheliograph needs to be light-tight. There are many ways to accomplish this, such as a black cloth bag or cardboard enclosure. I use three layers of black plastic grocery bags, affixed with twist-ties, and a dark bath towel. This works well, and I can focus the imaging lens and rotate the grating by feel through the bags. A friend 3D-printed a hoop that I mounted around the diffraction assembly to prevent the bags from sagging into the light path.

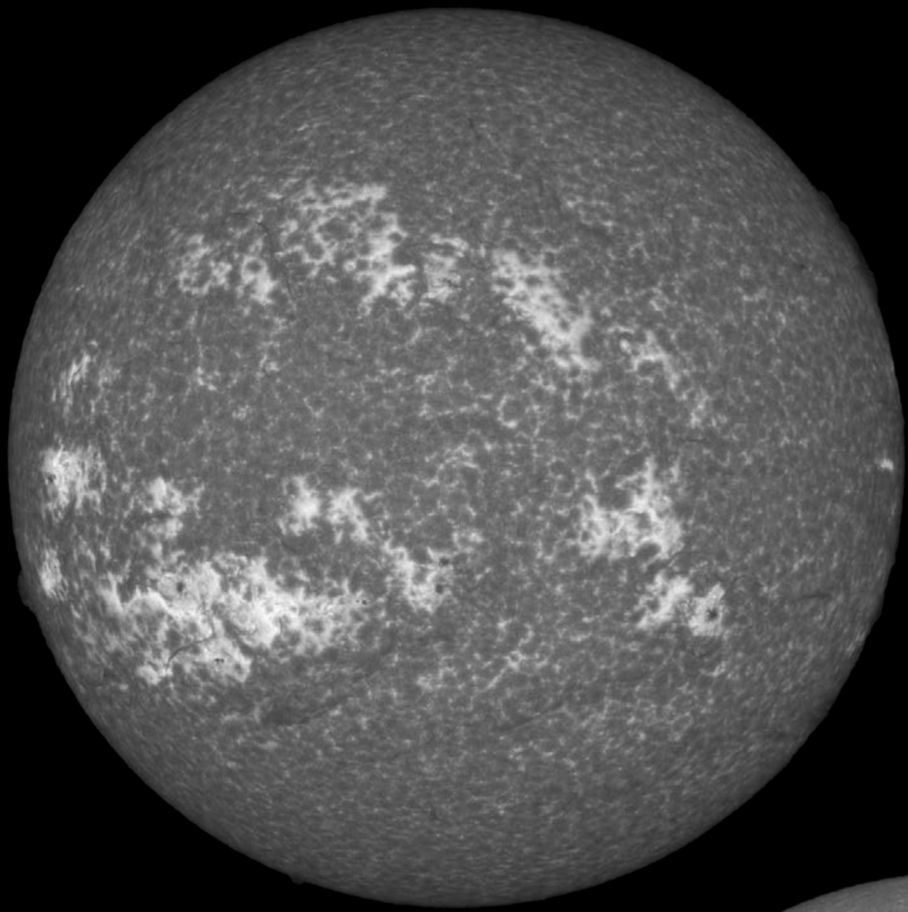
Assembling the Parts

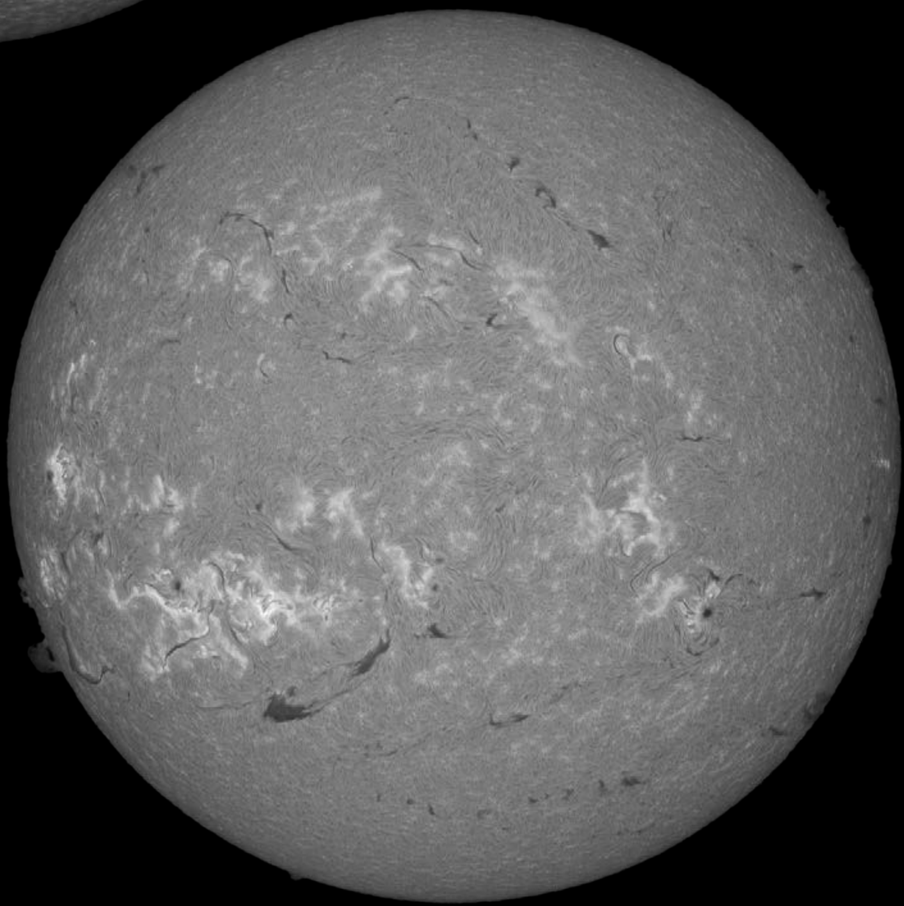
To put the spectroheliograph together, start with the 31-inch dovetail plate. Attach your telescope mounting rings with the focus knobs facing away from the plate. You'll need to determine where the focus point of the scope is in order to



◀ **SPECTRAL VIEW** This image shows the entire frame from the author's ZWO ASI183MM camera, with the dark absorption line of Hα (656.3 nanometers) centered. When focusing the spectrograph, first adjust the sharpness of the spectrum with the imaging lens, then fine-tune focus using the telescope's focuser knob while watching the very left or right ends of the spectrum.

▲ **ULTRA-NARROW** A typical video frame of the targeted Hα wavelength shown above doesn't look like solar images you're used to seeing. Cropping the detector using a region-of-interest selection acts as a virtual second slit, which is necessary for isolating the wavelength.





FROM SPECTRUM TO SPECTACLE
This pair of images recorded with the spectroheliograph shows the Sun on June 27, 2024, at 396.9 (calcium H) and 656.3 (Hα) nanometers at top left and lower right, respectively.

roughly position the slit without racking the focuser out very far — this is in order to prevent the focuser from sagging under the load of the collimating lens.

The specific parts you may need in order to connect the collimating lens and slit depends on which lens you choose. I needed a series of extension tubes and adapters. From the telescope focuser out, I have an 80-mm, 2-inch-format extension tube fitted with a 2-inch UV/IR-blocking filter, a 40-mm-long, T-to-2-inch camera adapter, and a 11-mm female-to-female T-adapter. I inserted the mounted slit in a 10-mm T-extension tube, followed by a 40-mm T-extension and an M42 × 1 mm to M42 × 0.75 (T) adapter used to connect the lens. I then insert the entire assembly into the scope's 2-inch focuser.

To put together the diffraction grating section, remove the knob-and-clamp section of an ADM D-series dovetail adapter and affix the diffraction grating to it with double-sided tape. On the acrylic disks, drill and tap a ¼-20 thread in their centers. The front face of the grating must be at the center of rotation, so align the grating face with the center of the mounting hole and secure the dovetail adapter that holds the diffraction grating to the disk. Attach this to the dovetail plate with a ¼-20 bolt. Make sure the grating is positioned in the center of the light path emerging from the collimating lens. The grating should be about 100 mm from the end of the collimating lens. Tighten the assembly against the mounting plate with enough friction to allow it to be turned to center a particular wavelength but still hold firm when imaging.

Now comes the camera and imaging lens assembly. Again, the parts may vary depending on the camera lenses you've chosen. I connect another M42 × 1 mm to M42 × 0.75 (T) adapter to the lens, followed by a series of T-extension tubes to position the camera's detector a millimeter inside the lens's 45.5-mm focal plane from the mounting flange of the lens. This permits some focus range with the lens. The ZWO camera threads directly onto the end of the T-rings. The entire setup is mounted on the 7-inch V-style mounting bar.

Connect the 7-inch bar with camera assembly to the 31-inch mounting bar at a 90° angle. This positions the imaging train to the side of the telescope so that the camera lens is angled toward the grating at about 30°. The distance from the front of the camera lens to the grating is about 100 mm.

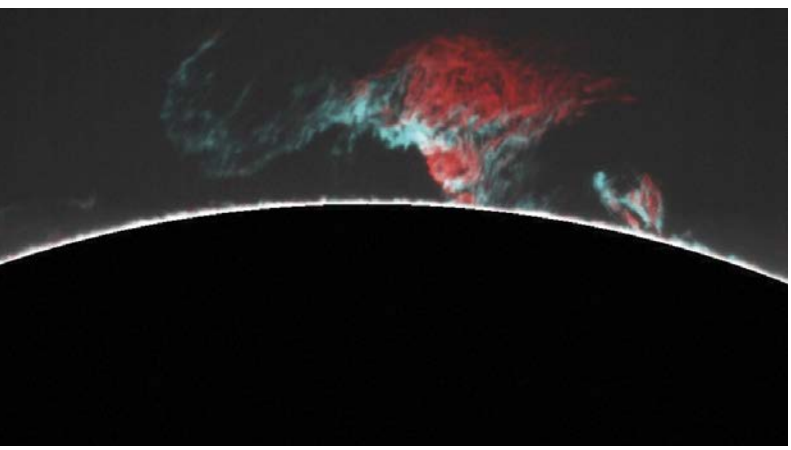
Before mounting the camera and collimating assemblies to the mounting plate, you focus the collimating lens so that the slit is in focus when aimed at the imaging assembly lens face-to-face, which is preset to infinity focus by aiming at a distant object. This is a tricky adjustment but only needs to be done once. When completed, tape down the focus ring of the collimating lens so it can't accidentally be moved.

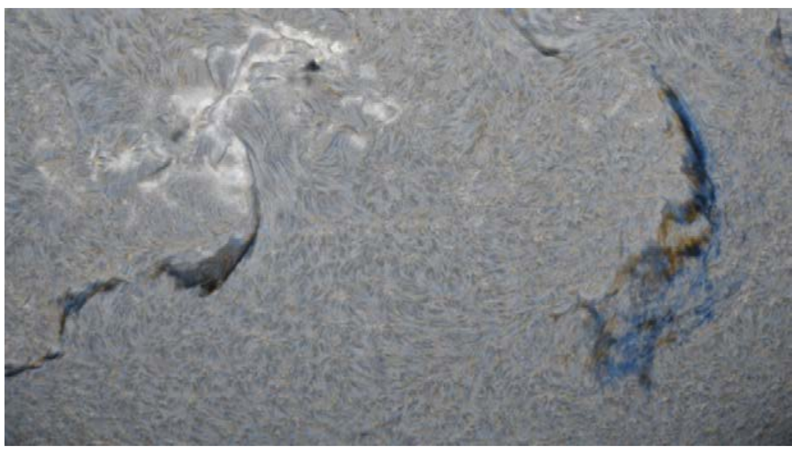
Scanning the Sun

Now that the spectroheliograph is assembled and ready, how do you use it? First, set the mount to solar tracking mode then aim the scope at the Sun (a solar finder comes in handy here, but minimizing the scope's shadow on the ground can work, too). After connecting the camera to your control computer and ensuring the assembly is light-tight, start the camera in your preferred imaging software and be sure that no ROI crop is active. If aimed correctly, the Sun's spectrum will appear on the computer screen. Center it on the camera chip.

Rotate the imaging assembly so that the spectrum is vertical and parallel to the left-right edge of the monitor. Next, rotate the collimating assembly within the telescope's focuser until the spectral lines appear horizontal. The lines will look slightly curved, but it's important to orient them as horizontally as possible so that the processed results don't appear oval-shaped, though this is correctable in the conversion software. Now pivot the diffraction grating to find a line of interest and center it vertically on the monitor. Focus the imaging lens until the spectral lines are sharp and then adjust the telescope's focuser until the left and right edges of the spectrum are sharp. At last, you're almost ready to record.

Using your camera control software, create a wide but short ROI box around your chosen spectral line (I typically



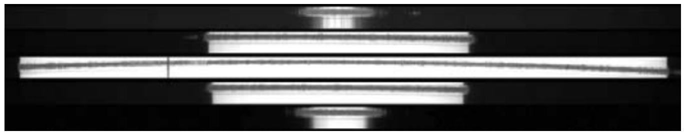


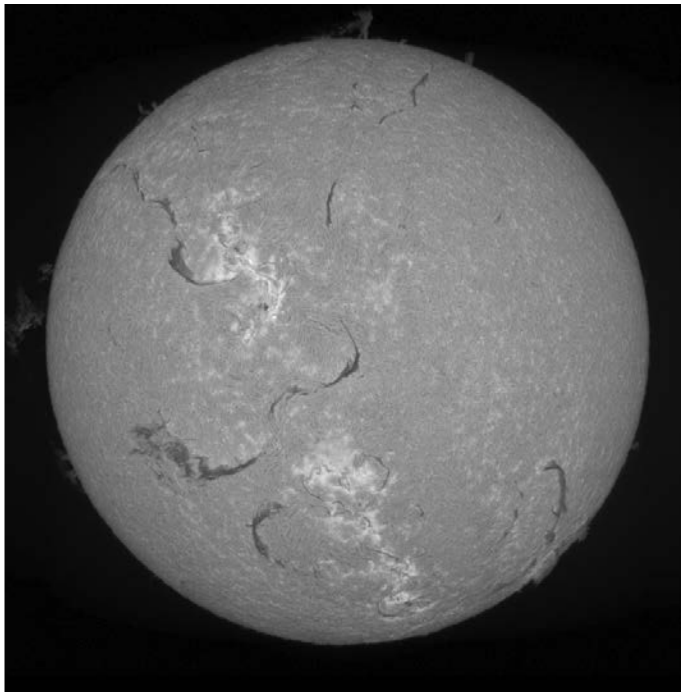
▲ **WAVELENGTH SHIFTS** These pictures combine two images within the Hα band shot with a 0.038-nanometer bandpass difference showing red- and blueshifts of plasma within filaments and prominences. Both pictures, recorded on November 11, 2024, were produced using separate areas from the same spectral line scan.

set mine to 3,208 × 92 pixels). Adjust the exposure and frame rate appropriately — you won't need to raise the gain level very high because the image is quite bright. If you're using *SharpCap*, you may need to adjust the Turbo USB slider setting to get the desired frame rate. The goal is to record at about 350 to 400 frames per second, but that may tax your USB connection and your computer's write speed to its limit, particularly if your camera doesn't have an onboard memory buffer. Your control computer should have a large solid-state drive of at least a terabyte, which usually has the fastest write speeds. Expect each video to occupy about 3 gigabits of storage space. You'll likely need a large portable drive or flash drive to move data off the control computer to make space for new data.

To begin an imaging run, set your control software to preview mode and center the spectral line of interest in the ROI box vertically and horizontally. Slew the scope north so the slit moves off the edge of the Sun. Stop slewing a couple seconds after the spectrum disappears. Then, begin recording a video in 16-bit SER format. Start slewing the scope south at 16× sidereal. As the slit moves across the Sun, the spectrum gets wider and then narrower. Continue the video a couple seconds after the spectrum disappears.

Congratulations! You've just recorded an image of the Sun. Repeat the process a couple dozen times reversing slewing direction each time so that you have many images to stack.





▲ **SCANNING THE SUN** These five spectrum strips at top were extracted from the video that resulted in the fine Hα picture above. This illustrates how the spectrum on the screen appears narrow at the polar limb and gets wider as you approach the Sun's equator, then narrowing again while approaching the opposite pole.

Turning Spectra into Pictures

As you may have guessed, converting spectral-scan videos into images requires specialized software. Current programs that perform this action include *JSol'Ex* (**https://is.gd/jsolex**), *INTI* (**https://is.gd/solarinti**), and *SHG* (**https://is.gd/solexrecon**). I prefer *SHG* because it does a good job of calculating a polynomial fit to the center of the spectral line curve, then constructing a solar image using pixel values from that line center. The software also includes handy functions like batch processing of multiple videos and can correct for oval or distorted solar disks due to a poorly oriented slit or recording at an inadequate frame rate. It also guides you to adjust your frame rate and slit rotation angle to minimize the need for software corrections. The program outputs images in either PNG or FITS format.

After converting your videos into solar-disk pictures, inspect them and reject any that show gaps and black lines caused by wind or dropped frames. For best results, I combine around 15 to 25 images in the stacking software *Autostakkert! 4* (**autostakkert.com**). You can perform final sharpening using any number of programs. (I'm particularly fond of the deconvolution and unsharp masking in *ImPPG* found at **https://is.gd/imageppg**.) A good tutorial on processing solar images appears on page 60 in the July 2024 issue.

Additional Considerations

There are a few caveats to using this spectroheliograph design. Since I'm operating at fairly high resolution (0.67 arcseconds per pixel), the system is strongly affected by local seeing conditions. I try to aim over grass or water and not a roof or asphalt. I also image in the morning when the seeing tends to be at its best. Scans recorded under poor seeing will have a "saw-tooth" edge artifact visible along the limb of the Sun that stacking doesn't eliminate. Windy conditions can also wreak havoc on the recordings, as the spectroheliograph is large and catches the wind easily. Affected videos display gaps and lines in the converted images. But when conditions are good, I can record some 30 videos in less than 10 minutes.

Building your own spectroheliograph not only connects you to a historic solar imaging technique, but also produces high-resolution, full-disk solar images nearly impossible to achieve by other means. Once you start imaging with a spectroheliograph, you'll wonder why you waited so long to give it a try.

■ **RICK SCHRANTZ** is a solar enthusiast residing in rural Kentucky. Read more about the construction and use of his spectroheliograph at **https://is.gd/solarchat**.

Askar's SQA55 Astrograph

The latest from Askar promises sharpness a cut above even their other refractors. Does it deliver?

Askar SQA55

U.S. Price: $795
Optional AF Kit: $87
www.sharpstar-optics.com

What We Like

Pinpoint stars with little vignetting

Auto-focus kit available

What We Don't Like

Play in fine-focus ring

JIAXING SHARPSTAR OPTICAL INSTRUMENT, under its Askar brand, has introduced series after series of refractor telescopes for visual and photo use. I've reviewed models from several of their lines in these pages. Each series offers some defining characteristic: The FRA astrographs (*S&T:* July 2022, p. 64) are marked by fast speed, up to f/3.9 with an optional focal reducer. The Askar V (*S&T:* Sept. 2023, p. 66) comes with two objective lenses and three flatteners, giving users six scopes in one. The APO series (*S&T:* Aug. 2024, p. 70) offers mid-sized aperture at low cost.

What else can Askar possibly offer to attract new buyers?

Well, the unique selling point of their new SQA series seems to be especially sharp star images across a well-illuminated field. The company loaned us the smallest model in the line, the SQA55, to see if it performs as promised.

The SQA Series

First to come out in the SQA line, the little 55-mm scope with its relatively fast f/4.8 speed competes with similar astrographs in the 50- to 60-mm aperture class. The SQA55 uses a helical focuser mounted mid-tube, like a telephoto lens. The larger SQA70, SQA85, and SQA106 introduced later incorporate a more conventional (for a telescope) rack-and-pinion focuser.

The hallmark of all the SQA models is their individual spot diagrams that promise nearly pinpoint stars out to the corners of a full-frame camera sensor. These plots show star sizes growing to only 4 microns (μm) across at the corners for the SQA55 and remaining round.

By comparison, the advertised spot diagrams of most telescopes show star images elongating at the corners due to some degree of astigmatism and lateral chromatic aberration. For example, Askar's published diagrams for its own FRA500 astrograph show stars enlarging to about 20 μm at the corners. I could see that aberration in my tests in 2022, but noted at the time it was nevertheless performance as good as I had seen in apochromat and flattener combinations I had reviewed up to that point.

The SQA series sets the bar even higher for corner-to-corner sharpness. Consider this — the sensors in most cameras used for deep-sky imaging have photosites (or pixels) typically around 3 to 6 μm across. Askar claims the SQA series produces star images the size of, or smaller than, the pixels trying to capture them.

The other significant promise of performance is in its field illumination. The SQA55 specs show vignetting of no more than 10% at the corners of a full-frame sensor.

Those are big promises to keep.

Photographic Performance

SQA stands for Super Quintuplet Astrograph. The optics employ a variation of the Petzval lens, named for 19th-century Hungarian mathematician Joseph Petzval who invented the design for use in portrait lenses.

The SQA55's version of Petzval's

◀▲ Weighing just 2.3 kilograms (5.1 lbs) and only 31 cm (12 inches) long with the dew shield in place, Askar's SQA55 astrograph is small but ideal for wide-field imaging. It's suitable for serious beginners or experienced users wanting to complement a large telescope.

ALL IMAGES ARE COURTESY OF THE AUTHOR

design incorporates a triplet-front objective with one element of unspecified SD glass, a single reducer lens of ED glass in the middle of the tube assembly, and a rear-mounted flattener lens. The SQA55 cannot be used visually with an eyepiece, so no star tests are possible — all my tests are photographic.

Except for some nebula images, I did all my testing using a Canon EOS R5, a 45-megapixel model whose full-frame (36-mm-by-24-mm) CMOS sensor has 4.4-µm photosites, the highest-resolution camera in my arsenal. Combining it with the 264-mm focal length of the telescope yielded a slightly undersampled plate scale of 3.4 arcseconds per pixel.

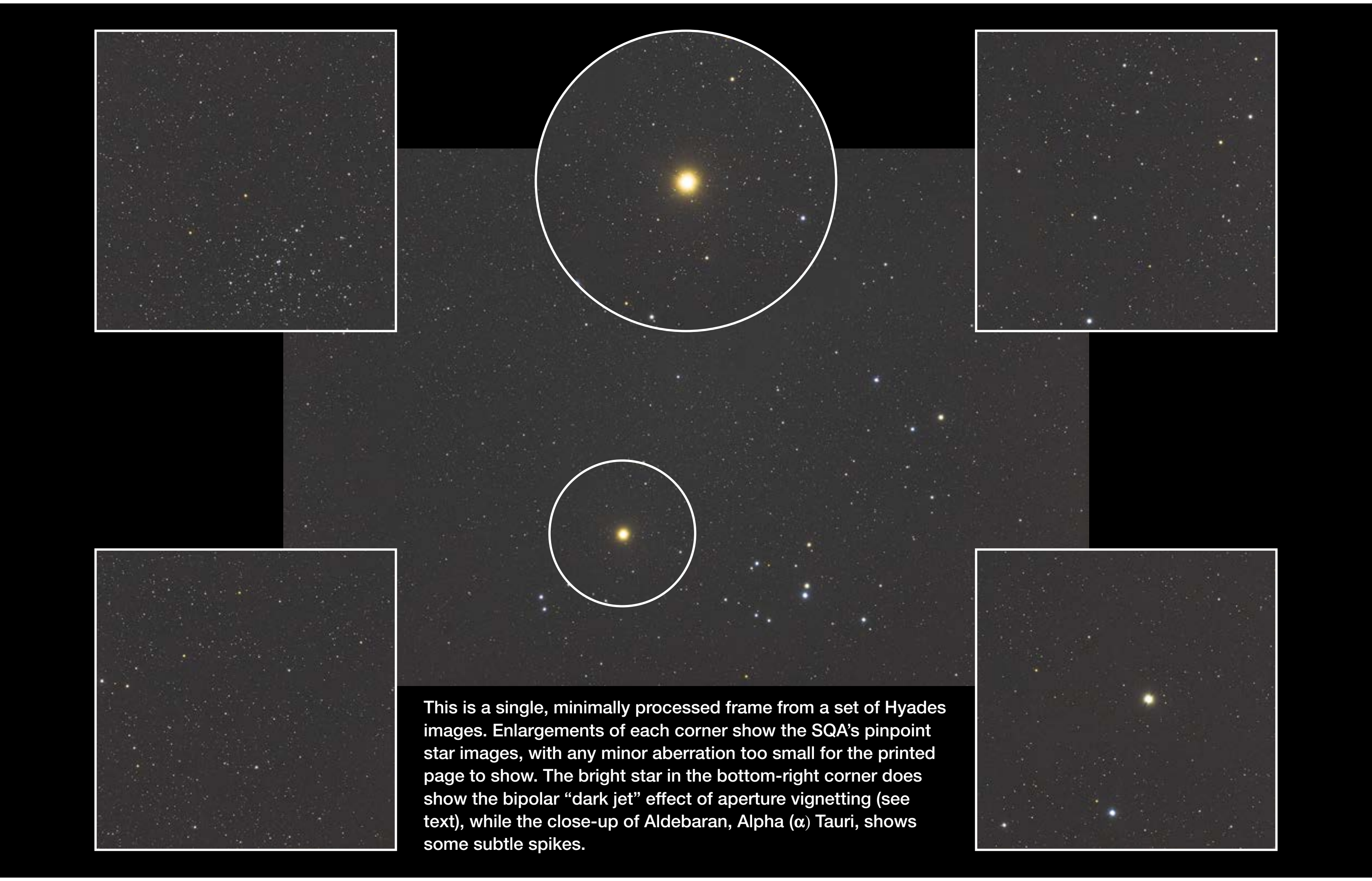
While this telescope should be tolerant of variations in back focus, I did all my tests with a T-adapter that provided 55 mm of back focus. I prefer to have my images sharp and flat to begin with right out of the camera and before any post-processing, and the SQA55 came as close to delivering that level of perfection as I have seen.

On-axis and corner sharpness of the SQA55 proved to be superb. There was no sign of misshaped stars due to coma or de-centered optics. If I really pixel-peeped, I could see the tiniest bit of star elongation at the extreme corners, but no soft stars nor color distortions due to chromatic aberration, either longitudinal (producing haloes) or lateral (elongating stars into colored streaks).

◀ The optics are fully multi-coated, and the tube's interior is well blackened with one baffle at the iris position. The lens cell accepts front-mounted 67-mm threaded filters. The metal dewshield is about 75 mm long and clicks into position with a bayonet mount.

The SQA55 provided the best corner-to-corner sharpness I've seen in any astrographic refractor. It was noticeably better than other models I've tested with similar aperture, which typically exhibited some degree of astigmatism at the corners that gives star images "wings."

With the SQA, the limiting factors to sharpness will be the multiple bugbears of seeing conditions, sensor tilt, autoguiding performance, and focusing accuracy, but not the optics.



This is a single, minimally processed frame from a set of Hyades images. Enlargements of each corner show the SQA's pinpoint star images, with any minor aberration too small for the printed page to show. The bright star in the bottom-right corner does show the bipolar "dark jet" effect of aperture vignetting (see text), while the close-up of Aldebaran, Alpha (α) Tauri, shows some subtle spikes.

I checked field illumination by taking images in deep twilight and in moonlight. They showed only a slight, gradual falloff toward the corners across the outer half of the frame. I measured the light drop at the very corners to be close to 10%, as advertised.

By comparison, in same-night shots, a competing 51-mm refractor showed about a 30% falloff that became steeper at the frame edges, producing notably dark corners, though still easily correctable with software.

True to its double-duty design as a telephoto lens, the SQA55 has an internal 14-blade diaphragm that can stop down the aperture, from f/4.8 to as small as f/22, with no less than 35 click stops (!) between the extremes. The iris can be useful for bright daytime or twilight subjects. Stopping down the aperture also reduces vignetting. But for deep-sky imaging, it only decreases resolution while increasing the exposure time.

With the SQA55, bright stars showed some diffraction spikes, even with the iris wide open. The effect was subtle and hard to trace to its source. At the corners, bright stars showed the commonly seen twin dark streaks, looking like bipolar jets. This isn't an optical aberration per se but is an inevitable consequence of the corners of the frame not capturing the full circular aperture of the lens.

The effect of this aperture vignetting is to render bright light sources at the corners, when defocused, not as circular blobs, but with a cat's-eye-shaped *bokeh*, to use the term common among portrait photographers. But in focus, point sources at the corners render with what look like twin shadows.

▲ Taken in deep twilight, this 30-second exposure of the sky around Deneb, Alpha (α) Cygni, illustrates the SQA's mild, gradual light falloff toward the corners. Contrast has been boosted considerably, as it would be for most deep-sky images.

Mechanical Quality

Achieving the SQA's potential for sharpness requires exact focus. On a couple of nights I missed focus slightly. As a result, stars looked ever so soft on-axis and exhibited slight but noticeable distortion at the corners.

Designed for dual use as a telephoto lens for daytime photography, the SQA55 has not one, but two helical focusers. The wide coarse ring allows the SQA55 to focus down to as close as 4.2 meters, and out to well past infinity. Supplementing it is a narrower fine-focus ring that can turn more than 180°, shifting the tube forward or backward over a range of just two millimeters. Both rings can be locked down.

The fine-focus ring proved to be the SQA's only notable flaw. While the coarse ring was smooth and precise, the fine-focus ring was stiff, lacking the buttery smoothness needed to easily make tiny adjustments. The force needed to turn the ring caused the image to bounce around when manually focusing, at least with the SQA on the lightweight Sky-Watcher Star Adventurer GTi mount I used for my testing.

The fine-focus ring also had annoying backlash — it could be rotated

▼ *Left:* The final adapter ring steps down from the focuser's male M59 threads to present male M48 threads for attaching a camera or T-ring. The adapter ring accepts 48-mm filters. The single rear element of the quintuplet set sits just inside the focuser. *Right:* From left to right is the silver aperture ring for stopping down the lens, as well as the helical fine-focus ring and the wider coarse-focus ring, both with locking knobs. At far right is the 360° camera rotator with four index lines and markings at 1° increments.

left and right by about 5 mm before it grabbed and took effect. That made precise focusing doubly difficult.

I contacted Askar about the issue. Without seeing it firsthand, they couldn't be sure it was a flaw unique to my loaner telescope. And without a second unit to test, I couldn't tell either. The fine-focus ring's mechanical flaws detracted from the otherwise excellent performance and pleasure of using the SQA55.

Mounting Accessories

For those who like to motorize their focusers, Askar offers an AF Kit that allows several third-party electronic-focus motors to attach to the tube and turn the coarse-focus ring using one of the toothed belts supplied in the kit.

Following the kit's instructions, I installed ZWO's popular EAF motor using the AF Kit's bracket that clamps into one of the tube's four mounting shoes. The installation proved a bit fiddly, but the result was solid. However, another instruction sheet that came with the telescope suggests using the aluminum bracket included with ZWO's motor, which might be simpler to install, though you still need the other hardware in the AF Kit.

Using ZWO's *ASIair* control app, the focus ring turned precisely under motorized control and auto-focused accurately.

I clamped my EAF to one of the side mounting shoes, allowing the tube's included handle to remain on the top. This Quick-Release Handle Bar is machined with a Synta-standard dovetail shoe for attaching accessories such as a guidescope, and Askar offers additional handle bars for $59. However, that's the only Synta dovetail attachment point available. The four attachment points on the SQA55 each use a quick-release clamp that securely snaps items into place. The clamp matches the design used by camera makers for attaching tripod feet to telephoto lenses. But attaching other astronomy accessories will require buying an additional Handle Bar.

▲ The SQA's foam-fitted plastic case should be watertight when closed. The dewshield is reversed for compact storage. Removable inserts provide some room for accessories but won't accommodate an attached focus motor.

The scope can rotate within the collar that holds the four quick-release shoes, but not once the AF Kit is installed. Fortunately, the rear of the tube has a separate 360° camera rotator, with markings that are etched in 1° increments. Except on subfreezing nights when it became hard to turn, the rotator was otherwise smooth and easy to position precisely without shifting focus or tilting the camera.

Recommendations

While Askar promotes the SQA55 as a telephoto lens for nature photography (even showing it being used handheld), without conventional autofocus or image stabilization I think its application for daytime use would be limited to shooting static subjects with the SQA on a tripod. I wouldn't count on it replacing a regular 200-mm or 300-mm telephoto lens for nature shots.

But for astro-imaging the SQA55 is superb, being sharper than most conventional telephotos you are likely to have. It also has the fittings needed to attach accessories such as guidescopes and dedicated astro-cameras, and to clamp it on a telescope mount. Optically, the SQA55 delivered on its promise, in my opinion. However, benefitting fully from its performance will require a high-resolution camera with a full-frame sensor.

■ Contributing Editor **ALAN DYER** is coauthor with Terence Dickinson of *The Backyard Astronomer's Guide*. He can be reached through his website at **amazingsky.com**.

▼ *Left:* Askar's optional auto-focuser kit comes with brackets, bolts, pulleys, and a choice of three drive belts for mounting an electronic focuser from one of several third-party brands. *Right:* The included foot accepts a 20-cm-long Vixen-style dovetail plate, which has a channel to slide onto the foot. Tripod use requires bolting a user-supplied plate onto the foot, which accepts either ¼-20 or ⅜-16 threads.

How Empty Is Space?

Astronaut Bruce McCandless II approached the void of space in 1984, having propelled himself briefly away from the Space Shuttle's safety. But how barren was that void?

NASA

SPACE, DOUGLAS ADAMS might have written, is empty. Really empty. You just won't believe how vastly, hugely, mind-bogglingly empty it is.

To understand how empty space is, let's start with the air we breathe. At sea level, there are some 30 trillion trillion molecules per cubic centimeter. (We'll write it from now on like this: molecules/cm^3.) A cubic centimeter, for reference, has about the same volume as a single green pea. Imagine squeezing 30 trillion trillion of anything into so small a size — that should give a sense for just how dense our atmosphere is.

We can make air a bit emptier, and we don't even need to leave the beach. Let's say you're at sea level drinking some lemonade through a straw. Before that liquid sunshine hits your tongue, you've already made a partial vacuum: Your lungs remove air from the straw, leaving roughly 20 trillion trillion molecules/cm^3 inside.

Reducing pressure by 30%, though, still leaves a lot of air. Fortunately, human ingenuity more than makes up for the frailty of our lungs. That ingenuity turns up, among other places, in vacuum cleaners. Most of these use a fan to move air and create a partial vacuum. A good one can evacuate down to 500 thousand trillion molecules/cm^3.

Still, we can do better. The very best vacuums humans have made are within particle accelerators, powerful facilities that set up collisions between subatomic particles. Engineers at CERN, the particle physics research center located on the Swiss-French border, have used various pumping technologies to create the best vacuum possible on Earth so far, with only 1,000 particles/cm^3. CERN's vacuum approaches the level of pressure at the Moon, where interactions between the lunar surface and the solar wind combine to create a gaseous exosphere of 100 atoms/cm^3.

Still, that's not exactly empty space. To find more evacuated regions, you'll need to go farther out into the Milky Way. In the space between stars, there is on average only a single atom or molecule per pea-size volume. But note that's "on average": The gas is actually clumpy, forming filamentary clouds of 10 to 100 atoms/cm^3. The interstellar space outside those clouds is even sparser, containing only 0.1 atom/cm^3, or 100,000 atoms in every cubic meter.

But that leaves 100,000 atoms floating in a volume slightly bigger than a hot tub. For a bit more elbow room, you'll need to leave our galaxy for the desolate reaches of the intergalactic medium. There, any given hot-tub–size space holds only a single atom.

Technically speaking, of course, *vacuum* is defined as a region devoid of matter altogether, and the universe never quite accomplishes that — thank goodness! As they say, a little goes a long way: The most far-flung of charged particles can still create a magnetic field, and the most rarefied matter in the space between galaxies may still interact with the oh-so-occasional passing photon. Even in the most mind-bogglingly barren of boondocks, space isn't quite as empty as it seems. ■

▶ SMART CAMERA

Chinese manufacturer ZWO expands its series of smart cameras with the release of the ASI585MC Air ($999). This deep-sky imaging camera includes an onboard control computer, an imaging sensor, and a smaller detector in the camera used for autoguiding that simplifies most astro-imaging setups. Its main imaging sensor is a Sony IMX585 color CMOS detector with a 3,840 × 2,160 array of 2.9-micron-square pixels. The guiding chip is an SC2210 detector with a 1,920 × 1,080 array of 4-micron-sqare pixels. The camera operates in 16-bit mode and boasts a quantum-efficiency of 91% with a full-well capacity of 40,000e. It wirelessly connects to your Apple or Android device via either Wi-Fi or Bluetooth and is controlled using the *ASIAir* app. The camera has 256 GB of storage and 2 GB of DDR memory. The ASI585MC Air also includes a built-in, four-port powered USB 2.0 hub to connect your telescope mount, focuser, and other accessories. Purchase includes several cables and adapters. Requires 12V, 3A DC power.

ZWO
6 Moon Bay Rd., Suzhou Industrial Park, Jiangsu Province, China
Phone: +86-512-65923102; zwoastro.com

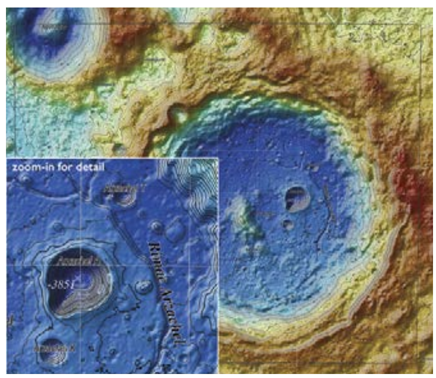
▶ COMPACT MINIGRAPH

Sky-Watcher rolls out a completely new optical design for traveling astrophotographers. The HAC125DX Minigraph ($995) is a 5-inch aperture, 250-mm-focal-length (f/2) telescope featuring a hybrid catadoptric optical design that delivers pinpoint stars across a 16-mm corrected field that's a perfect match for cameras with a Sony IMX433 or IMX585 sensor. The primary mirror cell includes collimation adjustment screws and a large helical knob on the rear of the tube assembly moves the primary mirror to focus. The minigraph measures just 40 centimeters (18 inches) long and weighs 3.8 kilograms (8.4 lbs). Each purchase includes tube rings, a Vixen-style dovetail mounting bar, a threaded dew shield, two quick-release finder brackets, both male and female T-adapters, and a T-to-1¼-inch camera adapter.

Sky-Watcher USA
475 Alaska Ave., Torrance, CA 90503
310-803-5953; skywatcherusa.com

▶ TOPOGRAPHIC LUNAR MAPS

Scientist and cartographer John W. Robbins has published *The Detailed Topographic Lunar Atlas - Near Side* (€49.99) as an ebook. This downloadable PDF atlas is based on three lunar digital elevation models developed by NASA. The atlas depicts the lunar surface in 1,204 individual topographic maps with color-coded elevation details at a scale of 1:500,000 for all but the polar regions, which are reproduced at a scale of 1:800,000. The maps include the six manned lunar landing sites, 915 main craters, 5,418 satellite craters, 51 mare regions, 54 mountains and promontories, 1,141 domes, and much more, as well as a comprehensive index of each named feature. A companion atlas of the lunar far side is also available for €39.99. 1,231 pages, ISBN 978-3-949370-16-8.



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Werner-von-Siemens-Str. 19, Erlangen, Germany 91052
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My Favorite Things

A celebration of amateur telescope making

▲ Some projects were simply too amazing not to write about. Seen here: Rik ter Horst's solid-glass Schmidt-Cassegrain telescope, which went into orbit in Portland State University's OreSat CubeSat (*S&T:* May 2022, p. 74).

I STARTED WRITING this column nine and a half years ago, stepping in when Gary Seronik moved on. I'd had several of my amateur telescope making creations featured in Gary's Telescope Workshop, but the first one under my byline was in the June 2016 issue. In that column, by way of introduction, I wrote about the many large and small astronomy-related items I would be featuring in times to come. The goal was to introduce yet another generation to the many things they could build themselves, and to the joy of using that home-built equipment out in the field.

I wrote about red and amber flashlights, Cheshire and laser collimators, adjustable chairs, light shields, simple finders, even homemade eyepieces. And those are just my own creations. I dedicated the majority of my columns to other people's designs, featuring projects as simple as a cardboard travel scope (page 24 in the June 2022 issue) to the vastly complex, equatorially mounted scope built by master machinist Detlef Werner Schmidt (November 2017, page 72). I tried to stick to projects that other ATMs might want to build as well, but there were occasional designs that were just too beautiful, too innovative, or simply too amazing not to share with the world.

◀ In the early days of amateur telescope making, equatorial mounts made from pipe fittings were de rigueur.

Judging from the emails I've gotten over the years, people have been largely happy with the mix. I even got fan mail a couple of times from our Editor in Chief! (Let me tell you, that's a sensation you don't forget.) I've gotten suggestions for topics to cover, some of which led to full-fledged feature articles. I got one patent infringement warning. (That's another sensation you don't forget.)

It's been a wild run. I often tell people that this is my dream job. I started out as a science-fiction writer, became an amateur telescope maker, and then got the chance to combine those two skills in this column. Writers typically don't retire, and neither do ATMs, so I could easily continue for another decade. But times change, and to be honest, most people don't. I'm a member of the "old guard," the people who grew up with equatorial mounts and thought John Dobson was a dangerous upstart. We later became converts, even acolytes and proselytizers, but that's as far as many of us were willing to bend. You won't find a computerized scope in my shop . . . unless it's to un-mount it and turn it into a Dobsonian.

A lot of us old-timers like to complain that amateur telescope making is dead. Astrophotography has taken the amateur astronomy hobby by storm, and that requires (mostly) store-bought equipment. New fully automated telescopes like the eVscope and the Seestar have buried even more the time-honored tradition of building things yourself — or even looking through an eyepiece. And 3D-printing a part when you could go out in the shop and saw up a piece of plywood? What's this world coming to?

I've tried to avoid that trap, giving Kathy the right to poke me in the ribs whenever I utter the words "When I was a boy . . . " and I think I've largely succeeded — I even bought a 3D printer! — but there's no denying that the most complicated part I've yet designed for it is an eyepiece cap.

Enter Jonathan Kissner. You've read about him in this column (January 2023, page 70). He's the designer of the

▶ In the 1970s, John Dobson changed everything (*S&T:* Apr. 2020, p. 36).

PIPE-FITTING EQUATORIAL MOUNT: DREW SORENSON; HIPPIE DOBSONIAN AND SOLID GLASS SCHMIDT-CASSEGRAIN: JERRY OLTION (2)

▲ One final build just for kicks: my Beany-Weenie Maksutov. Above all else, ATM projects should be fun!

Hadley telescope, a 4½-inch scope with mostly 3D-printable parts — a simple, cheap, and effective way for newcomers to get into telescope making and astronomy in general. Jonathan is living proof that amateur telescope making is far from dead, and he's plugged into the next generation of builders who are designing things I could barely dream of. Starting next month, Jonathan will be bringing a new perspective and a new voice to this column, continuing on the tradition that started with Ralph Bates in 1941 and will, we hope, continue on even after Jonathan becomes "old guard" to yet another generation of creative tinkerers.

Sky & Telescope has a new Editor-in-Chief in Diana Hannikainen. Former editor Edwin Aguirre has returned to the staff as Associate Editor to fill her previous position. And Jonathan will be carrying this column forward, part of the inevitable — and entirely welcome — march into the future.

I look forward to reading Jonathan's columns in the years to come. Many people tell me that Astronomer's Workbench is the first thing they look at when the magazine shows up in their mailbox. Of course that's been the case here at my house, too, and it will continue to be the case for as long as I'm still around to read it.

Welcome, Jonathan! I look forward to seeing your new discoveries. Send your ideas to him at **workbench.kissner@gmail.com**.

■ Contributing Editor **JERRY OLTION** wishes to thank all the ATMs and the readers who have made this truly his dream job.

JERRY OLTION

GALACTIC ARCH OVER THE SINAI
Osama Fathi
The winter Milky Way from Cassiopeia to Scorpius glitters above Jabal Mūsā (Mountain of Moses) in Egypt. NGC 7000 in Cygnus (center left; see page 78) and the Rho Ophiuchi region surrounding Antares in Scorpius (right) add additional color to the scene.
DETAILS: *Modified Nikon Z6 camera and Nikkor 14-to-24-mm lens. Mosaic of 21 exposures each 20 seconds at f/2.8, ISO 1000.*

CONTINENTAL DIVIDE

Warren Keller and Michael J. Griffin

The North America Nebula, NGC 7000 (left), and the Pelican Nebula, IC 5070 (right), in Cygnus, are actually a single, massive cloud of emission nebulosity measuring 50 light-years across. The dark swath of dust and gas dividing them forming the iconic Gulf of Mexico is LDN 935.

DETAILS: *Askar FRA400 APO refractor and ZWO ASI2600MC-AIR camera. Total exposure: slightly more than 8 hours through dual-bandpass, narrowband filters.*

◁ STAR BUBBLE

Jim Johnson

Roughly 70,000 years ago, intense stellar winds from the Wolf-Rayet star EZ Canis Majoris blew its outer layers into space, resulting in the faintly glowing nebula in Canis Major known as Sharpless 2-308. Its bluish color is due to the dominance of doubly ionized oxygen.

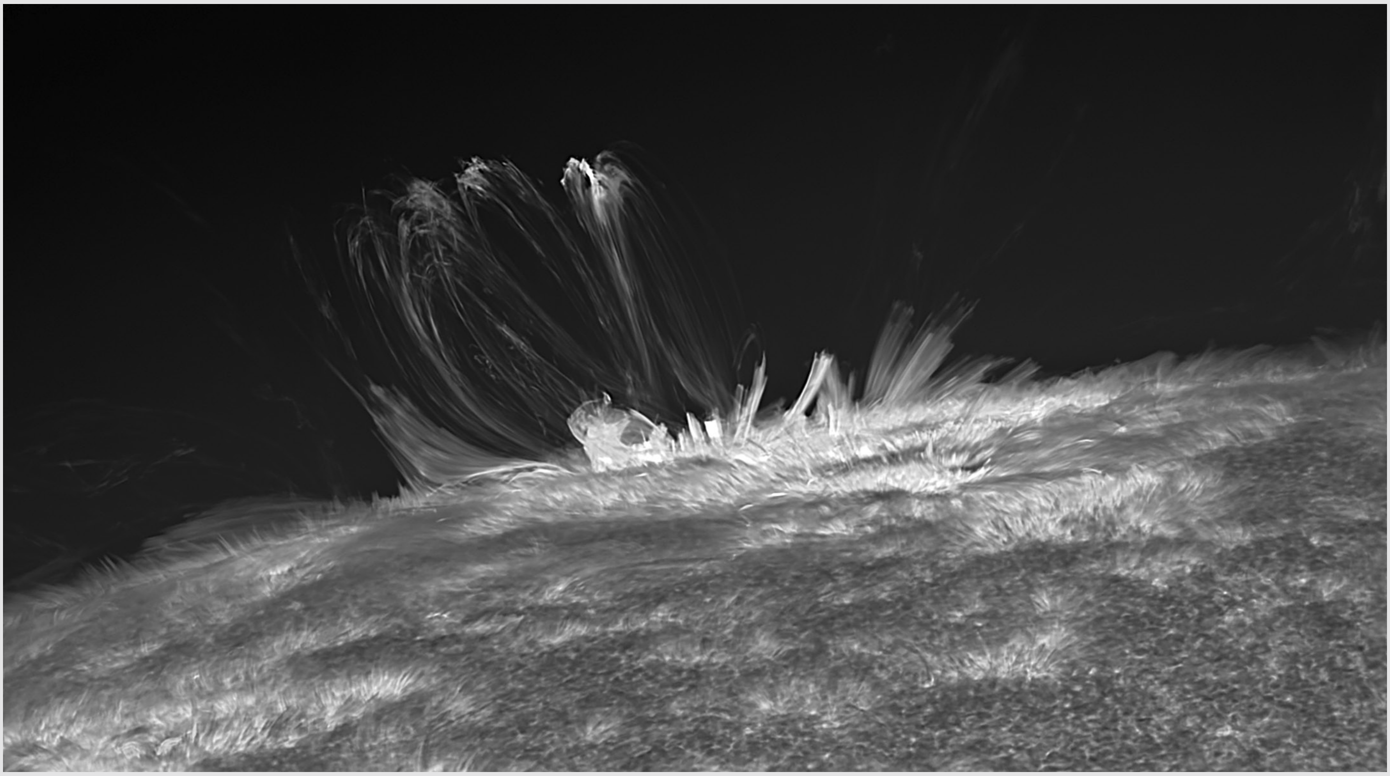
DETAILS: *Tele Vue-NP101is refractor and ZWO ASI6200MM Pro camera. Total exposure: 7.33 hours through narrowband filters.*

▽ SUNSCAPE

Christian Viladrich

Several tall, looping prominences spring from AR 3768 at the Sun's western limb on August 2, 2024. Many smaller wisps of plasma cover the solar surface in this high-resolution image.

DETAILS: *300-mm custom solar Newtonian and ZWO ASI462MC camera. Stack of 150 video frames recorded through double-stacked calcium-K filters.*



Gallery showcases the finest astronomical images that our readers submit to us. Send your best shots to gallery@skyandtelescope.org. See **skyandtelescope.org/aboutsky/guidelines**. Visit **skyandtelescope.org/gallery** for more of our readers' astrophotos.

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Astronomy equipment manufacturers and dealers are a valuable resource for amateur and professional astronomers alike. Patronize our advertisers in this issue and enjoy all the benefits of their expertise.

Product Locator

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Event Calendar

Here's the info you'll need to "save the date" for some of the top astronomical events in the coming months.

August 16–24
MOUNT KOBAU STAR PARTY
Osoyoos, BC
mksp.ca

August 18–24
MAINE ASTRONOMY RETREAT
Washington, ME
astronomyretreat.com

August 20–24
SASKATCHEWAN STAR PARTY
Maple Creek, SK
sssp.saskatoon.rasc.ca

August 20–25
NORTHERN NIGHTS STAR FESTIVAL
Palisade, MN
mnastro.org/northern-nights

August 21–24
STARFEST
Ayton, ON
nyaa.ca/starfest.html

August 21–24
THEBACHA & WOOD BUFFALO DARK SKY FESTIVAL
Fort Smith, NWT
tawbas.ca/dark-sky-festival.html

August 22–24
NOVA EAST
Smileys Provincial Park, NS
novaeast.rasc.ca

August 22–26
ALMOST HEAVEN STAR PARTY
Spruce Knob, WV
ahsp.org

September 13–21
PENNYRILE STARGAZE
Dawson Springs, KY
facebook.com/southstarparty

September 17–21
YORK COUNTY STAR PARTY
Susquehannock State Park, PA
yorkcountystarparty.org

September 18–20
ILLINOIS DARK SKIES STAR PARTY
Chandlerville, IL
sas-sky.org

September 18–21
BOOTLEG FALL STAR PARTY
Harmon, IL
bootlegastronomers.com

September 18–21
SJAC FALL STAR PARTY
Belleplain State Forest, NJ
sjac.us/events

September 19–20
HIDDEN HOLLOW STAR PARTY
Bellville, OH
wro.org/hidden-hollow-star-party

September 19–21
BLACK FOREST STAR PARTY
Cherry Springs State Park, PA
bfsp.org

September 19–21
CONNECTICUT STAR PARTY
Goshen, CT
asnh.org

• For a more complete listing, visit https://is.gd/star_parties.

The Road Will Rise Up

Sometimes it helps to focus on what you can control rather than despair about what you can't.

LIKE SO MUCH of what called me to a scientific career, my favorite story about becoming a scientist begins with the stars. It's a story about a little girl named Bonnie. Eleven years old in 1961, she marched up to her sixth-grade teacher's desk and proclaimed, "When I grow up, I want to be an astronaut!"

Her teacher could have quashed her dreams in an instant. There was no such thing as a woman astronaut in that day. (Soviet Valentina Tereshkova, the first woman in space, wouldn't fly until 1963.) This teacher could have told Bonnie to stop daydreaming. Instead, she did something brilliant.

She said "Bonnie, if you want to be an astronaut, you're going to have to learn algebra."

And little Bonnie Dunbar, who in 1985 would fly her first of five Space Shuttle missions, walked back to her desk, picked up her algebra textbook, and went to work.

I heard Dunbar tell this story at a luncheon in Seattle a few years ago. The audience gasped at the simplicity of her teacher's words. Focus on what you can control. Focus on what is right in front of you. Don't worry about the outside world and its limitations. The world can change. The world can rise up to meet you.

How important it is to remember that hope right now. This year, we've seen funding disappear for scientists working on everything from climate change to cancer cures. At the American Association for the Advancement of Science (AAAS) conference in Boston in February, the organization's CEO admitted that the professional scientific community was in for a rough ride with the cuts to federal scientific research. He counseled patience, even as news of revoked research grants beeped on attendees' mobile phones.

> I believe this with all my heart: Science will find its footing again.

I sat in the audience and sighed. I remembered a long-ago dagger to my heart: a science fair when I was a high-school student in the late 1980s. An all-male panel of scientists judging my work chuckled when I told them I wanted to be an astrophysicist. They told me I had a big ego. A more helpful comment would have been to urge me to concentrate on calculus. In college I gave up on science after getting a B in first-year chemistry. It took 25 years for me to return to my first academic love. I learned that a B was a *really* good grade in college chemistry.

Many moons have passed since those days. This year, I completed a post-baccalaureate degree in biochemistry at the University of Washington. From kid astronomer, I became a second-career scientist with experience working in research labs and writing about gnarly technical topics such as astrochemistry (*S&T:* July 2025, p. 34) and immunotherapy.

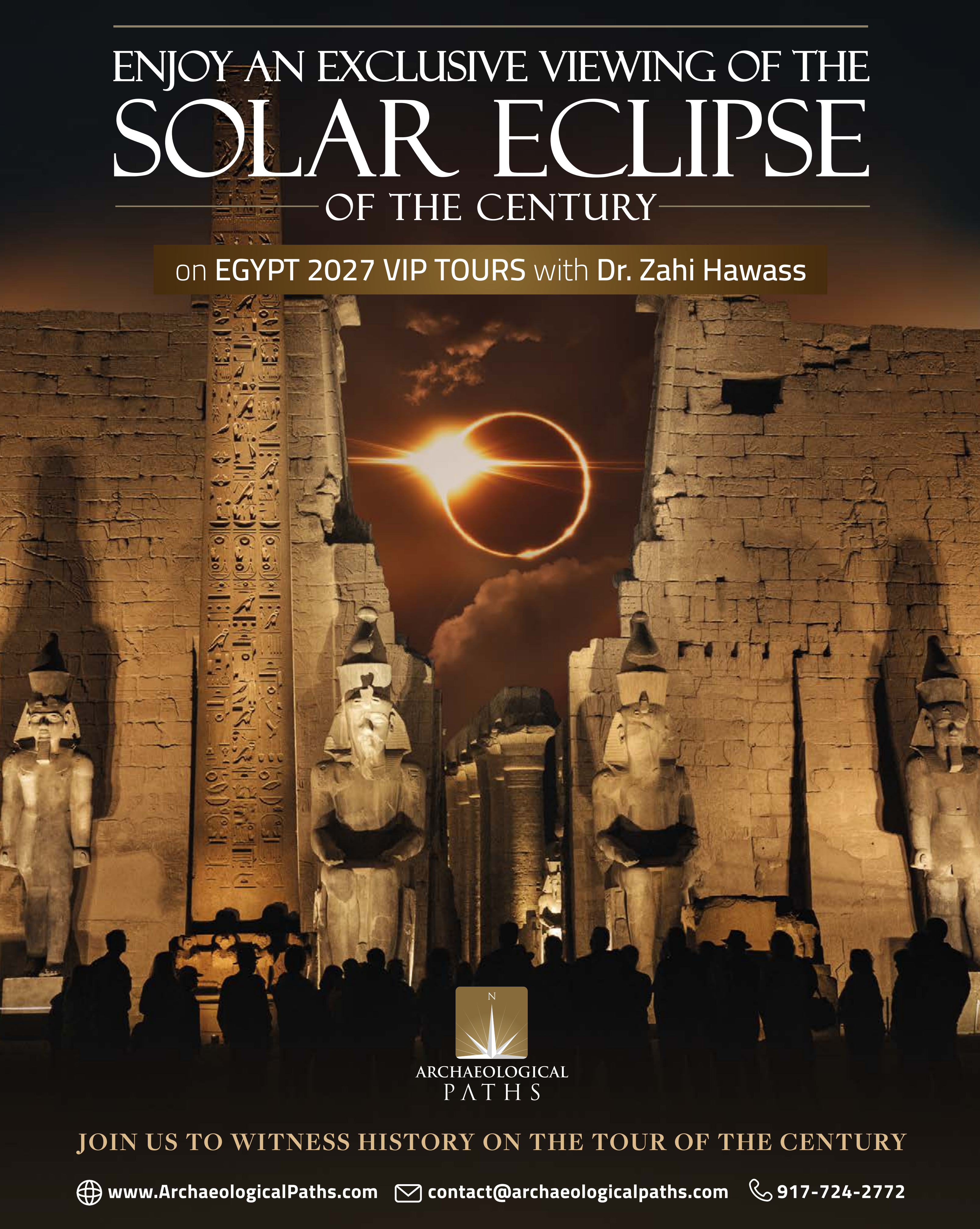
Completing my degree has felt like a rite of passage. Today I count myself among the community of working scientists. I'm committed to telling the stories of great scientific achievements — from the astonishing discoveries of the Hubble and James Webb space telescopes to cutting-edge treatments for leukemia made possible because we've spent decades researching how immune system cells work. I love it all.

Heeding Dunbar's sixth-grade teacher, all of us in the scientific community need to commit to the work that is right in front of us. I believe this with all my heart: Eventually, the road will rise up to meet us, and science will find its footing again.

Let's not lose sight of what's important to us.

JANIECBROS / GETTY IMAGES

■ **NICOLE BOECK** (née Nazzaro) writes about science from her home in Edmonds, Washington.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