OBSERVING:
Small Scope, Winter Sky
PAGE 22

WHEN THE CALL COMES:
Chasing Cosmic Flashes
PAGE 36

IMAGING:
Photograph Dark Nebulae
PAGE 60

SKY & TELESCOPE

THE ESSENTIAL GUIDE TO ASTRONOMY

DECEMBER 2021

DAVA SOBEL ON THE LIFE OF Henrietta Swan Leavitt

Page 12

See Comet Leonard at Dawn

Page 48

Tips for Sidewalk Astronomy

Page 84

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CONTENTS

SKY & TELESCOPE

THE ESSENTIAL GUIDE TO ASTRONOMY

December 2021 VOL. 142, NO. 6

RON BRECHER

FEATURES

Cover Story:

OBSERVING

S&T TEST REPORT

COLUMNS / DEPARTMENTS

ON THE COVER

H. S. Leavitt's key Cepheid discovery enabled modern cosmic distance measurements.
DAVID CURTIS

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Swan Song

A CENTURY AGO, science was a male domain. With rare exceptions, women who hoped to participate were relegated to minor positions with low pay and few prospects or recognition. There's hardly a more pointed example of this lamentable disparity than the career of Henrietta Swan Leavitt, the subject of this month's cover story.

When I first read the opening line of Dava Sobel's feature about Leavitt on page 12, I couldn't help but think of Albert Einstein. In some ways, the two were on parallel tracks, and a comparison of their career paths is instructive.

Einstein toiled away quietly in the Swiss patent office before publishing his special theory of relativity in 1905. Leavitt toiled away quietly at the Harvard College Observatory before publishing her initial discovery of the period-luminosity relation in 1908. Einstein went on to publish his general theory of relativity in 1915, transforming physics. Leavitt went on to publish her definitive findings on what's now widely known as Leavitt's Law in 1912, transforming astronomy.

▲ Henrietta Swan Leavitt (1868–1921)

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After tests during the 1919 solar eclipse gave clear support for general relativity, Einstein became world-famous. Leavitt remained almost completely unknown outside of the observatory and died that way in 1921, the same year Einstein won the Nobel Prize in Physics (though not for relativity). Today, Einstein is a household name; Leavitt's languishes in obscurity. Would that be so if she'd been a man?

Even today, over a century later, Leavitt's discovery has lost none of its luster or its enormous usefulness to astrophysicists. As Adam Riess, who shared the 2011 Nobel Prize in Physics, has commented, "Henrietta Leavitt gave us a tool to gauge the size and expansion rate of the universe. That tool remains to this day one of our very best for studying the universe."

And what of the status of women in astronomy today? Every five years or so the American Astronomical Society reports on gender distribution among its members — a reasonable proxy for the discipline as a whole. In its most recent accounting from 2016, the AAS noted that for at least the past half century, the fraction of its members who identify as women has been growing steadily.

That's good news, but the results don't say anything about these women's career paths. They don't reveal women's compensation levels and how they compare to men's, or how many women are promoted to tenured or leadership positions. (The AAS is working on a new study to ferret out such data.)

As in society in general, parity for women in professional astronomy still falls far short of equal. But one would hope that, if Henrietta Swan Leavitt had made her revolutionary discovery today, she'd have quickly gained the support and the accolades she so richly deserved.

Peter

Editor in Chief

Editorial Correspondence
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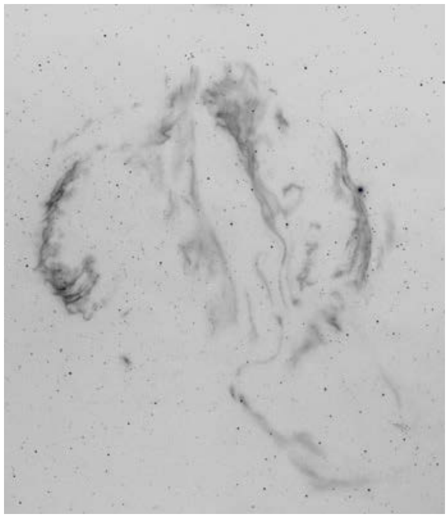
Admiring the Veil

Howard Banich's exquisite sketches of deep-sky objects published in *Sky & Telescope* through the years have helped me immensely in teasing out details during visual observing sessions. Using an 18-inch (46-cm) f/4.5 Dobsonian and his drawings in "The Five Veils of the Cygnus Loop" (*S&T:* Sept. 2021, p. 28), I spent 90 minutes completely blown away by the detail that I saw while using his drawings as a guide. Once I got a feel for the extent and layout of the Veil Nebula, I could freely (and slowly) move the scope and tour the grandness of this object. The best views were at 91× magnification with an OIII filter, though I spent a satisfying first half of my time observing without a filter.

Thank you, *Sky & Telescope* staff and contributors, for all the information and tools that enable me to see even more of the beauty hidden in the clear night sky.

John Teleska
Rochester, New York

▼▶ The Veil Nebula is a large supernova remnant in Cygnus. It's around 120 light-years in diameter and stretches across 3° of the sky.



I'm an assiduous reader of *S&T*, and of all the articles I have read to date, "The Five Veils of the Cygnus Loop" is one of my favorites. Howard Banich's descriptions are exquisite. I had an image of the Cygnus Loop on my iPad while reading the article. The author's descriptions guided me through the many details of the Veil Nebula that often go unnoticed. During my next imaging session, the first thing I am going to do is point my telescopes and cameras towards that region to capture and enjoy its beauty to the fullest.

Banich wrote the article in such a way that it doesn't matter whether one is a visual observer, sketcher, or imager, we can all greatly benefit from the detailed description he provides. I look forward to reading more articles like that in the future.

Wanda Conde
Caguas, Puerto Rico

The articles on Cygnus and the Veil Nebula in the September 2021 issue are outstanding. One of the most influential images for me [though not appearing in the issue] was the picture of the Veil in *The Universe* by David Bergamini. I was 10 or 12 years old when I saw the photograph, and it set my course to learn more about astronomy.

I have a copy of that book from 1971, from my grandfather's library, that I hadn't looked at in many years. After reading the September articles, I opened it back up to that image. These articles brought back great memories from when I started my journey as an amateur astronomer.

Ken Caine
Crafton, Pennsylvania

Pondering Plasma

In his article "The First 10 Seconds" (*S&T:* Sept. 2021, p. 22), David Garrison says, "Our oldest fossil is the *cosmic microwave background* (CMB), the radiation released when the early universe cooled down enough for photons to travel freely." He also says that it formed approximately 380,000 years after the Big Bang. The accompanying graphic shows that this is also when neutral atoms formed, and the universe became transparent.

Statements like these always puzzle me because plasma is transparent to light above a certain frequency, which depends on the density of the electrons. The current universe is full of plasma and yet transparent. By my calculations, the density of electrons 380,000 years after the Big Bang would have led to a plasma frequency of about 2 megahertz, well below that of visible light. So what is the reason for the statement that the universe became transparent when neutral atoms formed?

R. C. Carlson
Folsom, California

David Garrison replies: *There are two things happening at the same time here: the formation of neutral atoms and the process of photon decoupling. The first happened during an era known as recombination, when particles' declining energy made the binding of nuclei and electrons possible. The second occurred when photons became free to travel without scattering. You are correct that the formation of neutral atoms was not necessary to enable the photons to travel without scattering (photon decoupling). The latter occurred once the plasma was no longer dense enough to impede the photons' progress. A plasma's density determines how energetic a photon needs to be in order to travel through it. Before recombination, the density of particles was so high that the energy threshold was much higher than the energy of the photons suffusing the plasma. But as time went on, the universe expanded and cooled. It's only around the time of recombination that the density dropped enough for the*

CYGNUS LOOP: KEES SCHERER / FLICKR; SKETCH: HOWARD BANICH *thermal photons to pass through. The fact that this happens just as neutral atoms are beginning to form may be a coincidence.*

Visions of Vega

Fred Schaaf is a master at what he writes. His Evenings with the Stars column on page 45 of the August issue captured the feeling of Vega that I've always enjoyed. The column positions one well to find and appreciate Vega.

Two facts about Vega were not mentioned in this column but are great conversation starters to use while observing the star. The first is that, due to the 26,000-year precession of Earth's axis, Vega alternates with Polaris as our North Star. And the second is that Vega's spin axis very nearly points toward our solar system. So if Vega has any inhabited planets, in roughly 13,000 years Vega will be our North Star — and our Sun could be theirs!

Jim Hartley
Fair Oaks, California

Jupiter at Opposition

I have often read about folks seeing things in the night sky for the first time and how it changes them. Back in August, my daughter mentioned she wanted to see Jupiter since it was so close that month (*S&T:* Aug. 2021, p. 49). We used to surf the night sky every once in a while, when she was small, but we hadn't had much time to do so. That day, I had time. So I dusted off my low-budget 4-inch (100-mm) reflector and got everything aligned and working again.

That night, I located Jupiter and Saturn for her and my son-in-law. I finally understood how it feels to show someone something new when my son-in-law said, "I've always seen these in pictures in books and stuff. But there is nothing like seeing it in real life. It's awesome. Thank you for showing me this." I told him there's plenty more.

I can't wait until my grandson is old enough to join us, too. Maybe it's time for a better scope as well.

Roger Baker
Asheville, North Carolina

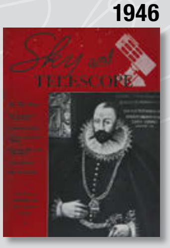
FOR THE RECORD

- Russell Hulse and Joseph Taylor discovered the first-ever binary pulsar (*S&T:* Aug. 2021, p. 36).
- Bray Falls' image on page 77 of the September issue depicts the lunar eclipse on May 26, 2021.
- In "The Case of the Dead Dinosaurs" (*S&T:* Oct. 2021, p. 18), scientists found that releasing 100 gigatons of sulfur into the Cretaceous atmosphere would have caused the planet's temperature to drop 25°C or 45°F.
- The Chicxulub impact released an estimated 400 billion tons of CO_2 (*S&T:* Oct. 2021, p. 24).

SUBMISSIONS: Write to *Sky & Telescope*, One Alewife Center, Suite 300B, Cambridge, MA 02140, 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

1946



1971

1996

◖ December 1946

Meteoric Bonanza "On the night of October 9–10, 1946, the Giacobinids provided a spectacle which can without doubt be called the greatest single predicted event of the century. . . .

"Shortly after the November issue went to press in mid-October, reports began to pour in from all parts of the country . . . At the height of the shower . . . a single observer could count from 60 to 100 meteors per minute . . . Simultaneous meteors were a bugaboo for many who tried to keep an accurate count during the height of the shower. . . .

"Walter H. Haas, of Albuquerque, N. M., was one of a group of six from the University of New Mexico who observed from a B-29, flying near 20,000 feet. He reports maximum between 8:50 and 8:55 p.m. MST, when the rate 'was about 100 a minute, in spite of the full moon and the dirt on the plastic blister.'"

This outburst in the annual Giacobinid (Draconid) meteor shower would soon be outdone. Rates reached an unbelievable 2,500 per minute during the great Leonid storm of 1966.

◖ December 1971

Newtonian Anniversary "The Great Fire of 1666 had swept through most of the city of London. Although cataclysmic in its effects, it nevertheless helped end the Plague, which had exacted such a terrifying toll the year before. . . . Thus the year 1671 seemed to usher in an era of hope and promise.

"One of the more significant advances in natural philosophy was made public at the end of that year . . . In December, 1671, a 29-year-old youth, relatively unknown outside academic circles in Cambridge, London, and parts of the Continent, presented to the Royal Society in London the 'first' working version of a magnifying instrument using mirrors. Isaac Newton called it the 'catadioptrical telescope.'"

R. A. Wells's article marked 300 years since the Newtonian reflector's birth. His accurate scale drawing and construction details inspired me and probably other readers to make our own working replicas.

◖ December 1996

Jupiter "Remembers" "Scientists studying the effects of Comet Shoemaker-Levy 9's July 1994 collision with Jupiter have found that the planet remained perturbed nearly two years after the [event].

"At a July symposium held in Meudon, France, André Marten (Paris Observatory) reported that both hydrogen cyanide (HCN) and carbon sulfide (CS) were still present in Jupiter's upper atmosphere as of May 1996. . . . Ammonia (NH_3) was still apparent eight months afterward, and both CS_2 and CO were still weakly detectable last May. [But only] the spectroscopic signatures of CS and HCN have remained prominent . . ."

Water vapor from the impact was still detectable in 2013.

EXOPLANETS

Potentially Moon-forming Disk Detected

FOR THE FIRST TIME, astronomers have clearly detected a dusty disk around a young giant planet, which might go on to form moons. The results appear in the July 20th *Astrophysical Journal Letters*.

Astronomers had previously imaged a disk around PDS 70 (*S&T:* Nov. 2018, p. 9), a young star in Centaurus, and detected two newborn planets, PDS 70b and c. Observers saw hints of a smaller disk around PDS 70c itself but couldn't distinguish it from the stellar disk.

Now, a team led by Myriam Benisty (University of Chile) has used the Atacama Large Millimeter/submillimeter Array (ALMA) to clearly show PDS 70c has a disk of its own. This giant world is the first exoplanet to have a directly detected circumplanetary disk.

◀ This ALMA image of PDS 70 shows the large dust ring that circles the star as well as the dusty glow around the planet PDS 70c (bright spot).

PDS 70c's disk could make moons in a couple different ways. Dust particles can get trapped in the disk and eventually stick together, forming pebbles, then rocks, then moons. Or, particles might spontaneously congregate into clumps and collapse into a satellite.

The other planet, PDS 70b, shows signs of tenuous dust nearby, but nothing actually encircling the planet. "The largest surprise is the non-detection of a circumplanetary disk around PDS 70b," says Sebastiaan Haffert (University of Arizona), who has also studied this system. "This probably means that it already has completed its potential satellite system."

While any moons that have formed wouldn't be detectable with current technology, this system still serves as a laboratory to study the growth of planets and their moons.

■ **LAUREN SGRO**

SOLAR SYSTEM

Saturn Has a Fuzzy Core, Too

NEW RESEARCH REVEALS that Saturn, like Jupiter (*S&T:* Dec. 2017, p. 14), has a "fuzzy" core that extends 60% of the way to its surface. This finding, published August 16th in *Nature Astronomy,* changes how we think about the formation of gas giant planets in our solar system and beyond.

Astronomers have been using Saturn's rings as a giant seismometer to investigate its interior. As the planet quivers like heavy Jello, its pull on the inner rings wobbles, corralling the ice particles into spiral patterns. NASA's Cassini spacecraft, which operated until its grand finale in 2017, imaged these ring spirals indirectly via *stellar occultations*, looking through the rings at background stars. But one particular spiral wave in the C ring had a low frequency that astronomers couldn't explain.

Now, Christopher Mankovich and Jim Fuller (both at Caltech) make the case that this frequency indicates a quiver that penetrated deep into the planet. That would only be possible if there were no hard boundary between the core and the outer envelope. Instead, rocks and ices in the planet's core must be "smeared out," dissolved into the fluid helium and hydrogen under intense pressure.

Combining the seismic data with Cassini's measurements of local gravitational fields and with computer models of Saturn's interior, the researchers concluded that the smeared core of the planet is 55 times Earth's mass, with rock and ice making up 17 Earths' worth (hydrogen and helium make up the rest). To maintain stability in the event of sloshing, the core must have layers, with the heaviest, most rock-rich material at the center of the core.

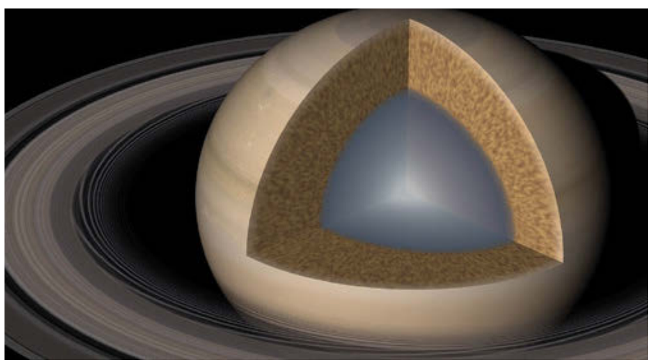
"This is a very interesting result that indeed changes the way we think about Saturn, and giant planets in general," says planetary scientist Ravit Helled (University of Zurich), who was not involved in the study.

Fuzzy cores argue against the *core accretion* scenario, in which giant planets grow as hydrogen and helium gas glom onto a rocky core. It could be that the rocky core disintegrated and diffused outward. Or it could be there was never a rocky core to begin with. These results extend beyond the solar system, with implications for how astronomers characterize giant exoplanets, too.

■ **MONICA YOUNG**

Read more at https://is.gd/fuzzySaturn.

▼ This artist's concept shows Saturn's "fuzzy" core, whose nature the astronomers deduced by measuring waves in the planet's inner rings.



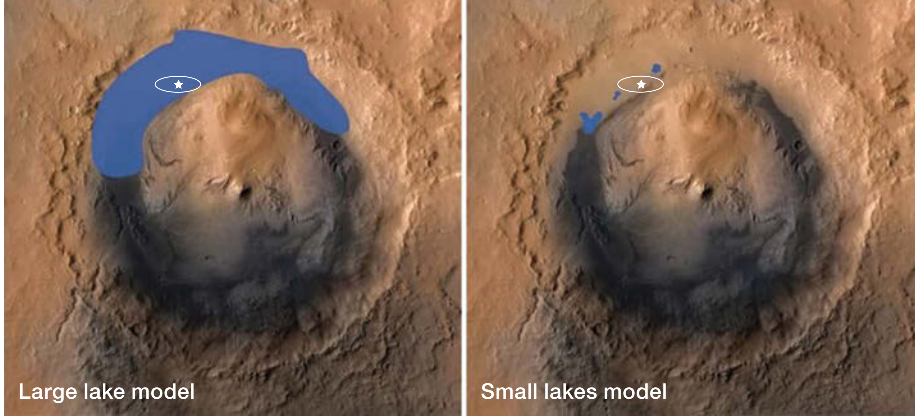
MOON-FORMING DISK: ALMA (ESO / NAOJ / NRAO) / BENISTY ET AL.; SATURN'S CORE: CALTECH / R. HURT (IPAC)

MARS

Gale Crater: Ancient Lake or Puddles?

WHEN NASA SENT the Curiosity rover to Gale Crater in 2012, scientists thought the site looked like a massive, ancient lakebed. But now, an independent analysis of both Curiosity data and recent imagery taken from orbit suggests that the rock layers previously thought to be deposits laid down by water might actually come from wind and chemical weathering instead.

In the August 6th *Science Advances*, Jiacheng Liu (University of Hong Kong) and colleagues point out that even though early observations indicated that Gale Crater once held a large body of water, few of the rocks Curiosity has examined actually look like lake deposits. At the very beginning of the journey, scientists identified mudstone at the bottom of Gale Crater, which likely formed when mud settled out of calm water. But since then, as the rover has traveled up to the base of Mount Sharp, it has seen few lake-formed rocks.



▲ These images of Gale Crater show two models, one in which it once hosted a large lake *(left)* and one in which only smaller, shallow ponds ever existed on the crater floor *(right)*. A star and oval mark the rover's landing site and landing ellipse.

The team thinks that this discrepancy is best explained if the crater only ever held a smattering of shallow ponds. In that case, the majority of the ground explored to date would be basalt sand and silt. The layers of different kinds of rock, which scientists thought were left behind by an ancient lake, could instead have been deposited by wind in a caustic atmosphere.

Data from Curiosity indicate that elements that stay put under chemical weathering, such as aluminum, become more prevalent at higher altitudes. Meanwhile, other elements that are more easily dispersed, such as iron, become scarcer.

This pattern is similar to what we see on ancient, exposed rock formations on Earth, which formed under a very different atmosphere than exists today. The researchers argue that a low-oxygen greenhouse atmosphere containing methane and hydrogen gas chemically weathered the rocks in Gale Crater.

"This new paper says you don't really need much water at all," says Bradley Thomson (University of Tennessee, Knoxville), who was not involved in the study. "It points out a possible ambiguity in the data that only more data — a lot more samples or even sample return — could resolve."

Perseverance Rover will collect multiple samples for eventual return to Earth, and it's possible that those rocks could provide more definitive clues to Mars's water history. Meanwhile, scientists will continue to analyze data coming in from Curiosity's slow trek up Mount Sharp.

■ ARWEN RIMMER

FAST RADIO BURSTS

New Observations Challenge Radio Burst Model

MOST ASTRONOMERS AGREE that the brief flashes known as *fast radio bursts* (FRBs) probably come from highly magnetized neutron stars (aka magnetars; *S&T:* Sept. 2020, p. 10). But astronomers can't yet explain why a minority of these sources flare repeatedly, even though most FRBs appear to be one-off events. A new study of a known repeating FRB published in the August 26th *Nature* "adds a new piece to the puzzle," says Victoria Kaspi (McGill University, Canada).

Astronomers have watched FRB 20180916B, located in a galaxy some 460 million light-years away, produce multiple bursts over a days-long "window," which recurs about every 16 days. That 16-day pattern was thought to be the orbital period of the magnetar and a companion star, explains first author Inés Pastor-Marazuela (University of Amsterdam). If the companion powered a thick, radio-absorbing wind, then the magnetar's bursts would only be visible when it was on "our" side of the orbit.

However, simultaneous observations of the source by the International Low-Frequency Array (LOFAR) and the 14-dish Westerbork Synthesis Radio Telescope (WSRT) in the Netherlands challenge the binary-wind scenario. Stellar winds should absorb more lower-frequency radio waves than higher-frequency ones, so astronomers expected that the bursts LOFAR observed (down to 110 megahertz) would be visible over a narrower time window than the ones WSRT witnessed (around 1.4 gigahertz).

"We found the exact opposite," says team member Joeri van Leeuwen (University of Amsterdam). Moreover, the peak in the number of high-frequency bursts preceded the low-frequency peak by a few days, which the binary model also doesn't predict.

"I agree that the observations are challenging for the model," says Kaspi, who has studied the LOFAR data for this object but was not involved in the current study. However, she's not ready to rule out the binary idea. "We need more sources and better statistics."

Even if this particular source is special, it could shed more light on the properties of FRBs in general.

■ GOVERT SCHILLING

ESA / HRSC / DLR

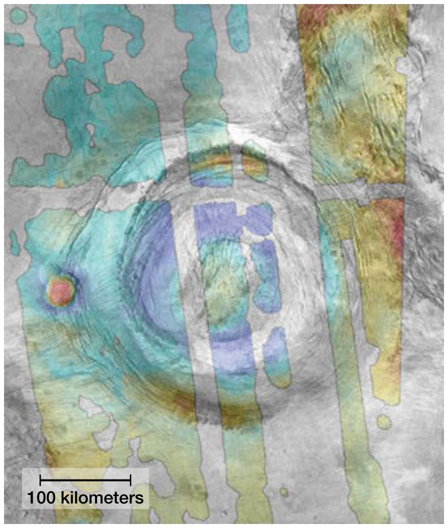
SOLAR SYSTEM

Venus: Thin-Skinned and Ready to Blow

A SMALL VOLCANIC FEATURE on the edge of a Venusian corona gives further credence to the theory that our sister planet has a thin outer layer and an active interior.

Megan Russell and Catherine Johnson (both at University of British Columbia, Canada) published an analysis of the peculiar feature in the August *Journal of Geophysical Research: Planets*. Dubbed Narina Tholus, the steep-sided volcanic dome perches on the edge of Aramaiti Corona, as seen in radar maps from NASA's Magellan orbiter. *Coronae* are common on Venus, thought to be giant volcanic upwellings that later collapsed in the center. Aramaiti is likely only 1.4 million years old, making Narina, which clearly formed afterwards, even younger.

Russell modeled the heat flow under the surface using a method that has



▲ A Magellan radar image of Aramaiti Corona shows Narina Tholus (red, center left).

been used extensively to study volcanic activity on Earth. Feeding radar images into a computer simulation, she then predicted the effects of the dome's "load" on its surroundings. She was able to reproduce the shape of Narina Tholus when the surrounding lithosphere was at most a third as thick as Earth's.

Paul Byrne (Washington University in St. Louis), who was not involved in this study, agrees that the result adds to growing evidence that Venus is an active world. "They've used very established techniques," Byrne says. "And they've been able to get results consistent with volcanic activity that is relatively geologically recent. This is important because anything that's relatively recent is probably ongoing."

The stereo radar needed to extend this analysis is currently only available for 20% of the planet's surface. Russell found 13 other coronae accompanied by steep-sided domes within those data, but none of those had the flexing pattern that she used to measure the underground heat flow. Future missions such as NASA's VERITAS and DAVINCI+, and the ESA's EnVision (*S&T:* Oct. 2021, p. 17) offer the hope of detecting other small features like Narina Tholus.

■ **ARWEN RIMMER**

STARS

Red Dwarfs Aren't So Bad (for Planets) After All

RED DWARF STARS APPEAR to flare preferentially at high latitudes, a feature that might keep their exoplanets habitable instead of hellish. The results appear in the October *Monthly Notices of the Royal Astronomical Society*.

Red dwarf stars make up 75% of the stars in the Milky Way. Also known as *M* dwarfs, they're much cooler than the Sun, and their churning guts and fast rotation make them prone to more extreme magnetic activity. To be potentially habitable, any planet would have to orbit a red dwarf closely, but that proximity would put it in a vulnerable position. Flares and energetic particles from the magnetically active star can strip a planet's atmosphere.

Now, a team lead by Ekaterina Ilin (Leibniz Institute for Astrophysics Potsdam, Germany) suggests that the flares might not be as destructive as once thought. Ilin and her colleagues combed through data from NASA's Transiting Exoplanet Survey Satellite to find four red dwarfs exhibiting flares that lasted longer than the rotation period of the star. Each star's spin left a rotational fingerprint on the light curve that enabled Ilin's team to pinpoint each flare's location on its star's globe.

The team found that the flares all occurred near the poles, at latitudes between 55° to 81°. That's different from solar flares, which as a general rule occur within 30° of the equator.

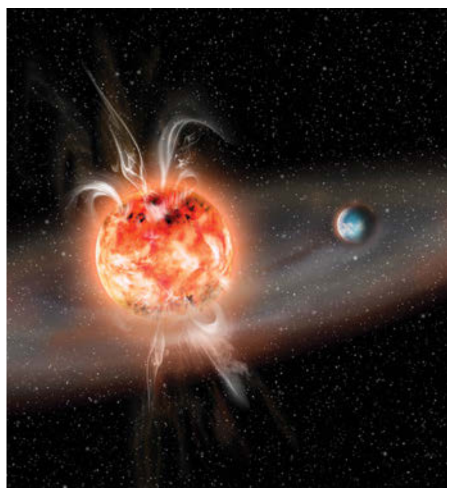
Although the sample size is small, Cynthia Froning (University of Texas, Austin), who was not involved in the study, thinks the results are significant. There's only a 1 in 1,000 chance that all the flares would have occurred at high latitudes if they were equally likely to happen at any latitude.

If *M* dwarf flares typically occur at high latitudes, planets orbiting in the plane of the star's equator — which is the case for worlds around such stars where inclinations are known — would never encounter the outbursts of energetic particles or intense radiation.

Perhaps the most common stars in the galaxy could host habitable planets after all.

■ **LAUREN SGRO**

Read more at https://is.gd/Mstars.



▲ An artist's impression shows a flaring red dwarf and its exoplanet.

CORONA MAP: PLANETARY SCIENCE INSTITUTE; RED DWARF: AIP / J. FOHLMEISTER

OBITUARY

Carolyn Shoemaker (1929–2021)

FAMED ASTEROID AND COMET HUNTER Carolyn Shoemaker died on August 13th at the age of 92. Her longest and most ambitious project, the Palomar Asteroid and Comet Survey, led to her discovery of hundreds of asteroids and 32 comets, including most spectacularly Comet Shoemaker-Levy 9. When that comet collided with Jupiter in the summer of 1994, it marked the most astonishing collision in the solar system that humans had ever witnessed.

Born Carolyn Jean Spellmann on June 24, 1929, in Gallup, New Mexico, she grew up in Chico, California, and attended what is now California State University, Chico. Although she initially had no interest in science, that changed after meeting and marrying a young geologist named Gene Shoemaker. Carolyn became enthralled by his passion for Earth as a world, its history written in pages of rock.


WENDEE LEVY

Carolyn began her married life as a teacher but found it to be tedious, so while her husband trained astronauts to conduct geology experiments during their field trips on the Moon, Carolyn raised the couple's three children, Christy, Linda, and Pat. As the children grew older, Gene suggested that Carolyn join his new program to search for asteroids that could pose a threat to Earth.

Their instrument of choice was a stereoscope through which Carolyn could view two pieces of film at the same time. With both exposures recording identical parts of the sky, her eyes would apparently see just one image. But if an object were to move in the sky between one exposure and the next, it would appear to float atop the background of stars.

Carolyn quickly became an expert at finding asteroids, work that continued after Gene's death in a car accident in Australia in 1997.

Carolyn's work earned several accolades. She and Gene shared the Rittenhouse Medal in 1988 and the Scientists of the Year Award in 1995. She received an honorary doctorate in 1990 from Northern Arizona University, Flagstaff, and the NASA Exceptional Scientific Achievement Medal in 1996. However, the experience of observing was the real joy of the many years Carolyn spent under the stars.

■ DAVID LEVY

To read Levy's personal remembrances, visit https://is.gd/Shoemakerobit.

IN BRIEF

A Double Venus Flyby

Two spacecraft experienced a close Venus encounter in early August: Solar Orbiter passed by on August 9th and BepiColombo on August 10th. Both approached Venus from its nightside, with the planet appearing as a crescent, but they left on divergent paths. After passing 7,995 km (4,968 miles) above Venus's surface, Solar Orbiter sped outward from the Sun, aimed at a November 27th encounter with Earth. The Earth flyby will place the spacecraft into its operational science orbit, beginning its prime mission observing the Sun. BepiColombo needed to lose speed in order to drop in toward Mercury's orbit. It passed just ahead of Venus in its orbit on the way to a flyby at an altitude of 552 km, the closest encounter since Venus Express in 2014. Venus's gravity tugged backward on the spacecraft, slowing it down and sending it on a path toward Mercury, which it will first approach on October 1st. The Venus flyby offered both Solar Orbiter and BepiColombo the opportunity to make observations of the planet's magnetosphere. Those data are still under analysis.

■ EMILY LAKDAWALLA

Find sights and sounds from the flyby at https://is.gd/Venusflyby.

American Astronomical Society Acquires Willmann-Bell

The American Astronomical Society (AAS), publisher of *Sky & Telescope* since 2019, has acquired the inventory of books, star atlases, and software produced and sold by Willmann-Bell, Inc., founded in 1973 by Perry and Patricia Remaklus of Richmond, Virginia. For decades, Willmann-Bell has been among the most respected publishers of books for astronomers, including amateurs interested in building their own telescopes, exploring the history of astronomical observing, improving their skills, and contributing to scientific research. The AAS expects to make Willmann-Bell titles available for purchase through *S&T*'s online store, **shopatsky.com**, by the end of October. Most of Willmann-Bell's existing books will remain available indefinitely, including such high-demand titles as the *Uranometria 2000.0* star atlas and the multivolume *Night Sky Observer's Guide*. The AAS also plans to publish new volumes in the popular *Annals of the Deep Sky* series; Volume 8 is already printed and bound and will be available for immediate shipment once new orders are being accepted. New titles will be commissioned to appear under the AAS/*S&T*/Willmann-Bell imprint.

■ RICHARD TRESCH FIENBERG

Blue And Gold Satellites Will Head to Mars

NASA has announced the selection of two spacecraft, dubbed "Blue" and "Gold," that will head to Mars in 2024, arriving in 2026 to study the Martian space-weather environment. The overall mission is named the Escape and Plasma Acceleration and Dynamics Explorers (ESCAPADE). Costing only $80 million, ESCAPADE is part of a NASA initiative to produce low-cost, quick-to-assemble interplanetary missions, called the Small Innovative Missions for Planetary Exploration (SIMPLEx) program. For comparison, the development phase of NASA's MAVEN spacecraft cost $671 million. Once in space, Blue and Gold will separate and cruise in tandem to Mars for orbital insertion. Orbiting on opposing sides of the Red Planet, the two craft will provide the first simultaneous stereo picture of how the solar wind interacts with the planet's upper atmosphere. Science collected by the ESCAPADE mission could paint a more detailed picture of how Mars lost much of its atmosphere to the solar wind early in its history. Plus, studies of the Martian ionosphere will characterize how it could interfere with future radio communications from the planet's surface.

■ DAVID DICKINSON

Remembering Henrietta Swan Leavitt

How one talented astronomer's meticulous work left an important legacy.

In the century since Henrietta Leavitt died, the observation that she first published in 1908, then elaborated in 1912, has achieved the status of an astrophysical law. Her quiet life has become the subject of books, stage plays, art exhibitions, poems, a doll, and at least one song. It was Leavitt who discovered a yardstick for gauging distances across space, enabling the first realistic appreciation of the size of the Milky Way, and, soon afterward, the breadth of the chasm separating our home galaxy from other island universes.

I first encountered Henrietta Leavitt at a meeting with astronomer Wendy Freedman, who is now the John and Marion Sullivan Professor of Astronomy and Astrophysics at the University of Chicago. At the time of our interview in the early 1990s, Freedman headed the Hubble Space Telescope Key Project to Measure the Hubble Constant to determine the expansion rate of the universe. She mentioned Leavitt as the person who had first documented the noteworthy trait of Cepheid variables that makes such stars useful as deep-space distance markers. Freedman stressed the point for my benefit: The entire research protocol for the Key Project rested on observations made by a little-known woman at the turn of the 20th century.

▲ **LEGAL SCHOLAR** From her desk at the Harvard College Observatory, Henrietta Swan Leavitt discovered that Cepheid variables can serve as deep space distance markers. Her celebrated period-luminosity relation is now becoming widely known as the Leavitt Law.

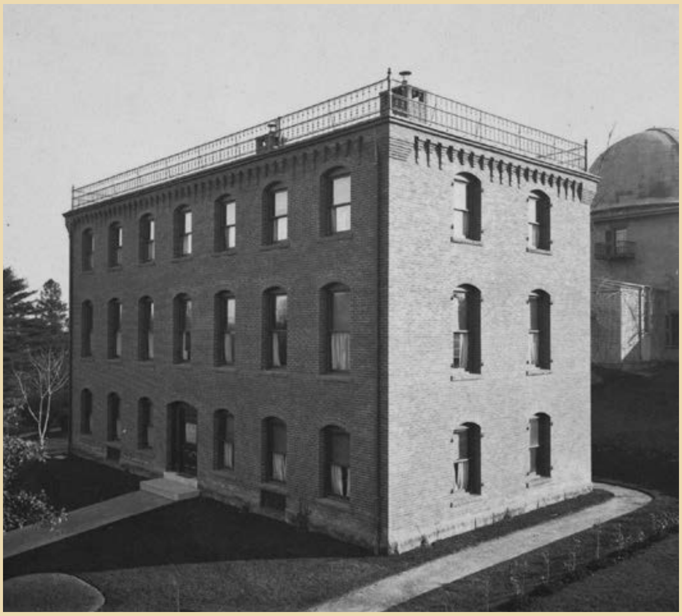
Meeting Miss Leavitt

Her full name, Henrietta Swan Leavitt, suggests she added a husband's surname to her own maiden name, but in fact she never married. She remained "Miss Leavitt" to her associates at the Harvard College Observatory in Cambridge, Massachusetts, throughout the 20-odd years of employment there. Everyone liked her. It was said she had a nature full of sunshine and a talent for seeing the worthiest, most lovable features in others. Her ability to descry the changing brightness of variable stars bordered on the miraculous. However, as her biographer, George Johnson, noted in the preface to his 1995 book *Miss Leavitt's Stars*, his chosen subject had left no diaries and only a few letters to help tell her life story.

Leavitt was born on the 4th of July in 1868, in Lancaster, Massachusetts, the first of seven children and the namesake of her mother, née Henrietta Swan Kendrick. Her father, the Reverend George Roswell Leavitt, moved the family to Cambridge and later to Cleveland, Ohio, serving in both those cities as pastor of Congregational churches. In 1885, 16-year-old Henrietta enrolled at the Oberlin Conservatory of Music in Ohio. She had grown up singing hymns but soon developed trouble hearing them, and over time she became increasingly deaf.

She switched to Oberlin College, where she excelled at mathematics, and after two years returned to Cambridge to continue her studies at the Society for the Collegiate Instruction of Women (later Radcliffe College). She lived with the family of her uncle Erasmus Darwin Leavitt, Jr., a respected

PORTRAIT: HARVARD UNIVERSITY ARCHIVES; ILLUSTRATION: DAVID CURTIS



▲ **LITTLE CITY OF SCIENCE** was the term a journalist used to describe the Harvard College Observatory in the 1890s, when numerous specially built domes and sheds housed a host of newly acquired instruments. The Brick Building, erected for safe storage of the glass photographic plates, is visible at far left. In the background stands the main observatory building with its two domes — the larger one for the Great Refractor and the smaller one for the west equatorial telescope.

▲ **SAFE HAVEN** Fearful of the potential for fire destroying valuable data, Observatory Director Edward Pickering oversaw the construction of a brick repository for the precious glass plate collection. The Brick Building, shown here shortly after its completion in 1893, stood only a few steps from the original wooden observatory. Within 10 years it had reached storage capacity and required a three-story addition to house the ever-growing number of plates.

HARVARD LIBRARY ARCHIVES / PUBLIC DOMAIN (3)

▼ **CHAIN OF STARS** The 1918 female staff of the Harvard College Observatory, plus two of the men, agreed to pose this way in front of the new addition to the director's residence. Henrietta Leavitt stands tall, sixth from left, wearing a dark tie over her white blouse. Annie Jump Cannon is fifth from right. The Brick Building can be seen behind telescope operator Frank E. Hinkley and chief of stellar photography Edward King (far right).

designer of steam engines, who may have encouraged her interest in science. Her four-year program included courses in astronomy, physics, and mathematics, and introduced her to the nearby astronomical observatory. She began volunteering there after graduation in 1892 and was hired as a "computer" to process astronomical data in 1895. Familial obligations and travels in Europe took her away from her post at several junctures, but she signed on in 1902 as a permanent staff member of the Observatory, where she remained until her death in December 1921.

Plates of Starlight

Astronomy was a day job for Henrietta Leavitt. She made all her discoveries without ever looking through a telescope. Instead, she studied images of the night sky recorded on glass photographic plates. Harvard Observatory Director Edward Charles Pickering had instituted a grand-scale program of astrophotography in both the Northern and Southern Hemispheres. The long-exposure pictures captured the light of stars unseen by even the most talented observers at the most powerful telescopes then in use, including Harvard's own 15-inch Merz and Mahler refractor.

Leavitt sometimes worked alongside as many as 20 other women in the so-called Brick Building, an 1893 addition to Harvard Observatory. The Brick Building afforded fireproof protection for the prized, ever-growing collection of hundreds of thousands of glass photographic plates.

Each morning she found a stack of plates awaiting her. They arrived at her desk either from Harvard's darkroom on Madison Street or in boxed shipments from the Observatory's southern outpost at Arequipa, Peru. She examined each plate by securing it in an upright wooden frame, tilted at a viewing angle of about 45°. At the base of this light lectern, an attached mirror caught sunshine from the room's big windows and reflected it up through the glass to illuminate the myriad stars.

Most images were negatives, showing the stars as black dots on a white background. A handheld magnifying loupe brought them more clearly into view. Her particular task was to judge the magnitude of each star. Early assessments of photographic magnitude depended on the relative sizes of star-dots. Leavitt's procedures grew ever more sophisticated, informed by knowledge of the spectral type of each star, as determined by her colleagues Williamina Fleming and Annie Jump Cannon. Two stars of a particular color could be successfully compared, whereas comparing two stars of different types would introduce errors.

She also factored in the limitations of the various telescopes used to create the photographic plates. In her painstaking work on establishing standard sequences of comparison stars, she combined data from more than a dozen telescopes ranging from small-aperture instruments on the Harvard Observatory grounds to the 60-inch reflector at the Mount Wilson Observatory in California.

Leavitt logged her magnitude determinations in ledgers in pencil, and sometimes jotted them right on the glass plates in colored ink. The smooth (non-emulsion) side of the plates provided a convenient writing surface.

A custom-made device known as a fly-spanker aided her labors. This was a small section of a glass plate showing model stars of known brightness — a sort of portable reference key. The miniature rectangle of glass, set in a wire

frame and attached to a long handle, recalled the shape of a flyswatter, though Leavitt liked to joke that it was too small to do a fly much damage.

Thanks in part to the standard sequences of stars that she established as a basis for comparison, as well as conversion factors for relating visual magnitudes to photographic ones, her photometry publications became trusted resources for astronomers everywhere.

Inconstant Suns

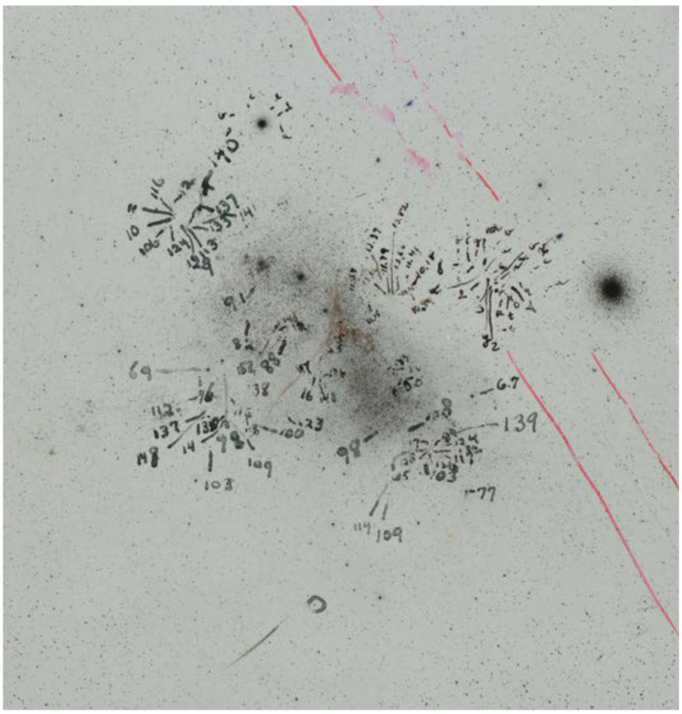
Variable stars attracted particular interest at Harvard in the early 20th century, when only a couple hundred were known, and the causes of their variability remained largely mysterious. In 1903, when Pickering sent Leavitt hunting for variable stars in the Orion Nebula, she complied by stacking a series of negative plates, one at a time, over a glass positive of the region. The black dots generally covered the white blobs of unchanging stars, while white halos around black dots helped her identify 90 new variables within two months' time.

From Orion she moved on to the Magellanic Clouds of the southern sky, the site of her greatest coup. She described these two nebulous regions — now recognized as satellite galaxies of the Milky Way — as unusually difficult targets. They were large and densely crowded with stars. She imposed some order on them by creating a ruled glass grid that she could superpose on the plates, thus corralling their component stars into boxes. Soon she was seeing numerous stars that varied in brightness from one plate to the next — but they were extremely faint, many of them fluctuating near the limits of detection at around 15th magnitude.

By early 1905 she had identified 900 new variables in the Small Magellanic Cloud alone. As she continued to search for more, she tabulated and analyzed her results. In 1908, in the *Annals of the Astronomical Observatory of Harvard College*, she published her compendium of "1777 Variables in the Magellanic Clouds." The lengthy paper included 12 pages of tables of numerical data, plus an analysis of 16 stars for which she had assembled complete light curves.

The 16 selected stars belonged to the class of Cepheid-type variables, so named for their prototype, Delta Cephei, first described in 1785. These stars tend to brighten suddenly, then dim slowly, in a regularly repeating fashion. Given that all her finds lay within the Small Magellanic Cloud, Leavitt assumed them all to be about the same distance from Earth. Therefore, the stars that appeared the brightest actually *were* the brightest. In other words, these stars didn't look brighter simply because they were closer to Earth than other stars in the group. This was a crucial finding. It occurred to Leavitt that the maximum brightness of such a star and the timescale of the variations might be linked. "It is worthy of notice," she concluded, that "the brighter stars have the longer periods."

In December 1908, soon after completing this work, she fell so ill as to require a hospital stay. People were discreet about personal health in those days, and the nature of her illness wasn't reported. The start of the new year found her recuperating at her parents' home in Beloit, Wisconsin.



▲ **PHOTO ID** Leavitt sometimes jotted her magnitude determinations in colored ink directly on the non-emulsion side of a glass photographic plate. In her logbooks, however, she always wrote in pencil, even though erasures weren't permitted.

▲ **VIEW FINDER** Specially constructed light lecterns held the glass plates in place for close study. Illumination came from below, via a mirror that caught daylight from a window and directed it up through the glass image to the observer's eye.

HARVARD COLLEGE OBSERVATORY, PHOTOGRAPHIC GLASS PLATE COLLECTION (2)

As time and her energy permitted, she returned to the observatory and continued to plumb her data by tracking another nine Cepheids in the Small Magellanic Cloud through their cycles. These stars followed the same intriguing trend as the previous 16, confirming her insight. Pickering showed his excitement by rushing her graphs into print on March 3, 1912, in a *Harvard College Observatory Circular* — the bulletin format he had introduced for announcing important new developments ahead of the annual *Annals*. He signed the report, as always, with his own name, but the opening sentence gave full credit where it was due: "The following statement regarding the periods of 25 variable stars in the Small Magellanic Cloud has been prepared by Miss Leavitt." The relation between the period and the brightness of these variables, which she had previously deemed "worthy of notice" she now declared "remarkable."

Other astronomers agreed. Ejnar Hertzsprung in Denmark immediately applied the newfound period-luminosity relation to the problem of distance measurement. He compared the apparent brightness of known Cepheids with those of Leavitt's study that had the same periods. According to the inverse square law, if one star lies twice as far away as its twin, it appears only one-quarter as bright. Hertzsprung estimated the distance to the Small Magellanic Cloud to be in the range of 30,000 light-years. This was an astounding figure at the time. Not only was the number gigantic, but it put a specific value on something long presumed to be unknowable. (Later, with better calibration and further research on Cepheids, the distance would be revised to about 200,000 light-years.)

In 1914, American astronomer Harlow Shapley began using the 60-inch telescope at Mount Wilson to pick out Cepheids in globular clusters, and he gauged their great distances by the period-luminosity relation. Later he extrapolated, extending the reach of the Cepheids to define the vast outlines of the Milky Way.

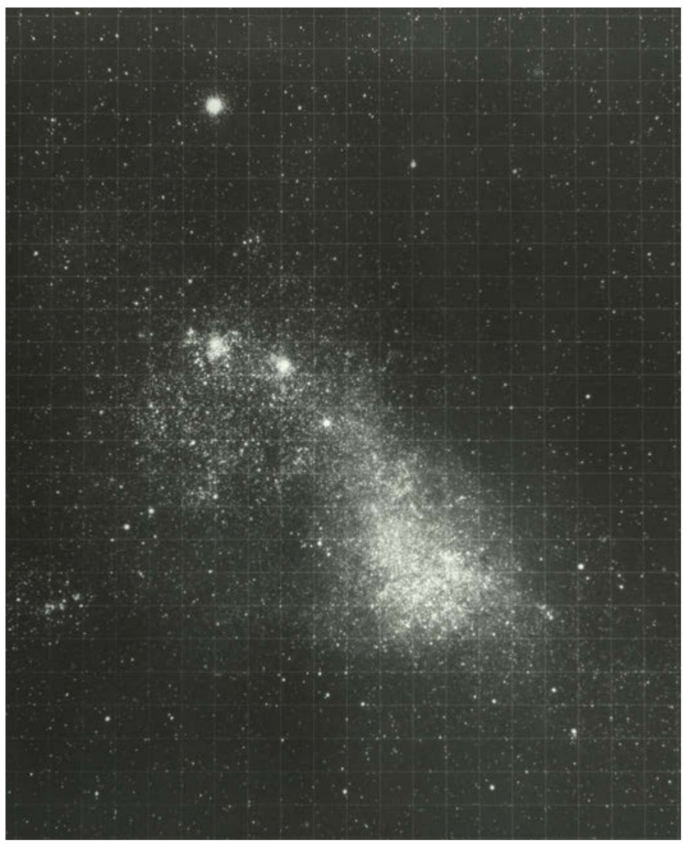
Stellar Tributes

By the spring of 1921 Henrietta Swan Leavitt had lost many members of her family and was sharing an apartment with her widowed mother not far from the Brick Building. The cancer that had often interrupted her work took her life near the end of that year, on December 12, at age 53.

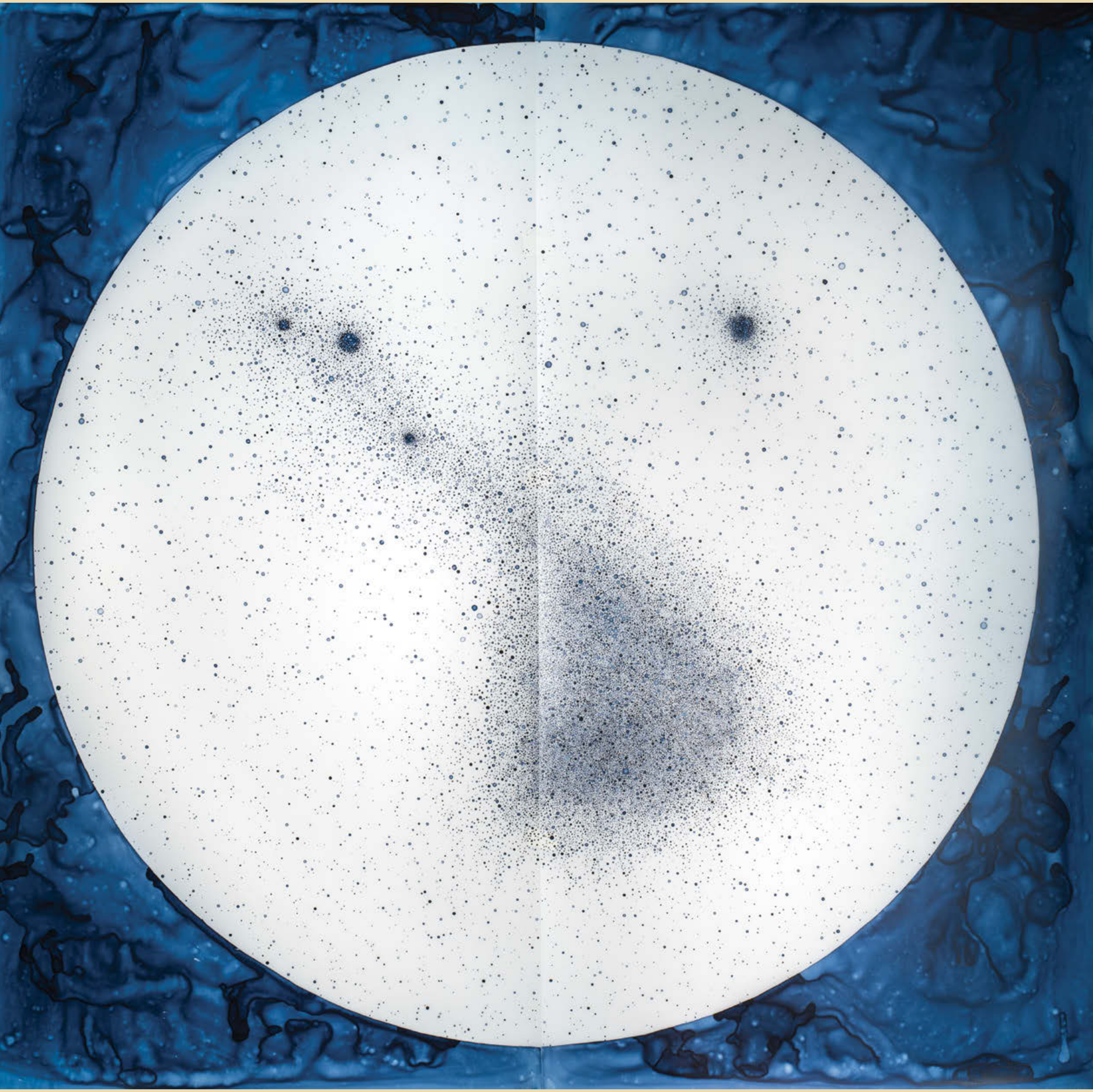
Observatory staff members attended her funeral at the First Congregational Church and wrote her obituary for *Popular Astronomy*. It cited her fruitful efforts to establish the photographic magnitudes for the North Polar Sequence (96 stars very close to the pole), as well as similar strings of standard star sequences for all 48 of Pickering's 1884 subdivisions of the sky. The obituary also noted her contributions to sections of the international *Astrophotographic Catalogue* and Jacobus Kapteyn's *Plan of Selected Areas*. In addition, Leavitt had detected four "new stars" (what would now be called supernovae), several asteroids, and 2,400 variable stars —
(continued on page 20)

▲ **SWAT TEAM** These helpful tools for assessing stellar magnitudes were called "fly spankers" because of their overall resemblance to miniature fly swatters. Leavitt liked to say they were too small to do a fly much damage.

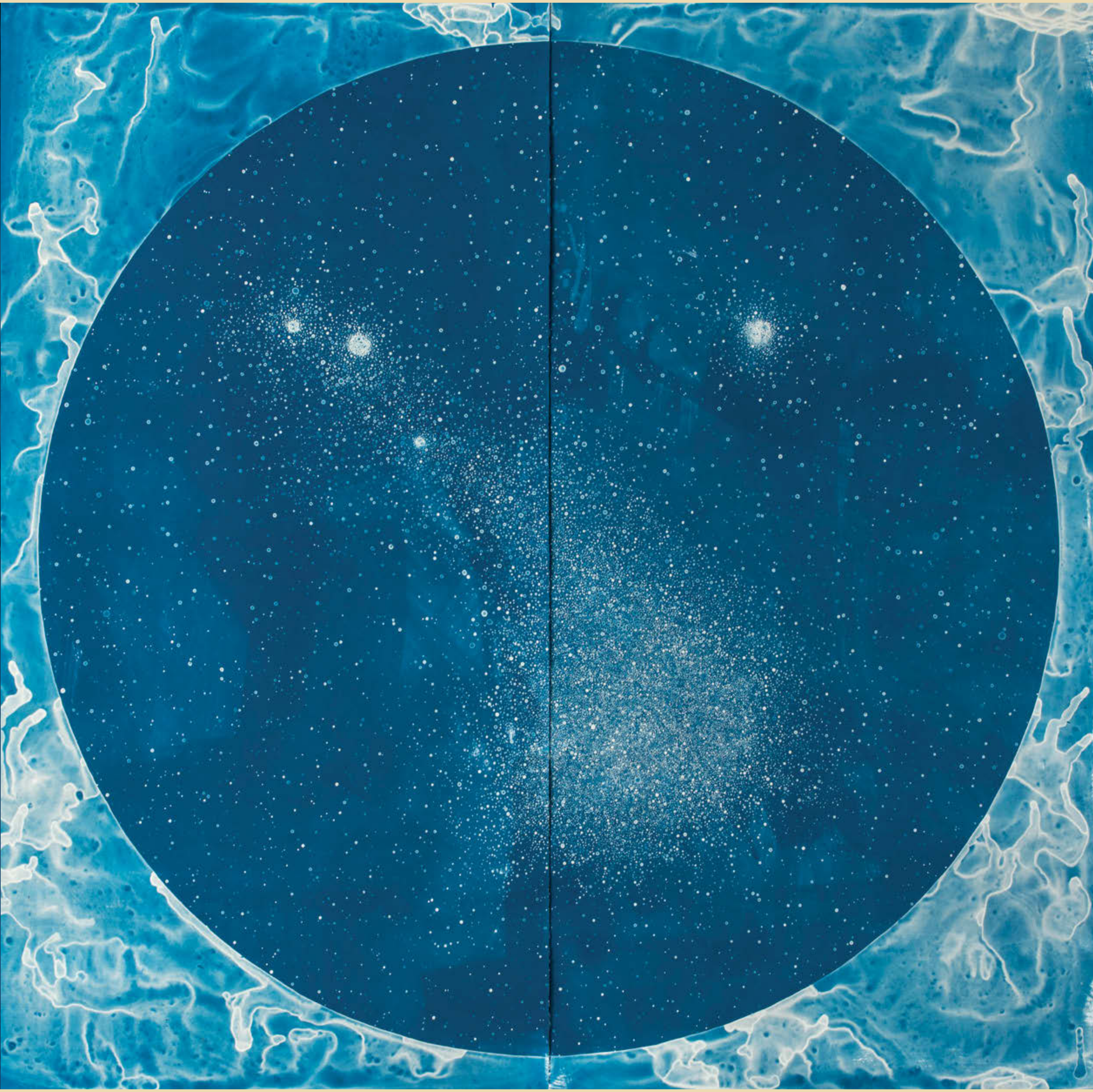
▼ **STARRY CLOUD** The galaxy pictured here is the Small Magellanic Cloud, one of the Milky Way's satellites, where Henrietta Leavitt discovered more than 900 variable stars. Although many were as faint as 15th magnitude, she nevertheless noticed a startling link between their brightness and the time it took them to cycle through their changes. This plate was captured on November 10, 1898, with the 24-inch Bruce telescope in Peru.



HARVARD COLLEGE OBSERVATORY, PHOTOGRAPHIC GLASS PLATE COLLECTION (2)



▲▶ **THE SMALL MAGELLANIC CLOUD, AFTER HENRIETTA SWAN LEAVITT** is a cyanotype diptych by artist Lia Halloran from her series Your Body Is a Space that Sees. On the left is Halloran's depiction, in ink on semi-transparent drafting film, of a glass photographic plate originally exposed to starlight at Harvard's southern station in Arequipa, Peru. Using her painted image as a negative, and placing it over an equally large sheet of chemically treated paper, Halloran set the pair outdoors to develop in sunlight, creating the cyanotype print on the right. The artist is represented by Luis de Jesus Los Angeles and is an Associate Professor of Art at Chapman University.



(continued from page 17)
about half of all known at the time. The large total included several hundred beyond the multitude she enumerated in the Magellanic Clouds.

"Miss Leavitt," the obituary concluded, "was of an especially quiet and retiring nature, and absorbed in her work to an unusual degree. She had the highest esteem of all her associates at the Harvard Observatory, where her loss is keenly felt."

In 1925, a member of the Swedish Academy of Sciences thought to nominate the author of the period-luminosity relation for the 1926 Nobel Prize in Physics. Unaware that Leavitt had died, he wrote to her requesting further information. Shapley, who knew the prize could not be awarded posthumously, replied:

Miss Leavitt's work on the variable stars in the Magellanic Clouds, which led to the discovery of the relation between period and apparent magnitude, has afforded us a very powerful tool in measuring great stellar distances. To me personally it has also been of highest service, for it was my privilege to interpret the observation by Miss Leavitt, place it on a basis of absolute brightness, and, extending it to the variables of the globular clusters, use it in my measures of the Milky Way. Just recently in Hubble's measures of the distances of the spiral nebulae, he has been able to use the period-luminosity curve I founded on Miss Leavitt's work. Much of the time she was engaged at the Harvard Observatory, her efforts had to be devoted to the heavy routine of establishing standard magnitudes upon which later we can base our studies of the galactic system. If she had been free from those necessary chores, I feel sure that Miss Leavitt's scientific contributions would have been even more brilliant than they were.

In the absence of any comments from Leavitt herself about her accomplishments, or any complaints about the work she was assigned, others looking back on her life have felt free to fill that vacuum. The North Polar Sequence in particular struck some later astronomers as comparable to the labors of Hercules, coloring their view of its creators so as to turn Pickering into a tyrant who bent the meek Leavitt to his will.

Shapley gave the first hint that Pickering hobbled Leavitt when he rued "those necessary chores" that kept her from making her contributions "even more brilliant than they were." This idea gained strength with Cecilia Payne (later Payne-Gaposchkin), who came to the observatory as a graduate student in 1923 and earned Harvard's first doctoral degree in astronomy. In her autobiography, *The Dyer's Hand* (privately published near the time of her death in 1979), she reported the work of her female predecessors, some of whom were still alive when she arrived in Cambridge, Massachusetts, from England. Although she never met Leavitt or Pickering, she wrote that the director had "ruthlessly relegated Miss Leavitt to the drudgery of fundamental photometry when her real interest lay in the variable stars that she had begun to discover in the Magellanic Clouds. She was the ablest of all the workers at Harvard at the turn of the century, but Pickering was a dictator, and his word was law."

A paragraph later, Payne reiterated her sense that Pickering's "harsh decision" regarding Leavitt had "condemned a brilliant scientist to uncongenial work, and probably set back the study of variable stars for several decades."

Or perhaps, given Leavitt's retiring nature, she would not have been as willing as Payne to follow her instincts and challenge authority on the strength of her own ideas.

The Leavitt Law

In 2012, Jonathan (Josh) Grindlay, who holds Pickering's honorary title as Robert Treat Paine Professor of Astronomy at Harvard, attended a centennial celebration of Henrietta Leavitt's pivotal discovery. At the day-long symposium, he suggested renaming her period-luminosity relation "the Leavitt Law," putting it on a par with the Hubble Law for establishing the distances of receding galaxies.

"All astronomy textbooks should use 'Leavitt Law' in describing the importance of Henrietta's discovery," Grindlay recalls telling the gathering. "It was not just a period-luminosity relation of Cepheid variable stars. It really transformed astronomy."

At Grindlay's urging, the executive council of the American Astronomical Society acted to endorse the name change. Many AAS members have since adopted the "Leavitt Law" in their publications, textbooks, teaching, and public speaking.

Grindlay's office belongs to a complex of interconnected structures on the observatory grounds, known today as the Center for Astrophysics, Harvard & Smithsonian. It incorporates the Brick Building, where approximately half a million glass plates still reside, stored in tall metal cabinets. For the past 15 years, the National Science Foundation has supported an ongoing project to digitize them for ready access by current and future astronomers. Several of the plates scrutinized and annotated by Leavitt, however, have been deemed too historically valuable to be subjected to the routine digitization process, which entails wiping the plates clean of all markings before scanning them. Instead, these particular plates will be scanned as they are, for the valuable data that can be gleaned between the penned notations.

Student groups and other curious visitors to the "plate stacks" learn about the collection from Lindsay Smith Zrull, the current curator of astronomical photographs (a job description born of necessity in 1899). "I always show one of Henrietta Leavitt's plates," Zrull told me. "It's impossible, of course, to know her personal thoughts and feelings, and many people say she was held back. But from looking at her plate notations and reading her notebooks, I think she must have loved what she did."

Some 2,600 logbooks — companion pieces to the glass plates — have been scanned page by page for public perusal. Volume XIX of the Henrietta Leavitt series is one that stands out, as it painstakingly identifies all the comparison stars she chose for her measurements of variable magnitudes in the Small Magellanic Cloud.

The original of that particular logbook is kept on hand at the John G. Wolbach Library that forms part of the observatory complex. Librarian Maria McEachern holds it up as a paragon of diligence and consistency. Compared to Annie Jump Cannon's notebooks, which McEachern described to me as "just wild," Leavitt progresses neatly and methodically from star to star, plate by plate. In places, she even affixed (with yellowing tape) several inch-square photos of relevant sections of annotated plates.

Were Leavitt to gain a window on today's world, she might well be pleased with the recognition afforded her, though she never actively sought any. Of greater satisfaction than the attribution of the Leavitt Law, Wendy Freedman thinks, would be the gratifying persistence of Cepheids as reliable distance indicators, their critical importance for cosmology, and the ever-deeper understanding of their complex behavior through CCD and infrared photometry.

On the day, just a few months ago, when she and I revived our discussion of Henrietta Swan Leavitt, Freedman had learned of observing time granted to her on the James Webb Telescope. "There may be aspects of the physics of pulsation that we don't yet understand," she said, "and, once again, Cepheids will be at the heart of the matter."

■ **DAVA SOBEL** has written about the history of astronomy in her books *Longitude*, *Galileo's Daughter*, *The Planets*, *A More Perfect Heaven*, and, most recently, *The Glass Universe*.

Appreciation and Inspiration

To appreciate and honor the level of sustained attention that Henrietta Leavitt achieved, artist Anna Von Mertens assigned herself a copying task — not a page of notes from a logbook, but several glass plates that had passed through the astronomer's hands. Except for the medium of pencil on paper, Von Mertens's drawings (below) of "Negative and Positive Plates B20667 and D16409, Nebula in Orion, Oct 26, 1897" are indistinguishable from the glass originals.

"I wanted to inhabit that same space," Von Mertens told me, "to examine those plates as closely as she did. What a gift Henrietta Leavitt gave me. I lived an intimate relationship with her while doing this work."

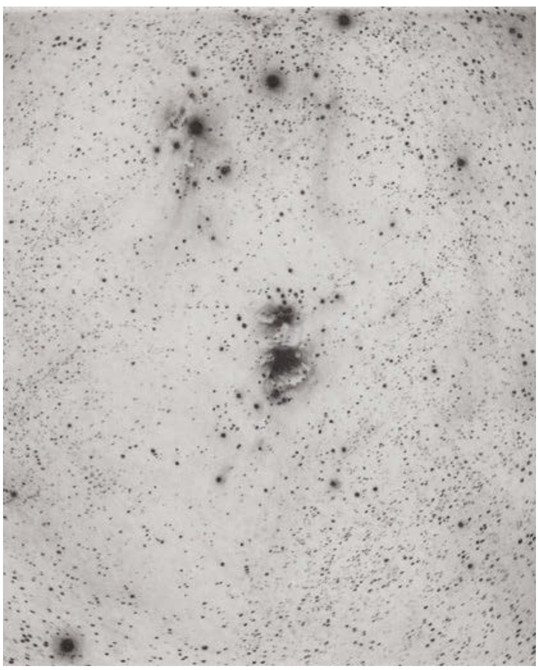
Von Mertens said that when she first saw pictures of the Harvard women bent over their work the scene reminded her of a quilting bee. As a quilter herself, she thought to stitch the outlines of Leavitt's life in two starscapes: the tracks of stars fading as day breaks on July 4, 1868, and of those coming into view on the evening of December 12, 1921.

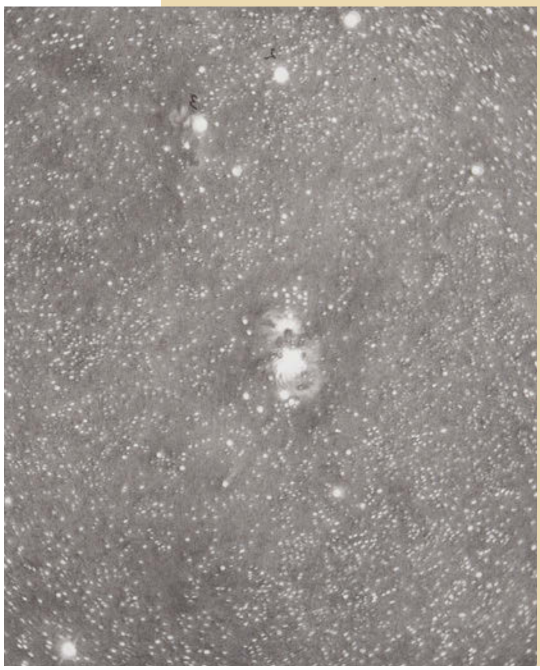
The Radcliffe Institute exhibited the quilted diptych and drawings two years ago. Since then Von Mertens has addressed other plates that Leavitt analyzed. These newer pieces, under the title "Artifacts: Drawings from Plate AX3309," will be showcased in fall 2023 at Oberlin College, Leavitt's first alma mater.

Leavitt's fixation with detail is often dismissed — by people who don't understand it — as "women's work," meaning tedious and repetitious. But surely the contemporary men's work at the observatory would seem just as tedious and repetitious to the uninitiated. Pickering, for example, made and recorded more than a million photometric measurements in his career, inspired by the importance he placed on such data. Others patiently guided balky telescopes through the hours required by specific observing goals.

"Henrietta Leavitt looked at tiny black dots in 2D," Von Mertens said. "She held the complexity of their patterns in her mind, and turned them into a way to measure the universe."

▼ **PAPER PLATE** The process of creating this exact pencil-on-paper rendering of a pair of glass plates helped artist Anna Von Mertens appreciate the extreme attention to detail that characterized Leavitt's work.





ANNA VON MERTENS / COLLECTION OF ARLIE STERN AND MATT TSANG (2)

DECEMBER DELIGHTS The long northern nights at the close of the year offer many opportunities for scanning the skies with small scopes.

Small-Scope Winter

Wander through winter skies and take in the delightful objects December nights offer.

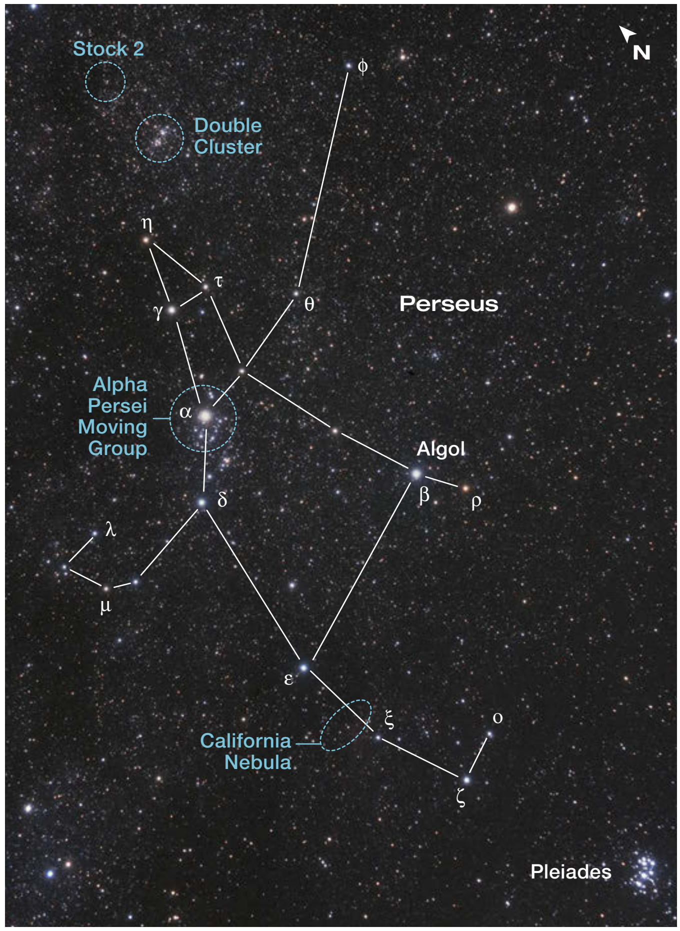
When it comes to telescopes, the laws of physics tell us bigger is better. Large-aperture scopes collect more light and deliver brighter images. They also resolve finer detail. But physics has a few kind words for small telescopes, too. They're usually lightweight and portable, which makes them ideal for grab-and-go observing. They can also deliver wide fields of view, which enable stargazers to take in more expansive views of the deep sky. Here, we'll embrace this feature of small telescopes and take a tour of the winter Milky Way, where we'll find plenty of vistas that not only look good in a small instrument but appear even better than in a bigger scope.

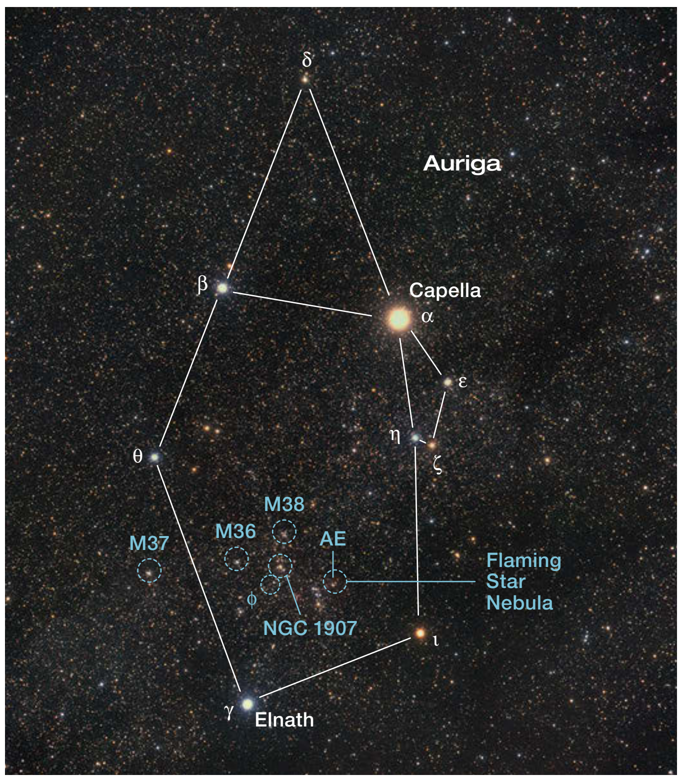
All stops on this winter sky tour lie within reach of scopes with a focal length of about 480 mm to 700 mm, as in an earlier article on corresponding summer sights (*S&T:* Aug. 2019, p. 22). For the observations outlined here, I used a Televue 85 refractor (focal length 600 mm). Matched with a 24-mm eyepiece with an apparent field of view of 68°, such scopes deliver true fields of 2.3° to 3.4°, while a similar 35-mm eyepiece delivers 3.4° to 5°. A nebula filter is a big help with some objects, and dark sky is a must to see many of these sights. Hopefully, imagers will also find plenty of ideas.

New Stars and Nebulae in the Northern Milky Way

We begin in the constellation Perseus, the Hero, with one of the finest sights in the northern night sky: the great Perseus **Double Cluster**, NGC 884 and NGC 869. This sparkling pair of open clusters — among the youngest known in the galaxy — presents a rich array of scintillating and colorful stars of sapphire blue, topaz, white, and red-orange. Each cluster contains hundreds of members, some of which are thousands of times more luminous than our Sun. The pair likely formed out of a single molecular cloud in the star-making machinery of the Milky Way's Perseus Arm. The cluster duo is also distant, more than 7,000 light-years away. Were the Double Cluster as close as the Pleiades (at about 446 light-years), the pair would span a quarter of our sky, and many of its stars would shine as bright as Vega.

The Double Cluster is nicely framed in a 2° field of view, but if you can manage a 4° field, look for a string of stars arcing from the eastern edge of the Double Cluster. Follow it north to **Stock 2**, an X-shaped group of uniformly bright





▶ **THE HERO'S TREASURES** *Top:* Perseus is a great place to start your celestial winter wander — it's already high in the sky as dusk deepens. If you've never laid your eyes on the Double Cluster, now's the time to do it. But don't forget to visit the multitude of other targets.

▶ **ATTRACTIONS IN AURIGA** *Bottom:* The Charioteer's trio of open clusters — M36, M37, M38 — is always a fun catch on cold winter nights. But that's not all there is to see in the constellation!

ALL IMAGES BY AKIRA FUJII UNLESS OTHERWISE NOTED stars. Gaze on it for a minute or two and you may see a headless stick figure emerge. Some see these stars as a man flexing his muscles, hence its moniker, the Muscleman Cluster.

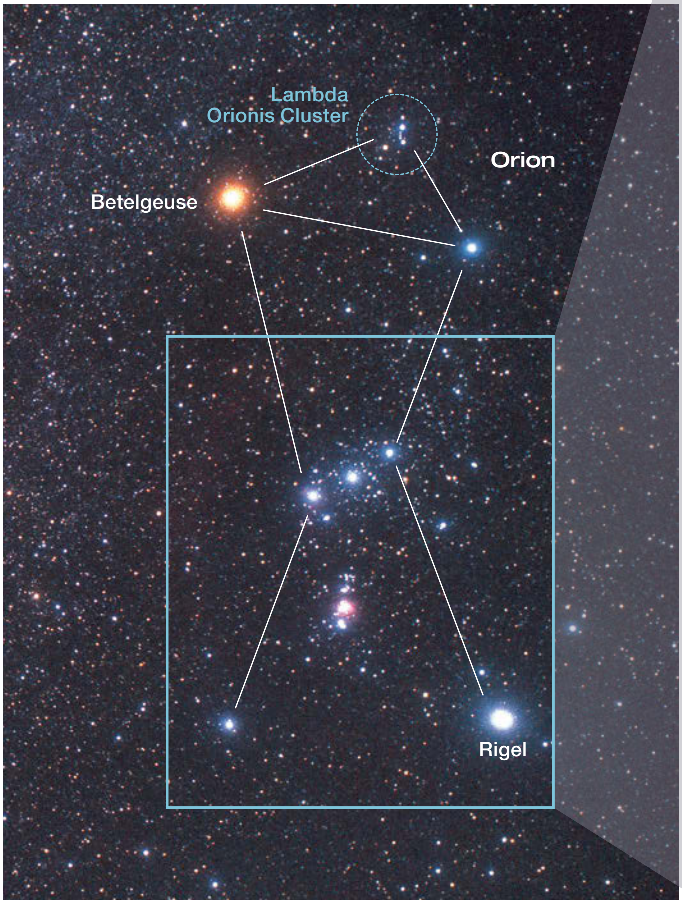
A favorite of imagers, the **California Nebula** (NGC 1499) presents a worthy challenge for visual observers. E. E. Barnard discovered it in the mid-1880s with a 6-inch refractor, but he was an acute observer unburdened by electric light pollution. The nebula's low surface brightness calls for extremely dark skies — and possibly a hydrogen-beta filter — for a glimpse in a small scope. This California spans around 2.5° × 0.5°, but its brightest portions lie about ½° to 1° northeast of Menkib, Xi (ξ) Persei, the hot star that lights up the nebula.

Look for Mirfak, also known as Alpha (α) Persei (the brightest star in Perseus), to see the loosely associated blue-white members of the **Alpha Persei Moving Group** spread across roughly 4°. This collection of stars is also cataloged as Melotte 20 and Collinder 39. The Group's brightest members lie between Alpha and Delta (δ) Persei, and at least a dozen shine brighter than 6th magnitude. See if you can find a long, winding shape of brighter stars that resembles a small sea monster — a mini version of the constellation Cetus, perhaps. This monster's bulbous head is formed by bright Mirfak and a ring of 6th-magnitude stars, while Sigma (σ) Persei marks the hump of the beast and Delta pinpoints the tip of the tail.

Let's move eastward now into Auriga, the Charioteer. Its best open cluster, **M37**, is a solitary object. But its companions (also open clusters), **M36** and **M38**, both fit in the same field of view. Spanning just 10′, M36 presents a lovely arrangement of blue-white stars. Dimmer M38 spans about 20′ and lies around 2° to the northwest. Both are at a distance of about 4,500 light-years. Just ½° south of M38 lies yet another open cluster, the compact, 8th-magnitude **NGC 1907**, a misty patch of unresolved stars. Not quite a degree farther to the southeast lies the 5th-magnitude, honey-hued **Phi (ϕ) Aurigae**.

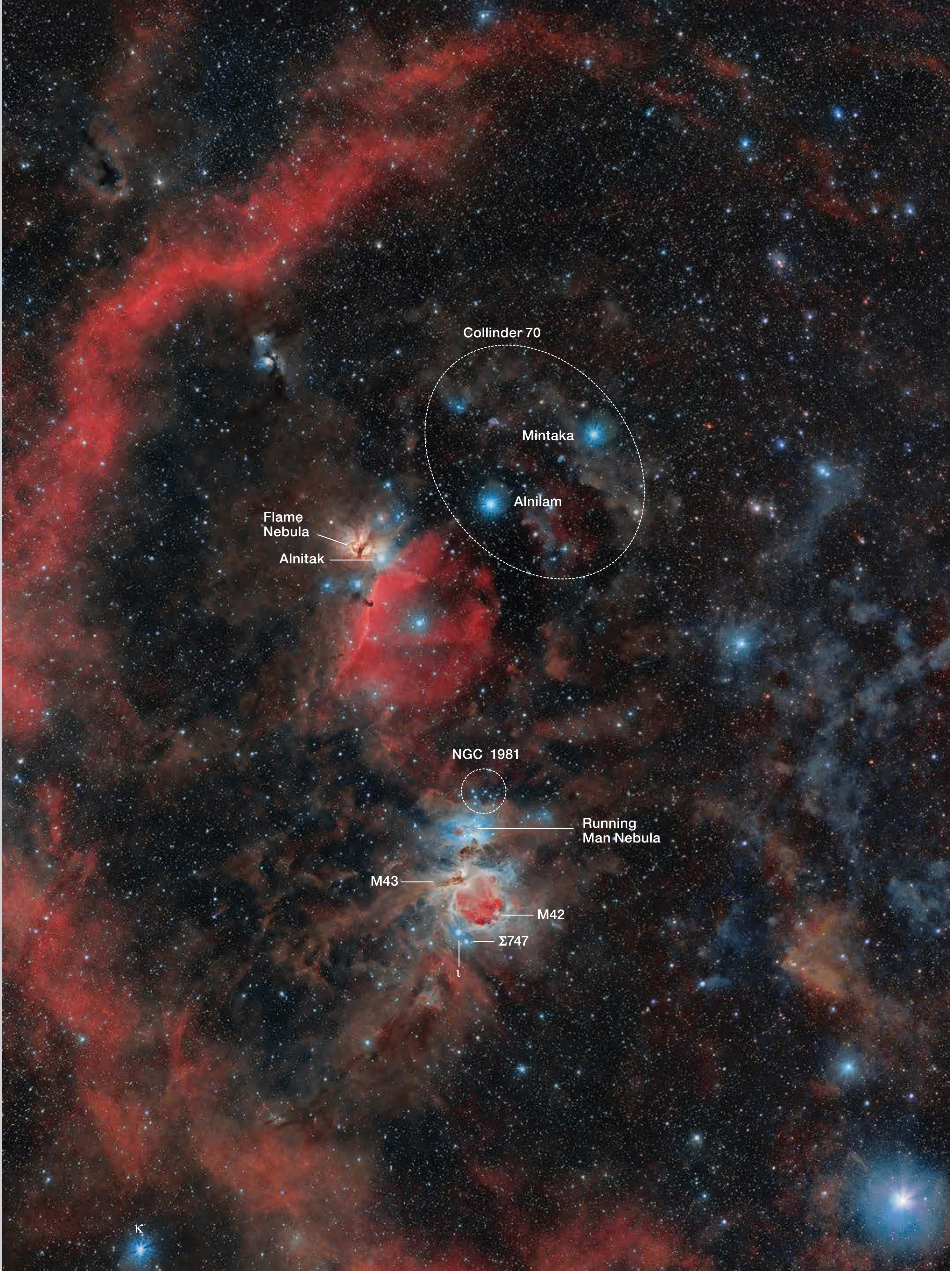
If your scope yields a 5° field, position M36 and M38 in the northeast of the view. Now, look for a glimmer of the icy-white mist of the emission nebula IC 405, the **Flaming Star Nebula**, at the southwestern edge of the field just northeast of the star **AE Aurigae**. This runaway star, which was likely ejected from the Trapezium star cluster in the Orion Nebula, is fortuitously passing through a cold cloud of interstellar gas, setting it alight.

▲ **SHIMMERING SPLENDOR** A perennial favorite, the Pleiades are a delightful sight, especially in small telescopes. The Seven Sisters are a great target for the unaided eye, too. How many stars can you spot without equipment?



▲▶ **VISTAS IN ORION** *Above:* The famed Hunter of mythology offers myriad objects upon which to feast your eyes. *Right:* Perhaps the most famous nebula of all, the Great Orion Nebula, is a perfect place to start your exploration of this iconic constellation.

THE PLEIADES: TERRY HANCOCK



TERRY HANCOCK

Across the border into the constellation Taurus, the Bull, we find perhaps the single best star cluster for a small telescope, **the Pleiades**. If only there were more objects like this in the night sky! By chance, this 100-million-year-old cluster is embedded in an interstellar dust cloud. It fits into a 2° to 3° field and presents a delicate lacework of nebulosity to observers with clean optics and a dark sky. The most accessible patch of haze lies largely south of **Merope**, where NGC 1435 (the Merope Nebula) appears frosty-white and barely brighter than the background sky. The nebulosity surrounding **Maia** (NGC 1432) is also within reach of a small scope.

Many multiple stars lie within the Pleiades cluster, which is ideal for low-power viewing. Look for a little triplet of 6th- to 9th-magnitude stars just northwest of **Alcyone**. **Sterope** (sometimes called Asterope) splits easily into a pair of 6th-magnitude stars. Fourth-magnitude **Taygeta** has an 8th-magnitude secondary a little more than 1′ to the north-northwest.

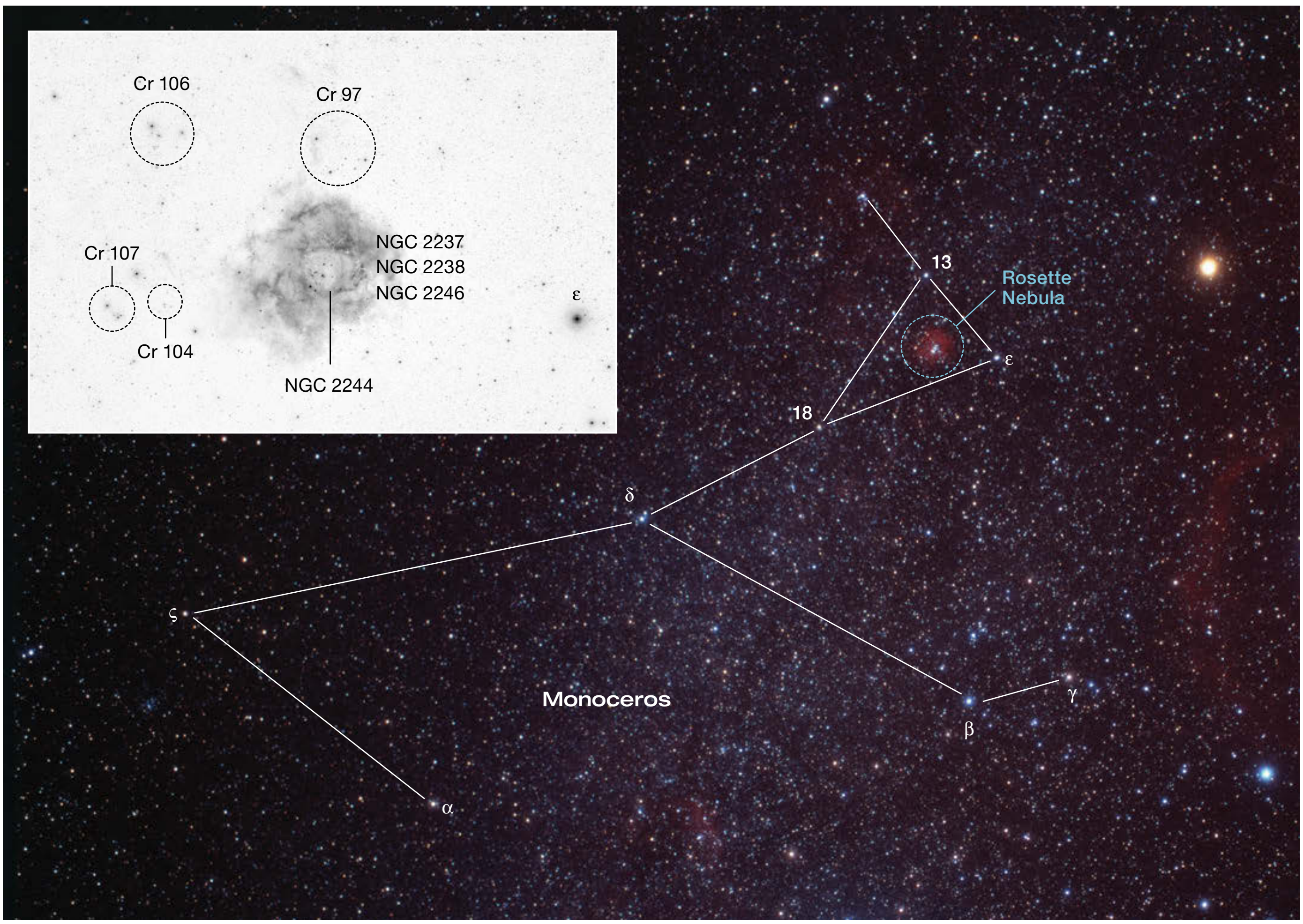
Vistas in Orion and Monoceros

Spoiler alert: This next view is likely the best on the tour, and one of the most beautiful in the entire night sky. It's the grand Sword of Orion, where a small telescope lets you take in half a dozen deep-sky sights at a glance, including the magnificent Orion Nebula, **M42**, where cold gas and dust — with a little help from gravity — turns into newly minted stars.

Most of Orion's Sword fits into a 2° field, but 3° frames it better. The showpiece of this field, M42, appears as a batwing-shaped glow with a mottled appearance even at low magnification. Most scopes resolve four of the stars in the Trapezium cluster embedded within the nebula. The sight of its faint outer wings forming a closed loop around the bright inner nebula is enough to get a committed stargazer out on a cold winter's night. *Sky & Telescope*'s Walter Scott Houston memorably wrote of the Orion Nebula, "No amount of intensive gazing ever encompasses all its vivid splendor."

Just north of M42 lies more nebulosity, including the comma-shaped **M43**. Half a degree farther north you'll find a nest of blue-white stars enmeshed in the "1970s," the nebulae NGC 1973, NGC 1975, and NGC 1977. Together they comprise Sh 2-279, also known as the **Running Man Nebula**.

▼ **UNKNOWN UNICORN** December nights are a good opportunity to visit this oft-overlooked constellation. Monoceros might not abound with targets for small scopes, but what it does offer is worth the effort. Several Collinder clusters decorate the constellation's jewel, the Rosette Nebula (see inset).



INSET: POSS-II / STSCI / CALTECH / PALOMAR OBSERVATORY

Another ¼° north sits the spanking new cluster **NGC 1981** with at least a dozen blue stars of 6th- to 10th-magnitude arranged in a ragged W.

The southern end of the Sword features 3rd-magnitude **Iota (ι) Orionis**, which has a 7th-magnitude companion star 11″ to the southeast and a 10th-magnitude companion 50″ to the east. Around 7′ southwest of Iota lies **Struve 747** (Σ747), a wide blue-white double of magnitudes of 4.7 and 5.5 separated by 36″. Immediately to the west, a mere 2½′ away, the fainter double **Σ745** is just a chance alignment of 8th- and 9th-magnitude foreground components separated by 30″.

Farther north, Orion's Belt hosts a dazzling display that includes — in a 3° field — dozens of the brightest blue-white stars of the Orion OB1 association. **Alnitak**, Zeta (ζ) Orionis, is the easternmost star of the Belt and lights up the **Flame Nebula**, making NGC 2024 (as it's also known) visible in a small instrument in a dark sky. The famed Horsehead Nebula, south-southeast of Alnitak, presents an easy target for imagers but is out of reach for visual observation with a small scope. A lovely S-shaped group of stars snakes north to south between the Belt's middle star **Alnilam**, Epsilon (ε) Orionis, and **Mintaka**, the rightmost star (Delta Orionis); together, these stars form the cluster **Collinder 70**. Mintaka itself makes a fine double star for a small scope, with its 7th-magnitude companion about 56″ away.

Orion's Head offers another excellent pitstop. Here you see the **Lambda (λ) Orionis Cluster** (Collinder 69), a little group surrounding the star Meissa. A 2° field nicely frames the cluster. Only six stars are particularly bright, while the rest blend into the background star field.

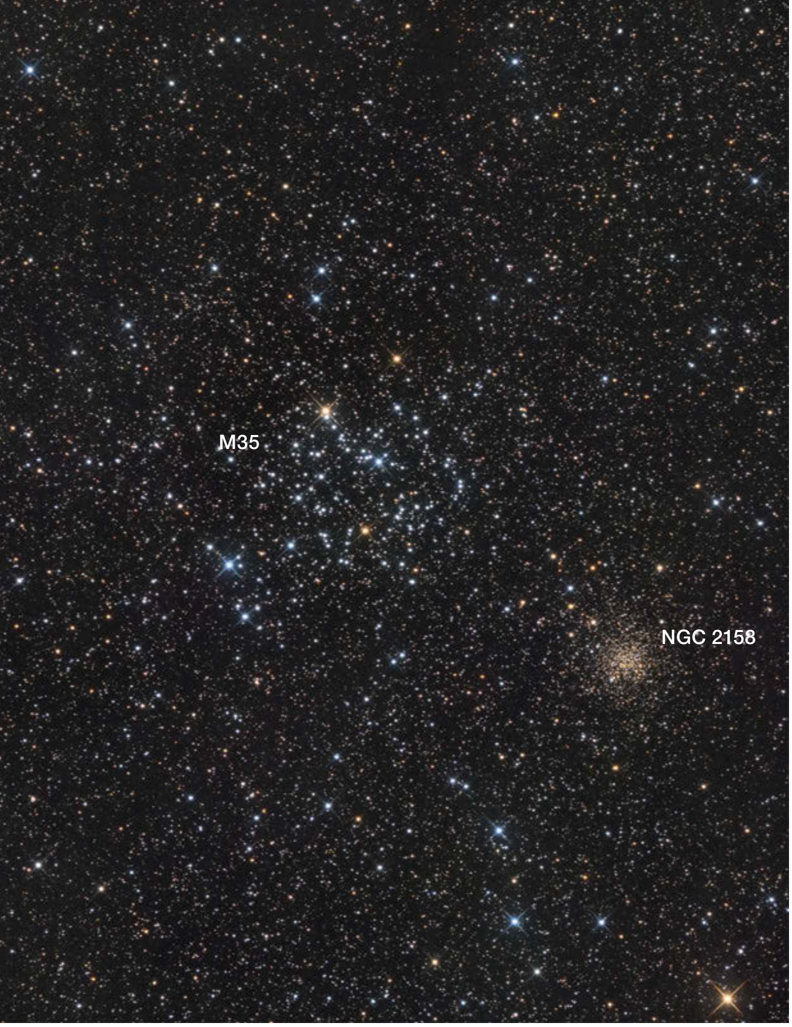
We'll slide over to Monoceros, the Unicorn, for our next stop, the **Rosette Nebula**, a star factory located 2° east-northeast of Epsilon Monocerotis. Spanning more than a full degree, the Rosette is more than three times as large as the Orion Nebula and three times farther away.

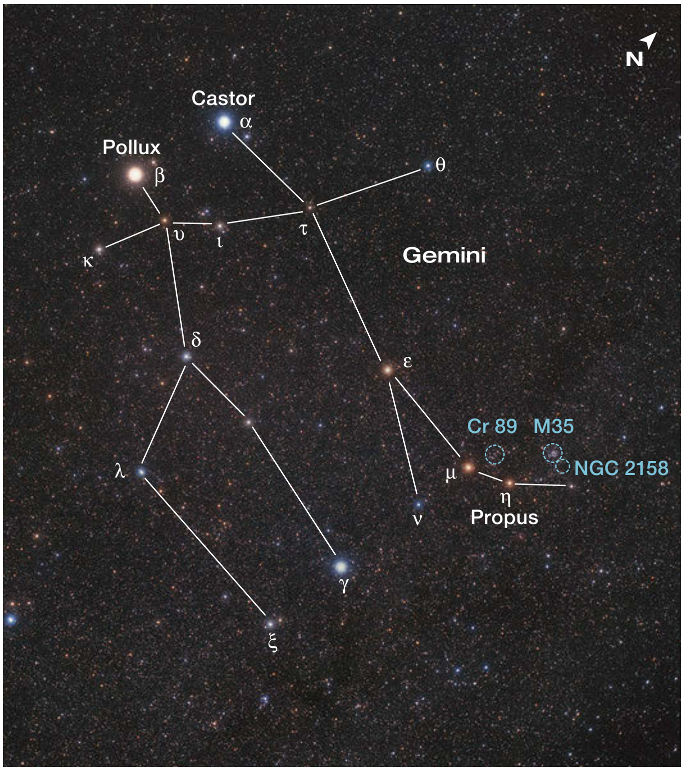
The Rosette was once considered a challenging visual target even in a big reflector. But since the advent of nebula filters in the 1970s and 1980s, it presents only a moderately difficult sight in smaller scopes. The brightest fragments surround a dark central region and lie within reach of an 80-mm refractor with an Ultra High Contrast filter in exurban skies.

Half a dozen open clusters appear in the same 3° field as the Rosette. Swedish astronomer Per Collinder was hard at work here cataloging four small and sparse clusters, including

CHURNING OUT STARS A splendid sight for small scopes, the delightful Rosette Nebula is well-placed in winter skies. You'll need to use a nebula filter, though.

TERRY HANCOCK





◀▲ **GEMINI'S GIFTS** The Twins bear several open clusters that are a delight in small scopes, such as M35 and NGC 2158 shown at left. If you happen to have imaging equipment, aim about 1° east of Propus to capture the supernova remnant, IC 443, also known as the Jellyfish Nebula.

Collinder 97, **104**, **106**, and **107**. But the showpiece is the open cluster **NGC 2244** at the heart of the nebula itself. These stars formed within the nebula about two million years ago.

Just north of Orion's upraised club, the twins of Gemini dip their toes in the winter Milky Way. Center your field halfway between the star Propus, also known as Eta (η) Geminorum, and the fine open cluster **M35**. Within a 4° field lies the partially resolved M35 along with the smaller and fainter open cluster **NGC 2158** on its southwestern edge. Two degrees east-southeast of M35 lies the sparse cluster **Collinder 89**. Propus itself shines with a lovely orange glow in the same field, while about one quarter the distance from Propus to M35 you'll see the dull red glow of the 6th-magnitude red supergiant 6 Geminorum. The entire field is a pleasure to take in against the background Milky Way. Observers with a big 5° field can include M35 at the northern edge and the emission nebula NGC 2175 at the southern edge.

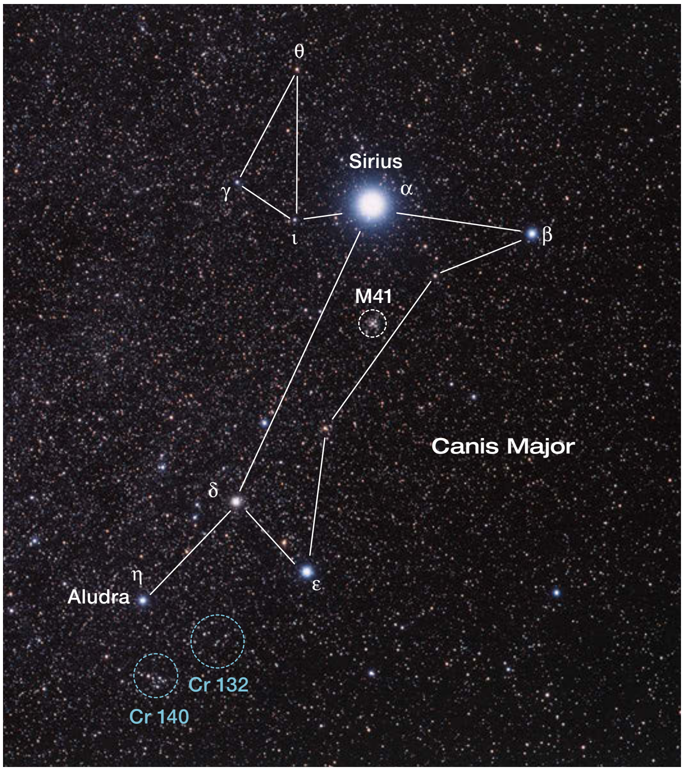
Southerly Milky Way Star Clusters

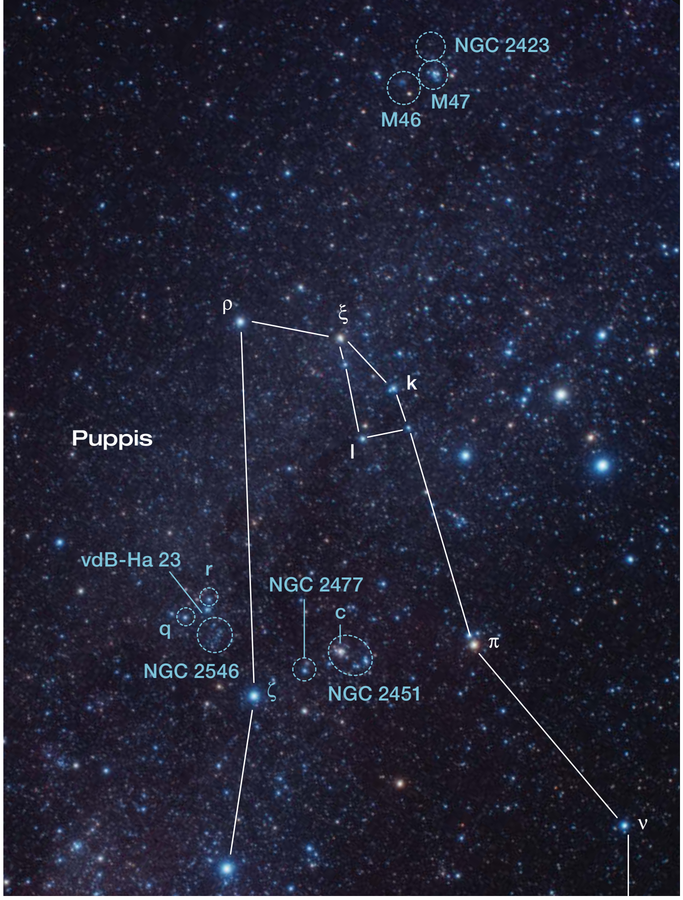
Move south of Orion and into the back legs of Canis Major, the Great Dog, and center your field about 2° southwest of Aludra (Eta Canis Majoris) to see the loose open clusters **Collinder 132** on the western edge of your field of view and the smaller **Collinder 140** on the southeastern edge. With a 4° field, brilliant Aludra joins the show. Look for its widely spaced line-of-sight companion 3′ to the west.

At last, we arrive at Puppis, the Stern, along the southern Milky Way. Most mid-northern observers will see this constellation low over the southeastern horizon on winter evenings, but a look at the open cluster **NGC 2546** makes it worth the effort. As with many southerly clusters, 18th-century astronomer Nicolas Louis de Lacaille, the patron saint of small-telescope astronomy, first glimpsed it with a tiny 1.5-inch refractor operating at 8×. At magnitude 5.3 and spread over a full degree, this cluster presents a superb, low-magnification sight set against the rich tapestry of background Milky Way.

Lacaille recorded two closely spaced patches of nebulosity here. The second was likely the smaller cluster **van den Bergh–Haffner 23**, which lies about 1.5° north of NGC 2546. Center your scope on NGC 2546, nudge it a degree to the northeast, and a 3° field of view will encompass both clusters along with the 4th-magnitude stars **r** and **q Puppis**. Centering again on NGC 2546, move your scope 1° to the southwest until the magnificent 2nd-magnitude star **Zeta Puppis** comes into view. One of the intrinsically brightest stars in the sky, Zeta Puppis has a mass of around 50 suns or more and burns about 800,000 times brighter, emitting most of its intense radiation in the ultraviolet.

Now look 6° west to find the jumbled but attractive open cluster **NGC 2451**. Astronomers once thought it a group of





▲ **'ROUND MIDNIGHT** *Left:* Several more collections of sparklers await you in the Great Dog, Orion's faithful companion, forever at the Giant's heels. *Right:* Toward the end of Northern Hemisphere winter evenings, close to midnight, Puppis, the Stern, delivers a fine collection of targets with which you can wrap up your observing sessions. They could prove a bit more challenging for observers at northern latitudes, but if you have clear skies and sightlines to the south, you might be able to bag some of them.

unassociated stars, but studies in the 1990s revealed two true open clusters here. The more concentrated northern section, NGC 2451B, centers on 4th-magnitude **c Puppis** and lies at a distance of about 1,200 light-years. The southern section, NGC 2451A, lies just 600 light-years away and includes a few stars around c Puppis, as well as a handful towards the southwestern edge of the cluster, including 5th-magnitude n1 Puppis and 6th-magnitude d2 and d3 Puppis. The brightest parts of each cluster fit in a 2° field. About 1.5° east-southeast of c Puppis, look for the fainter and smaller open cluster **NGC 2477**.

Of the many clusters that fleck the magnificent tableau of the southern winter Milky Way, the open clusters **M46** and **M47** rank among the finest — and they fit nicely in a 2° field. Their striking and contrasting appearances will put a smile on the face of nearly any small-telescope connoisseur.

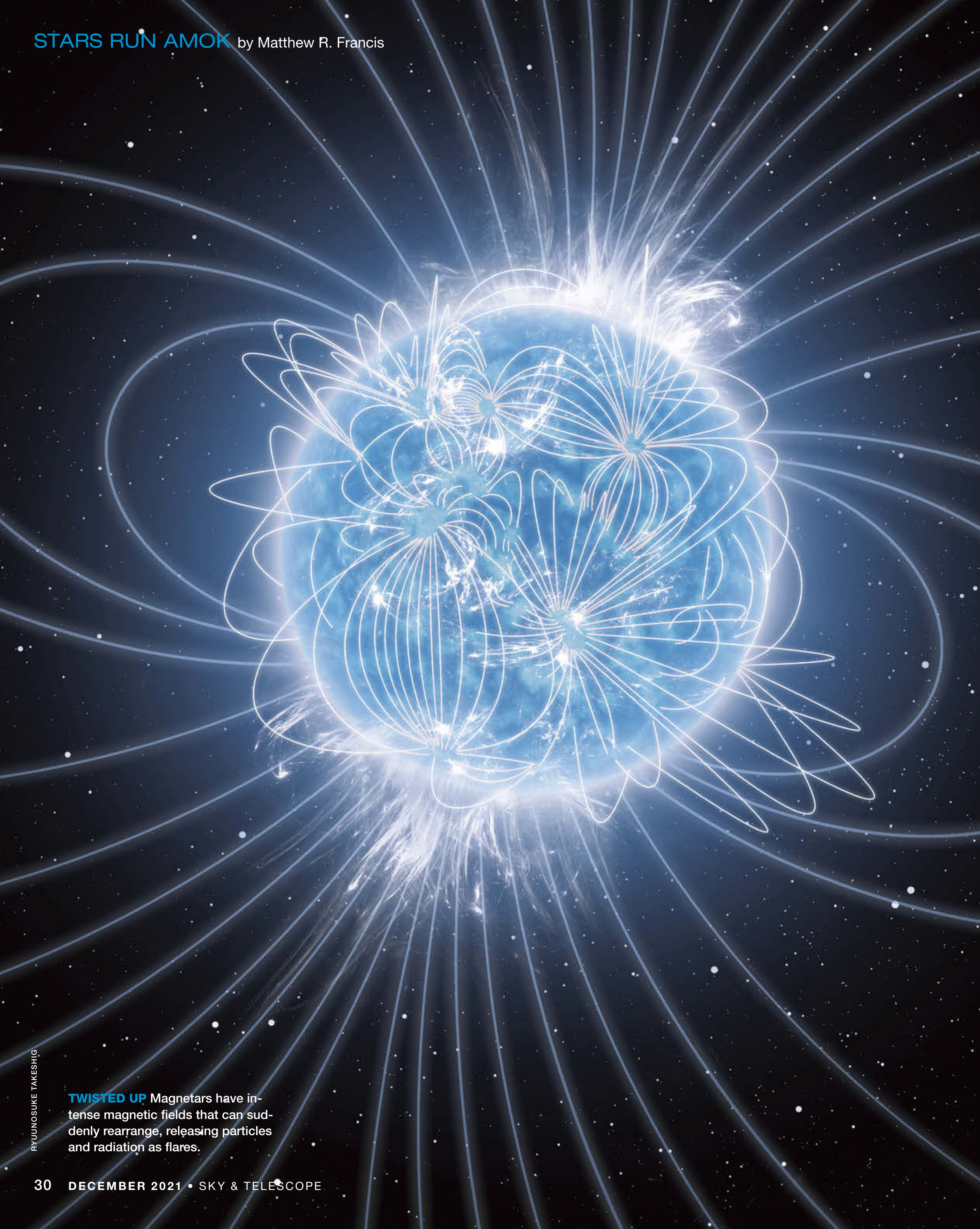
At a distance of 1,600 light-years, the relatively compact and young M47 appears as a scattering of about 50 stars as if it were assembled from odds and ends. M46 looks as large as M47, but it's three times as distant and intrinsically much larger and more uniform. It shows perhaps 100 stars to the limit of visibility of a small scope. The cluster also seemingly harbors the planetary nebula NGC 2438, evidently a foreground object. From a moderately dark observing site you can glimpse the planetary — with some effort — in an 80-mm refractor. A little less than a degree north of M47 the faint open cluster **NGC 2423** rounds out this glittering field.

Big scopes will always have their place in amateur astronomy, and a case of aperture fever strikes nearly every stargazer at some point. But as I hope I've shown you, there's still plenty to see in a small instrument. You may — with a little practice and a good star map — come up with your own favorite sights for a small scope, especially along the main thoroughfares and byways of the Milky Way.

Observing Aids

Star charts are not only very useful in guiding you to your targets, but they're also lots of fun to peruse! You could do like Brian Ventrudo did for both his small-scope articles and use *Sky & Telescope's Pocket Sky Atlas* to navigate your way around the sky. Get your own copy at **https://is.gd/ST_pocket_sky_atlas**.

BRIAN VENTRUDO is a writer, scientist, and longtime amateur astronomer. Although he never turns down a look through a big Dobsonian, he usually observes with smaller telescopes from the relatively dry and clear skies of Calgary, Canada. Ventrudo writes about astronomy and stargazing at his website **CosmicPursuits.com**.



RYUUNOSUKE TAKESHIGE

TWISTED UP Magnetars have intense magnetic fields that can suddenly rearrange, releasing particles and radiation as flares.

THE SHORT, VIOLENT LIVES OF MAGNETARS

Neutron stars with extreme magnetic fields are behind some of the brightest outbursts in the Milky Way. Their story might reveal the answers to many cosmic mysteries.

On December 27, 2004, Earth's atmosphere shook with the impact of a cosmic blast. The thin air high above the surface reverberated under the assault, the radiation setting off a cascade of ionization deep into the atmosphere. The Burst Alert Telescope aboard the newly launched Neil Gehrels Swift Observatory, designed to detect the most powerful explosions in the universe, was saturated with high-energy photons.

The culprit behind this colossal event wasn't a supernova or even a collision between two dead stars, like the type seen by LIGO and Virgo (see page 36). Instead, it was a burst of gamma rays from a *magnetar*: the collapsed core of a dead star known as a neutron star, but one with extreme and tangled magnetic fields. And unlike with supernovae or gravitational-wave-producing collisions, the star survived to flash again.

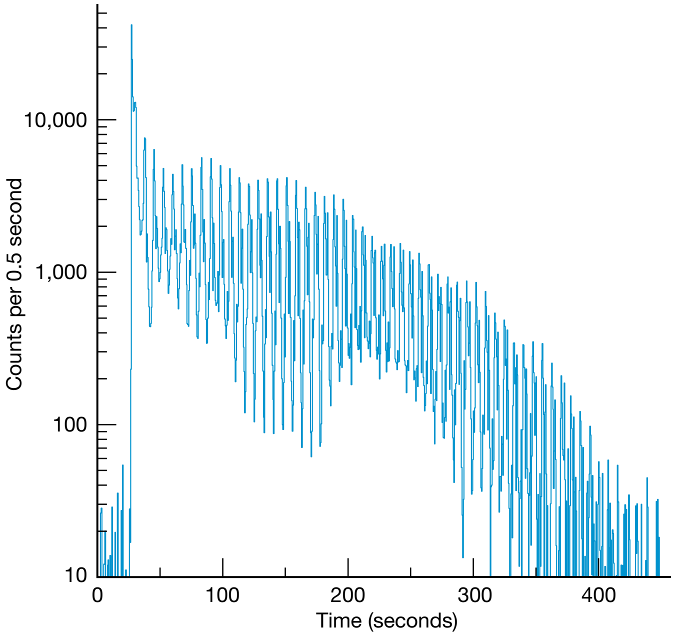
This object, known as SGR 1806-20, is located roughly 50,000 light-years away within our own galaxy. The thicker air in Earth's lower atmosphere shielded us from the worst of its radiation, so none of us surface-dwellers saw or felt anything on that day. However, gamma-ray observatories, radio telescopes, and atmospheric observers all saw SGR 1806-20. The sheer magnitude of the blast — dumping as much energy into space in a tenth of a second as the Sun emits in 150,000 years — illustrates how powerful magnetars are. Their magnetic fields are approximately a quadrillion (10^{15}) times that of the Sun, and 1,000 times greater than the fields generated by typical neutron stars, which are themselves among the most extreme objects in the cosmos.

"Magnetars are amazing laboratories of dense-matter physics and strong magnetic fields that we really don't have anywhere else in the universe," says Daniela Huppenkothen (Netherlands Institute for Space Research). "They are quite mind-blowing if you think about it."

Their extreme nature is why astronomers think magnetars are responsible for a wide range of cosmic phenomena. In addition to the gamma-ray flares that marked the earliest observations, magnetars might even be responsible for some of the strange radio bursts that have puzzled researchers since their discovery in 2007.

POWERFUL BLAST

The 2004 flare from SGR 1806–20 disturbed Earth's daytime atmosphere down to an altitude of 20 km (12 mi) for more than an hour. That corresponds to the ozone layer in the stratosphere.



▲ **2004 FLARE** When SGR 1806–20 unleashed its 2004 flare, the initial spike saturated detectors on the RHESSI spacecraft within a millisecond. After the detectors recovered some 200 ms later, they caught the flare's fade and oscillation. The oscillatory period matched the magnetar's rotation period of 7½ seconds and persisted for nearly 400 seconds.

"Twenty years ago, there were 10 people in the world working on magnetars," says Nanda Rea (Institute of Space Sciences, Spain). "They were thought to be very rare objects, but we are starting to find out that they are connected to the most extreme explosions in the universe. Most of the transients in time-domain astronomy are actually connected with the existence of magnetars. They are giving us a lot of answers connecting different branches of astronomy."

"Soft Gamma Repeaters"

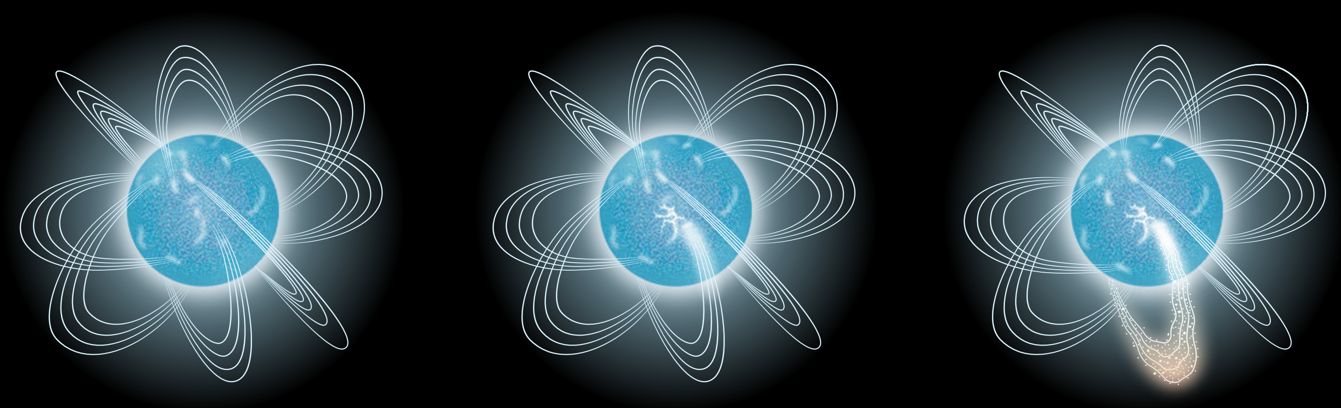
The theory predicting neutron stars preceded their observational discovery by more than 30 years, but the first hint of a magnetar was observational: a powerful gamma-ray flare detected in 1979. At that time, astronomers were still in the early stages of understanding cosmic events involving the highest-energy photons, lumped together under the name *gamma-ray bursts* (GRBs). However, it was evident that the 1979 flare was a little different than other explosions that would later be identified as colliding neutron stars and extreme supernovae: It was followed by smaller bursts in subsequent years, rather than being the single powerful explosion characterized by normal GRBs.

In 1986, astronomers called the objects producing these repeating signals *soft gamma repeaters* (SGRs), with the very first one given the designation SGR 0526-66 (where the numbers represent its celestial coordinates). "Soft" sounds almost cuddly, but it refers to the lower-energy gamma radiation produced in the later bursts; the initial flare and other GRBs are primarily "hard" gamma rays. Observatories also detected two other events in 1979 that were later grouped with the SGRs, but what made SGR 0526-66 special was that spacecraft across the solar system — including the Earth-orbiting Einstein Observatory, the Pioneer Venus Orbiter, and the Sun-orbiting Venera 11 and 12 probes — detected the blast. (As with GRBs, satellites designed to look for illicit nuclear weapons also spotted SGR 0526-66, though those data weren't released to scientists until later.) The range of detections enabled astronomers to locate the source of the flare in the remnant of a supernova in the Large Magellanic Cloud (LMC), which is the closest substantial galaxy to the Milky Way (*S&T:* June 2021, p. 20).

Over the next few decades, astronomers identified many

OSCILLATING FLARE GRAPH: K. HURLEY ET AL. / *NATURE* 2005; HOW MAGNETARS FLARE: GREGG DINDERMAN / *S&T*

HOW A MAGNETAR FLARES



Magnetars have strong magnetic fields locked into place by the star's crust, both inside and out.

Magnetic stresses and electric currents combine to force the internal magnetic fields to twist into a new configuration. The movement within fractures the surface.

The fracture makes the magnetic fields vibrate and releases a surge of particles. For powerful, long-lived bursts, this cooling fireball whips around as the star spins, imprinting the magnetar's rotation period in the observed flare.

more SGRs and eventually determined that all were located inside the Milky Way and its close neighbors. In contrast, researchers established by the early 2000s that GRBs all occur in distant galaxies.

Gamma-ray aftershocks proved to be key to understanding the astronomical objects responsible for SGRs. In 1992, astrophysicists Robert Duncan (University of Texas, Austin) and Christopher Thompson (University of Toronto) predicted the existence of neutron stars with anomalously strong magnetic fields and relatively slow rotation rates. They coined the term "magnetar" to describe this new subtype of stellar remnant. Although the duo initially proposed magnetars as part of an attempt to understand neutron star formation, the researchers realized quickly that they were also a solution to the SGR mystery.

From that beginning, high-energy astronomer Chryssa Kouveliotou (now at George Washington University) and her collaborators connected multiple aspects of SGRs to magnetars. In 1998, a new giant SGR flare allowed them to draw all the available observational evidence together; as it faded, it fluctuated in rhythm with the pulsar's slowing spin, establishing the magnetar-SGR relationship once and for all.

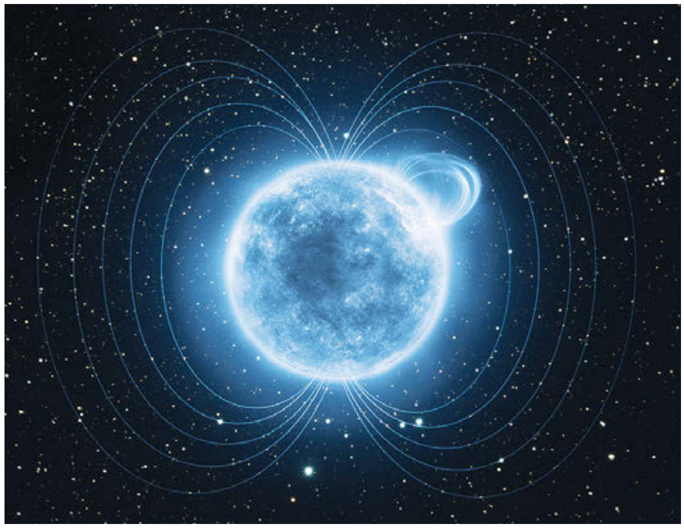
Since then, the number of known magnetars has continued to grow. As of September 2021, there were 24 confirmed magnetars and 6 candidate ones. The 2004 magnetar flare that made Earth's atmosphere dance came from one of the first SGRs discovered. In addition, astronomers connected magnetars to another observational mystery: *anomalous X-ray pulsars* (AXPs). Unlike normal pulsars, which emit X-rays mostly if they are stripping matter from a companion star, AXPs are very luminous in X-rays yet don't live in binary systems.

A Magnetar Is Born

Neutron stars — including magnetars — are apparently perfect spheres of dense matter, packing the mass of a star into an object between 16 and 32 kilometers (10 to 20 miles) wide. Understanding neutron stars requires combining nuclear physics, strong gravity, intense magnetic fields, and the behavior of extremely dense, hot matter. These conditions can't be recreated in laboratories on Earth. Astrophysicists also don't have a complete knowledge of the neutron star's *equation of state,* which provides insight into internal structure and governs how big these objects can grow (*S&T:* July 2017, p. 18).

10%
Minimum fraction of young neutron stars that are magnetars

Magnetars have the same basic physical characteristics as ordinary neutron stars, but their history seems to make the difference in how they behave. A key insight on that point came from the environments in which magnetars were discovered: relatively young supernova remnants. That indicates magnetars are fairly young objects, so their extreme magnetic fields and slow rotations are probably due to how they formed.



ESA / ATG MEDIALAB

▲ **SNEAKY MAGNETAR** SGR 0418+5729 long appeared to have a surprisingly weak magnetic field for a magnetar. But X-ray observations spotted signs of a small magnetic structure (perhaps solar-like loops?) above the star's surface with a field of roughly 10^{15} gauss, matching measurements from other magnetars.

A typical neutron star is born from the death of a supergiant star that began life with between approximately 8 and 20 times the mass of our Sun. When that star runs out of its usable nuclear fuel, its core collapses into a neutron star, while the outer layers are blown off in a supernova. According to one magnetar formation theory, if the original core was spinning fast enough — about once every 10 milliseconds — the magnetic fields inside it would get twisted up and grow to be extremely strong. In cores with slower rotations, the interior magnetic fields simply never become as intense in the first place; those more sedate neutron stars become pulsars, such as the famous Crab Nebula pulsar.

A newborn magnetar's rapid spin separates its interior into layers that rotate at different rates; the magnetic field from each layer conflicts with that produced by other layers, acting as a brake. The rotation slows until it takes several seconds to complete a rotation — that's fast on our terms, but slow compared to the sub-second rotations of most pulsars. The moving magnetic fields also produce electric currents inside the magnetar that ultimately spell the end of the magnetar stage of life.

"Those currents make the magnetic field decay on time scales of mega-years," says Rea. "Between the magnetar's birth and when it is one mega-year old, the decay of the magnetic field drives everything: what kind of emission it has, how it will slow down, what is the temperature of the surface, and how many flares the source will have. The younger the source, the more active the burster will be. The magnetic field [of a young magnetar] will be very tangled, so there will be a lot of energy to move."

However, there are other formation scenarios. Some GRBs are the result of two neutron stars colliding, and in some

MAGNETARS HAVE THE MOST EXTREME MAGNETIC FIELDS WE KNOW OF IN THE UNIVERSE.

instances they may merge into a single higher-mass neutron star, with the remaining cases resulting in a black hole. Genevieve Schroeder (Northwestern University) studies that type of GRB to see if there's any sign they make magnetars.

"We need two neutron stars that merge together and have a mass that is below or just a tiny bit above the maximum mass [for neutron stars]," she says. The newly formed star might sustain such an exceptionally high mass for a short period of time if different parts of its interior start off rotating at different rates.

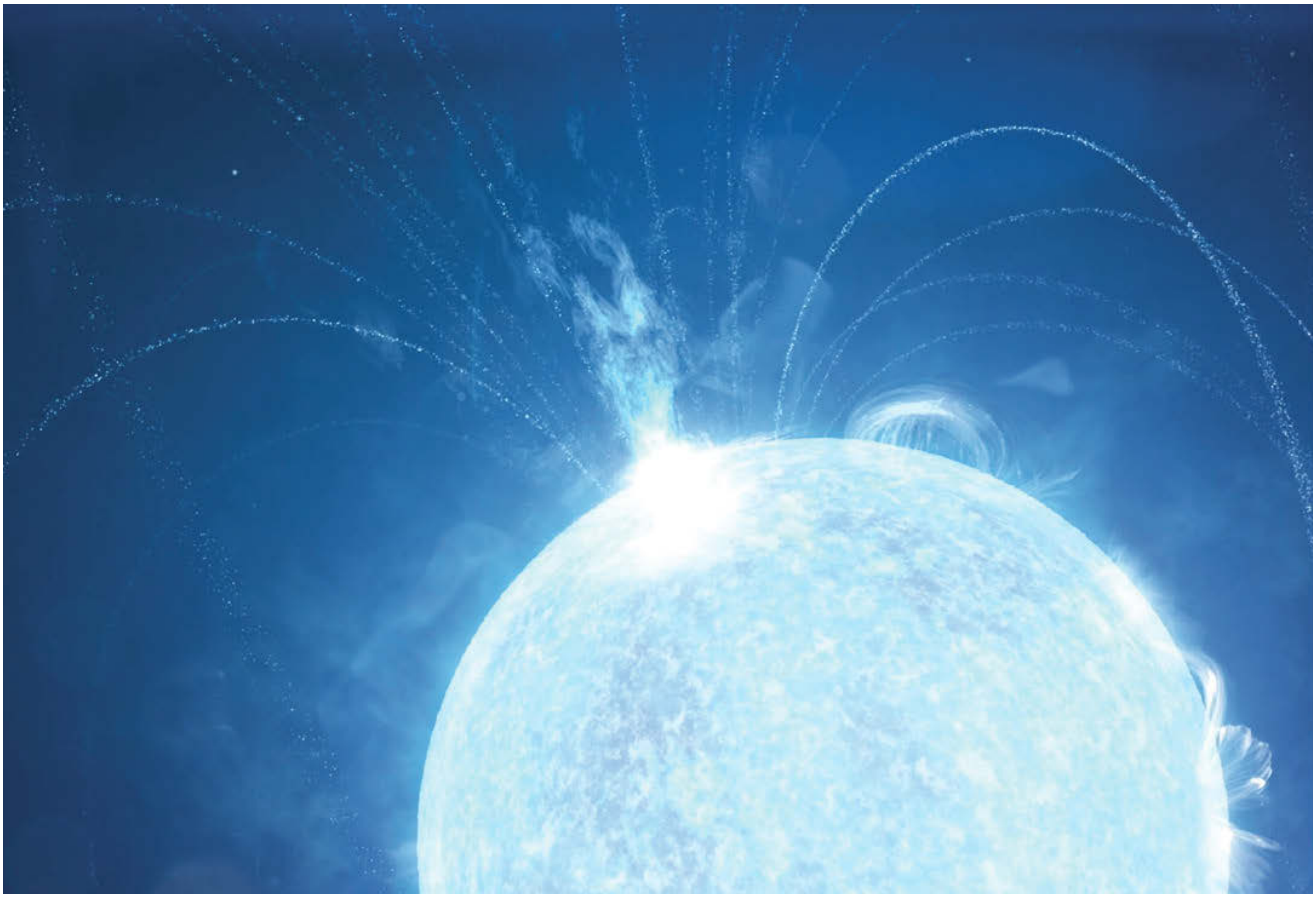
As with the supernova formation theory, magnetars forming from GRBs require specific conditions. "The idea is that these two neutron stars already have pretty high magnetic fields, so when they merge together they could in theory create another neutron star with an even higher magnetic field," Schroeder explains.

Starquake!!!

Whichever way they form, the resulting magnetars have the most extreme magnetic fields we know of in the universe. Those fields are tangled up inside the neutron star from their formation, and that mess means many of the fields repel each other, just as north poles of bar magnets repel other north poles. The tension and complex interplay between magnetic fields and electric currents in the magnetar interior work to disentangle the fields. But neutron stars also have solid crusts, which pin the magnetic fields in place where they pierce the surface.

"As the magnetic field lines move, they pull on this crust," says Huppenkothen. "If you pull enough on something that you're anchored in, you're gonna rip it apart. And that is how you get starquakes."

Since everything about a magnetar is intense, starquakes are, too. The energy released when the crust cracks has to go somewhere, and the result is gamma-ray flares, including the ones powerful enough to affect Earth's atmosphere. Radiation from the Sun ionizes atoms and molecules high above our planet's surface, creating a layer known as the ionosphere; the giant flares in 1979 and 2004 dramatically increased the



NASA GSFC / CHRIS SMITH (USRA)

▲ **FLARE-UP** This illustration depicts a powerful burst that erupted on April 28, 2020, from the magnetar SGR 1935+2154. Both X-ray and radio telescopes detected the event, which resembled the mysterious *fast radio burst* signals seen from other galaxies.

ionosphere's size for a brief time.

The same processes may also be responsible for some or all *fast radio bursts* (FRBs), which as the name suggests are brief — on the order of milliseconds! — but intense, usually non-repeating flashes of radio emission (*S&T:* July 2016, p. 24). Thanks to the understanding that other high-energy outbursts were driven by magnetars, some astrophysicists suspected FRBs might also be neutron star–powered. However, known magnetars were all in our galaxy or its nearest neighbors, and FRBs were all suspected to be much more distant. The first real demonstration of the link came when researchers detected an FRB-like flare from a known magnetar in the Milky Way on April 28, 2020 (*S&T:* Sept. 2020, p. 10).

"I believe that FRBs, or at least a large percentage of them, can indeed be related to the first decades of newly born magnetars," Rea says. "[FRB numbers] are very aligned with how many young magnetars you expect in other galaxies."

Beyond the Horizon

Huppenkothen and her collaborators have an even more ambitious purpose for studying starquakes, based on the harmonics produced in the magnetar crust as it oscillates.

"We study Earth's interior by studying earthquakes and their propagation through Earth," she explains. "We don't have any way to look into the interior of the [magnetar], but one thing these oscillations depend on is the neutron star equation of state, which is one of the big holy grails of neutron-star physics."

Much of her PhD research involved looking for those smaller reverberations in SGR data, and she's found fluctuations that might be them. But she points out that much work is still to be done: "Is it really a starquake? We don't know yet because the theoretical models are complicated. Our statistical methods were all designed to look for ripples on a still pond, but I had [to find them in] something like a tropical storm on an ocean."

In addition to the challenge of finding starquake signals, it's incredibly difficult to find magnetars in distant galaxies, which is where all observed GRBs occur. However, in January 2021, researchers announced they had detected a powerful gamma-ray flare in the galaxy NGC 253 (also known as the Sculptor Galaxy), which matches the behavior of magnetar flares in the Milky Way. This galaxy is undergoing huge levels of star formation and supernova creation as the largest stars burn through their short life cycles, so it's an obvious place to look for young neutron stars. And along with the identification of an FRB with a Milky Way magnetar, the discovery lends hope that we will see more and more of them outside our galaxy.

Similarly, Rea is excited about the possibilities of studying matter in the extreme magnetic fields outside magnetars, the region known as the magnetosphere. Modern physics predicts that super-strong magnetic fields generate exotic quantum effects, but those are out of reach of present-day laboratories.

"If you put an atom of hydrogen in a strong magnetic field, the shape is not the typical shape: It has a shape like spaghetti," she explains. If hydrogen — the simplest type of atom in the cosmos — is affected that strongly, "you can imagine how material of any kind can be affected by the presence of the field. To study this very strong regime, the only place we can go is observing these stars."

ESO

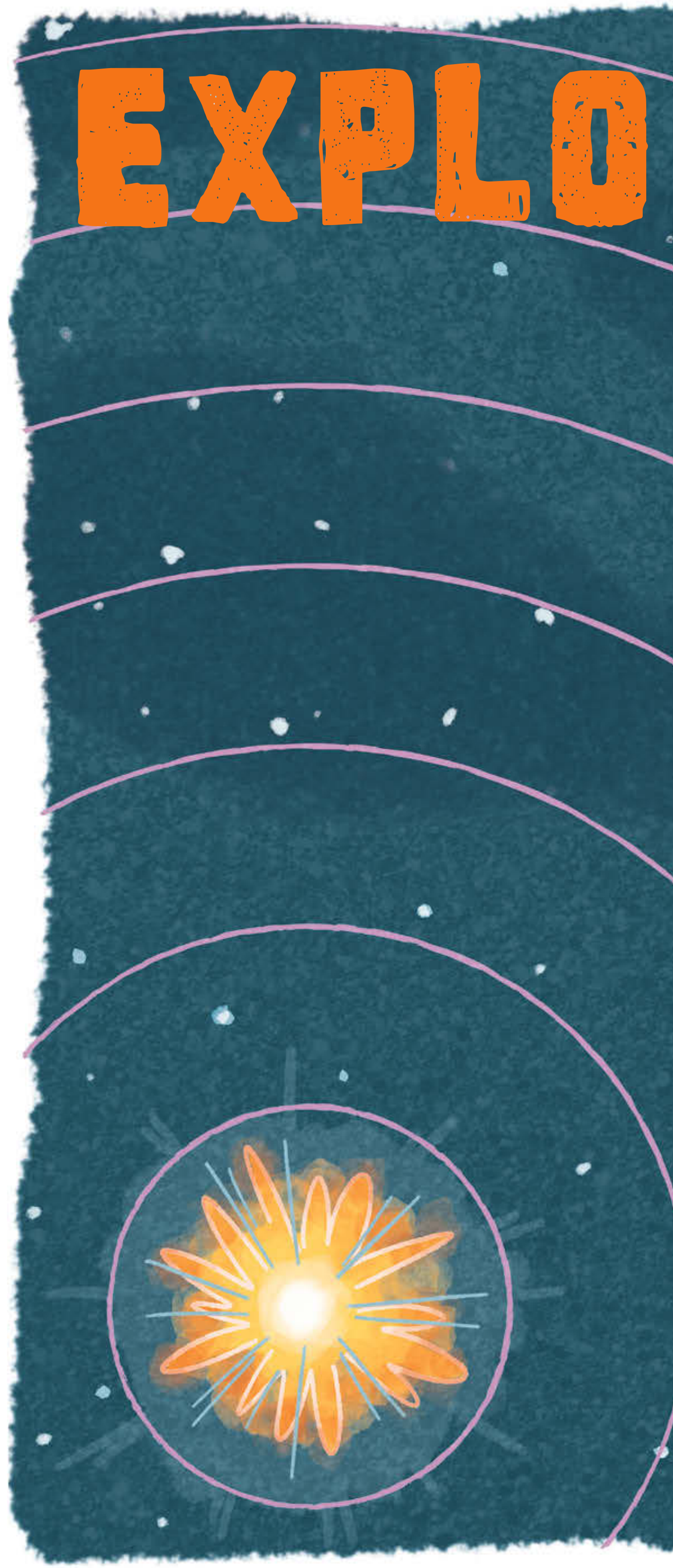
▲ **NGC 253** This elegant spiral in the constellation Sculptor was home to a powerful gamma-ray flare that matched those seen from magnetars in the Milky Way. The galaxy lies about 12 million light-years away.

Rea is involved with two forthcoming observatories. The ground-based Square Kilometre Array (SKA) will provide high-resolution radio observations of pulsars and magnetars, while the Athena X-Ray Observatory will be able to study in unprecedented detail the behavior of matter swirling around in the magnetospheres.

If the prevailing theory is correct, magnetars may only last a few thousand years before their magnetic fields decay. That's long on human scales but short in cosmic terms, so finding them during their relatively brief lives is as much chance as anything. However, as observatories continue to improve in sensitivity and resolution, astronomers have a better chance of finding magnetars at larger distances. The first was discovered a mere 42 years ago; with the huge leaps in understanding since then, who can say what the next 42 years might bring?

■ **MATTHEW R. FRANCIS** is a physicist, science writer, and frequent wearer of jaunty hats. Find more about his work at **bowlerhatscience.org**.

Cosmic



Astronomers drop everything to look for flashes from gravitational-wave mergers, but often their searches turn up empty.

It was an afternoon in the summer of 2017. Andrew Levan waited in line at McDonald's with his two kids. His thoughts were on his heavily pregnant wife when his work phone went off. "Come on, not now," he thought to himself, but curiosity and his sense of duty got the better of him. From a deluge of incoming messages, he learned that the LIGO gravitational-wave observatory had just detected what looked like a merger of two neutron stars.

As a seasoned astronomer, Levan (now at Radboud University, The Netherlands) immediately realized the implications: It was what he and his colleagues had been dreaming about for decades. In the month to come, he would repeatedly find himself lying in bed, a newborn baby in one arm and a laptop in his lap, organizing follow-up observations of the neutron star merger GW170817, which would become one of the most famous cosmic explosions to date. "In the end, it worked more smoothly than you might imagine, but it was not stress-free," he says. "It was probably the most exciting but also the most demanding period in my career."

Astrophysical *transient sources* — those that appear and disappear — pop up in the sky all the time. Caused by different physical phenomena, one transient can differ a lot from another. What is common to all is their unpredictable nature and fast evolution.

Gravitational waves produced by mergers of compact objects are the latest addition to the transient zoo. GW170817 radiated both gravitational waves and electromagnetic radiation, and it was the latter (called the *counterpart*) that especially excited Levan and thousands of other astronomers. That single electromagnetic counterpart confirmed the predicted link between short gamma-ray bursts (GRBs) and neutron star mergers, provided a novel way to measure the Hubble constant, and taught us that mergers produce rare earth elements, a category of metals. But counterparts have even more to offer than that, and we have been trying to catch more of them ever since.

Mergers of Stellar Relics

Under the right conditions, mergers of two neutron stars (BNS) or a neutron star and a black hole (NS–BH) produce light across the electromagnetic spectrum. In the moments

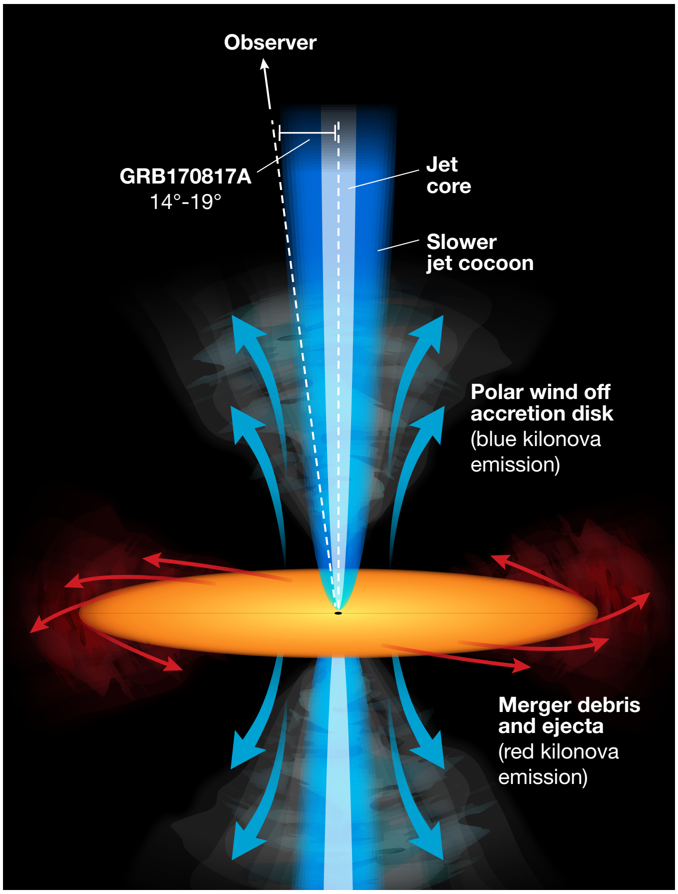
LEAH TISCIONE / S&T

SION Hunters

DROP EVERYTHING
When a distant merger sends gravitational waves rippling through detectors, an alert goes out to astronomers around the world, who utilize an array of ground- and space-based telescopes to look for the source.

before the merger, tidal forces disrupt or completely tear the stars apart. Some of the resulting debris swirls around the newly formed central object, makes an accretion disk, and launches two powerful jets moving at nearly the speed of light. The jets emit a short GRB and, upon colliding with the surrounding medium, give rise to a longer-lived afterglow emission. Some of the debris may be flung away from the central object, giving rise to a bright transient called a kilonova that can stay visible for a few days to a few weeks (*S&T:* Feb. 2018, p. 32).

To everyone's surprise and delight, GW170807 produced everything we could have imagined: a GRB, an afterglow, and kilonova emission. Nevertheless, the breakthrough left us with many questions. How different is one kilonova from another, and what is their yield of rare earth elements? Does every merger produce a GRB? We were also anxiously awaiting the first detection of the NS–BH counterpart. Building on the experience with GW170817, we started to think of the best way to find the next counterpart. We had pulled it off once — how hard could it be?



◀ **ANATOMY OF A GRB** When two neutron stars collide, a hot disk of debris forms around them and a powerful, ultrarelativistic jet shoots away from each pole. Sheathing the jet is a slower-moving cocoon of material. With GW170817, observers saw both bluish and red/infrared light, which they think came from different parts of the debris.

LEAH TISCIONE / *S&T*

Needle in a Haystack

Gravitational-wave observatories cannot pinpoint the location of detected mergers very well. So to find the counterpart, we need to find a new and short-lived source of light in an area stretching over hundreds to thousands of square degrees of sky. But that source of light may be too faint for our telescopes. Or even worse, the merger might have played out without producing the counterpart in the first place.

It doesn't help that the universe sparkles and twinkles like a Christmas tree. A swarm of transients hangs out in that big patch of the sky. Among all that clutter, we need to find our counterpart and be smart about it — we wouldn't want to spend all our resources on a transient that turned out to be nothing more than a boring supernova.

Preparation is key to success. In truth, planning takes up most of the work. Research groups spend years and many resources building their own telescopes dedicated to the transient search. Others write proposals to get time on existent state-of-the-art machines. Scientists need to develop observational tactics and write software to automate and expedite real-time analysis.

Our research group even had a dry run to improve our reaction times and decision process. Senior members set up a scenario with a mock gravitational-wave event and a virtual observatory. Once the simulation started, the organizers sporadically fed us new pieces of information to guide us in our follow-up process. The tension peaked when an error caused by something as mundane as file mismanagement led one group of participants to triumphantly announce the discovery of a kilonova, causing confusion among others who couldn't find the claimed signal. Thank goodness it was a dry run and not the real thing.

Scientists are a competitive bunch, but faced with the challenging task of transient follow-up, we have to close ranks and work together. Recently, large collaborations between institutions from all over the world have emerged, such as the Caltech-led project Global Relay of Observatories Watching Transients Happen (GROWTH). "The idea behind GROWTH is to establish a large collaboration distributed around the world, but also distributed in wavelength," says Alessandra Corsi (Texas Tech University).

European researchers combined their resources at the European Southern Observatory and formed the Electromagnetic Counterparts of Gravitational Waves at the Very Large Telescope (ENGRAVE) collaboration. Levan, the chair of ENGRAVE's executive committee, points out that there is another angle to large collaborations. "You get more voices, you're more likely to make a good decision," he says. "It means that all our data come into one clearinghouse. When you're making decisions about follow-up, you have the full picture, not just part of the picture."

And then we wait. Patiently, we proceed with our everyday lives until the sudden ringing of our phones sets the hunt in motion. It begins with the detection of gravitational waves by at least one of three observatories: the two LIGO detectors in the United States and the Virgo detector in Italy. At once, algorithms automatically send us an alert through the Gamma-ray Coordinates Network (GCN). The network, originally envisioned to facilitate the search for GRB afterglows, does more than just inform us of a new detection; it also serves as a platform where astronomers promptly communicate their observations and results to the community.

The alert can catch you anywhere and anytime. Whether you are in a pub, on a leisurely Sunday morning walk, or fast asleep, you have to run to a computer and start compiling information. Is the gravitational wave signal strong and trustworthy? What was its likely progenitor? A binary black hole merger? There is a very small chance that such a merger produces a counterpart, perhaps we should just let it go. Is a neutron star involved? Now that is interesting! How well is its location known, and can it be promptly observed with any of the telescopes in our network? We infer all that from the initial alert, but soon additional information starts trickling in.

Position in the sky determines which telescope we trigger first. Smaller telescopes with large fields of view are useful to scan the localization area as quickly as possible, searching for bright transients. Large telescopes see much smaller portions of the sky, but they can find fainter objects. Instead of pointing them blindly at random patches, we use a shrewd scheme by targeting luminous and red galaxies, which are more likely to host mergers because their stellar populations are older.

We scrape through data in the search for transients. By comparing the positions of any we find to cataloged transients, we automatically identify, and discard, most of them. But many are new, and there is little else we can do but conduct additional observations to learn more about them. A few hours after the alert, tens of unidentified transients

Patiently, we proceed with our everyday lives until the sudden ringing of our phones **SETS THE HUNT IN MOTION**.

keep thousands of astronomers busy. Ideally, things calm down once somebody identifies the real counterpart, and then all the eyes and resources focus on that one source.

How Lucky Were We with GW170817?

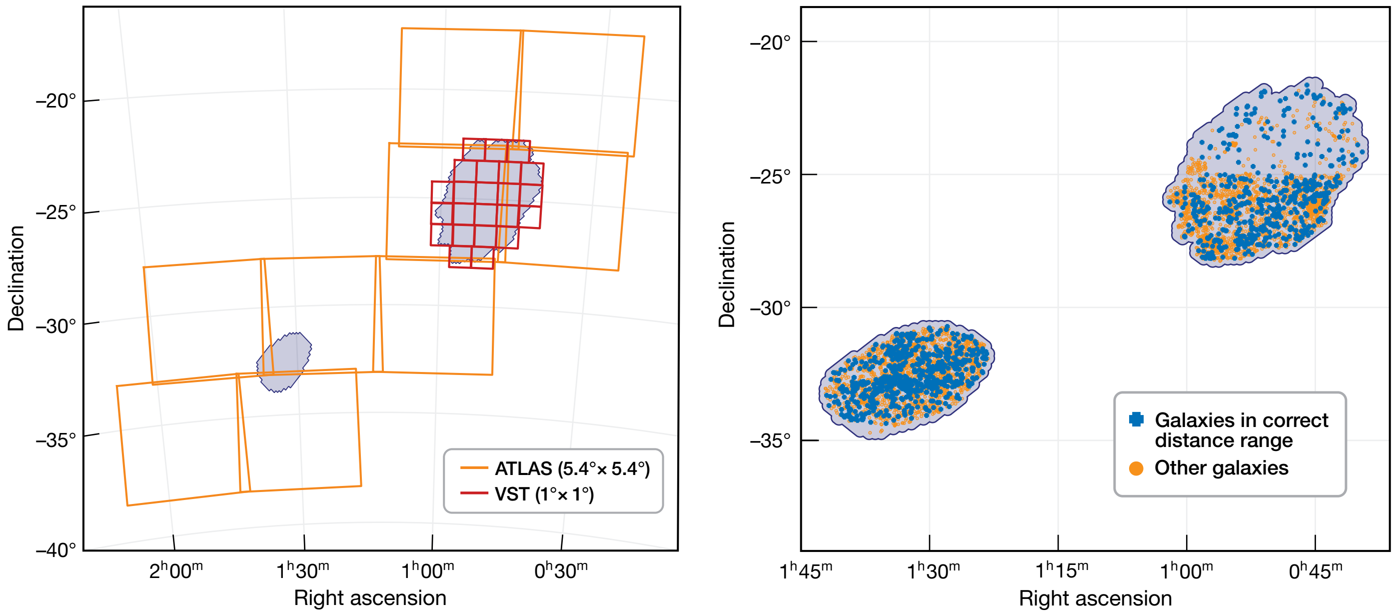
The LIGO and Virgo observatories carried out their third and most recent observational campaign between April 2019 and March 2020. As of late August 2021, scientists have published results on 41 new gravitational wave events, adding to the previous sample of 11. From the point of view of the gravitational wave community, the campaign was a phenomenal success. However, despite the formidable numbers, we haven't detected a single convincing electromagnetic counterpart to any of these mergers.

Two mergers seemed promising. GW190425 was very likely a binary neutron star merger, only the second one detected so far. But even if an electromagnetic counterpart existed, the bad localization and its considerable distance made for a challenging and ultimately unsuccessful search. GW190814 appeared to be more auspicious. The two compact objects involved in the merger were a 23-solar-mass black hole and a mysterious object of 2.6 solar masses that could have been either the most massive neutron star or the lightest black hole ever observed (*S&T:* Oct. 2020, p. 8).

The excellent localization made GW190814 a perfect target for ENGRAVE. With the Very Large Telescope and a fleet of smaller survey telescopes at our disposal, we launched

▲ **WORLDWIDE ENDEAVOR** GROWTH and ENGRAVE are two of many collaborations searching for flashes and afterglows from gravitational-wave events. Each network utilizes telescopes on the ground and in space.

ILLUSTRATION: LEAH TISCIONE / S&T; MAP: GREGG DINDERMAN / S&T



▲ **SKY SEARCH** *Left:* Estimates of where the merger GW190814 took place covered two patches of sky (purple, revised from initial announcement). Astronomers scoured the regions using several telescopes with different fields of view, two of which (near-Earth asteroid hunter ATLAS and the VLT Survey Telescope, or VST) are shown here. *Right:* The same regions, with all galaxies with spectroscopically determined distances in them marked.

K. ACKLEY ET AL. / *ASTRONOMY & ASTROPHYSICS* 2020

a thorough search campaign. For a week, we were pointing our telescopes from galaxy to galaxy in the hope of finding the counterpart. A few new transients kept us on our toes for several days. One transient detected in radio light gave us a thrill. Its unusual behavior even prompted us to observe it with the Hubble Space Telescope, a valuable resource not used lightly. But the more we looked at it, the less convinced we were. It was either a peculiar transient or an active galactic nucleus, but not the counterpart we were looking for. Alas, the search was in vain.

Follow-up of the first two unequivocal detections of NS–BH mergers, GW200115 and GW200105, did not fare much better. In fact, theorists predict that the neutron stars in all three of these mergers were pretty much swallowed whole — if counterparts existed, they must have been very faint.

Only now are we beginning to realize how lucky we were with GW170817. We detected the accompanying GRB because the jet was turned more or less towards us: It was a signpost screaming, "I'm here, come and find me!" The merger occurred only about 130 million light-years away, which is practically on our doorstep. This was the closest short GRB for which the distance has been measured, and such events are extremely rare. Most detected mergers occur much farther away; their counterparts are generally fainter and thus more difficult to detect.

Even though we were a bit disappointed about the outcome, we did get precious experience for the future. The diversity of the detected mergers fills Corsi with optimism. "Even though we haven't had another GW170817, we now have a sense of a tangible prospect for exploring some of the most puzzling inhabitants of the stellar graveyard," she says.

When the Trickle Becomes a Flood

New gravitational wave observatories will soon join the network. The first one will be KAGRA, an observatory built in the Kamioka mine in Japan. The combination of four detectors spread across the world will dramatically improve our ability to pinpoint future mergers. The typical localization area will improve to a few tens of square degrees, which is a factor of 10 or so better than the current values.

Each generation of detectors is also more sensitive, which ironically poses a challenge. The detectors will likely find more than 10 BNS and NS–BH mergers in the next observational cycle. But most will occur far away. Their electromagnetic counterparts will be even more elusive, and our resources will be spread thin with so many targets to follow up on.

"The challenge is that the trickle becomes a flood," says Levan. "The situation when you can throw every bit of resource you have at every object that comes along is going to go away very quickly."

Corsi points out that the progress in radio and optical instrumentation should continue in tandem with that of gravitational wave detectors. The competition between different research groups also needs to be replaced with cooperation. "It is my hope that at some point we can go after the huge sky map in a more efficient way. We don't want everyone looking at the same patch of the sky."

A search for transients is a game of chance: You play the cosmic roulette, and sometimes you hit the jackpot. But we know the rules of the game, and we are becoming pretty good at it. It is only a matter of time.

■ **JURE JAPELJ** is an astronomer and freelance science writer.

1 **DUSK:** Jupiter, Saturn, and Venus form a line above the south-southwestern horizon. Enjoy this view all month long.

4 **EVENING:** Algol shines at minimum brightness for roughly two hours centered at 11:49 p.m. PST (see page 50).

6 **DUSK:** Look toward the southwest to see the two-day-old Moon hanging some 2½° below Venus. Catch this pleasing pair before they set (turn to page 46 for more on this and other events listed here).

7 **DUSK:** The waxing crescent Moon is now around 5½° below Saturn.

7 **EVENING:** Algol shines at minimum brightness for roughly two hours centered at 8:38 p.m. PST (11:38 p.m. EST).

8 **DUSK:** The Moon, Jupiter, and Saturn form a triangle that graces the south-southwestern horizon.

10 **EVENING:** Algol shines at minimum brightness for roughly two hours centered at 8:27 p.m. EST.

14 **DAWN:** The Geminid meteor shower is expected to peak in the early morning hours (see page 49). The waxing gibbous Moon sets around 3 a.m. local time, after which viewing conditions will improve.

16 **EVENING:** Look high in the southeast to see the nearly full Moon in Taurus bracketed by the Pleiades and the Hyades.

21 **DAWN:** In the west, the waning gibbous Moon sits just shy of 3° from Gemini's brightest light, Pollux.

21 **THE LONGEST NIGHT OF THE YEAR** in the Northern Hemisphere. Winter begins at the solstice at 10:59 a.m. EST (7:59 a.m. PST).

22 **DAWN:** This morning the Moon has popped into Cancer and lies some 3° upper right of the Beehive Cluster (M44). Look high in the west-southwest.

27 **EVENING:** Algol shines at minimum brightness for roughly two hours centered at 10:22 p.m. PST.

28 **DAWN:** The waning crescent Moon shepherds Spica, in Virgo, as they climb in the south-southeast in brightening twilight; some 4½° separates the pair.

29 **DUSK:** Look toward the southwest after sunset to spot tiny Mercury and blazing Venus low above the horizon. Binoculars will enhance your view.

30 **EVENING:** Algol shines at minimum brightness for roughly two hours centered at 10:11 p.m. EST.

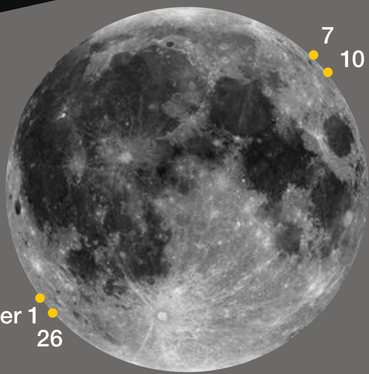
31 **DAWN:** Make sure you get up early on this last morning of the year to catch the delightful sight of the slender lunar crescent, Mars, and smoldering Antares arranged in an equilateral triangle in the southeast.

— DIANA HANNIKAINEN

▼ The Flaming Star Nebula, also known as IC 405, is a pretty sight in the constellation Auriga, the Charioteer. It's high in the sky on December evenings (go to page 22 for more winter targets). The 6th-magnitude star AE Aurigae, visible at lower right, lights up the nebula.

MAKIS PALAIOLOGOU / STEFAN BINNEWIES / JOSEF PÖPSEL / CAPELLA OBSERVATORY

DECEMBER 2021 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	31	

NEW MOON
December 4
07:43 UT

FIRST QUARTER
December 11
01:36 UT

FULL MOON
December 19
04:35 UT

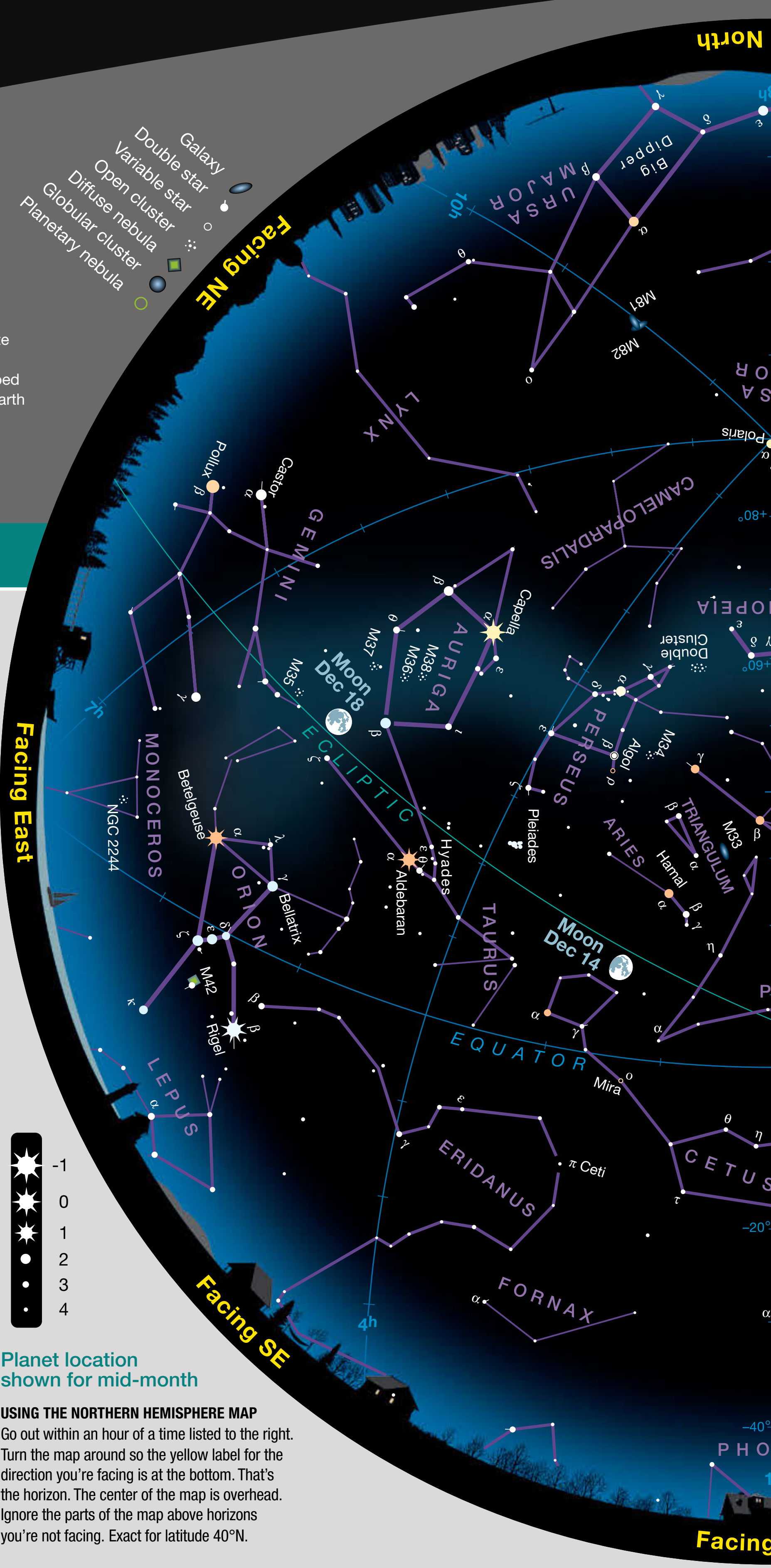
LAST QUARTER
December 27
02:24 UT

DISTANCES

Perigee	December 4, 10^h UT
356,794 km	Diameter 33′ 29″
Apogee	December 18, 02^h UT
406,320 km	Diameter 29′ 25″

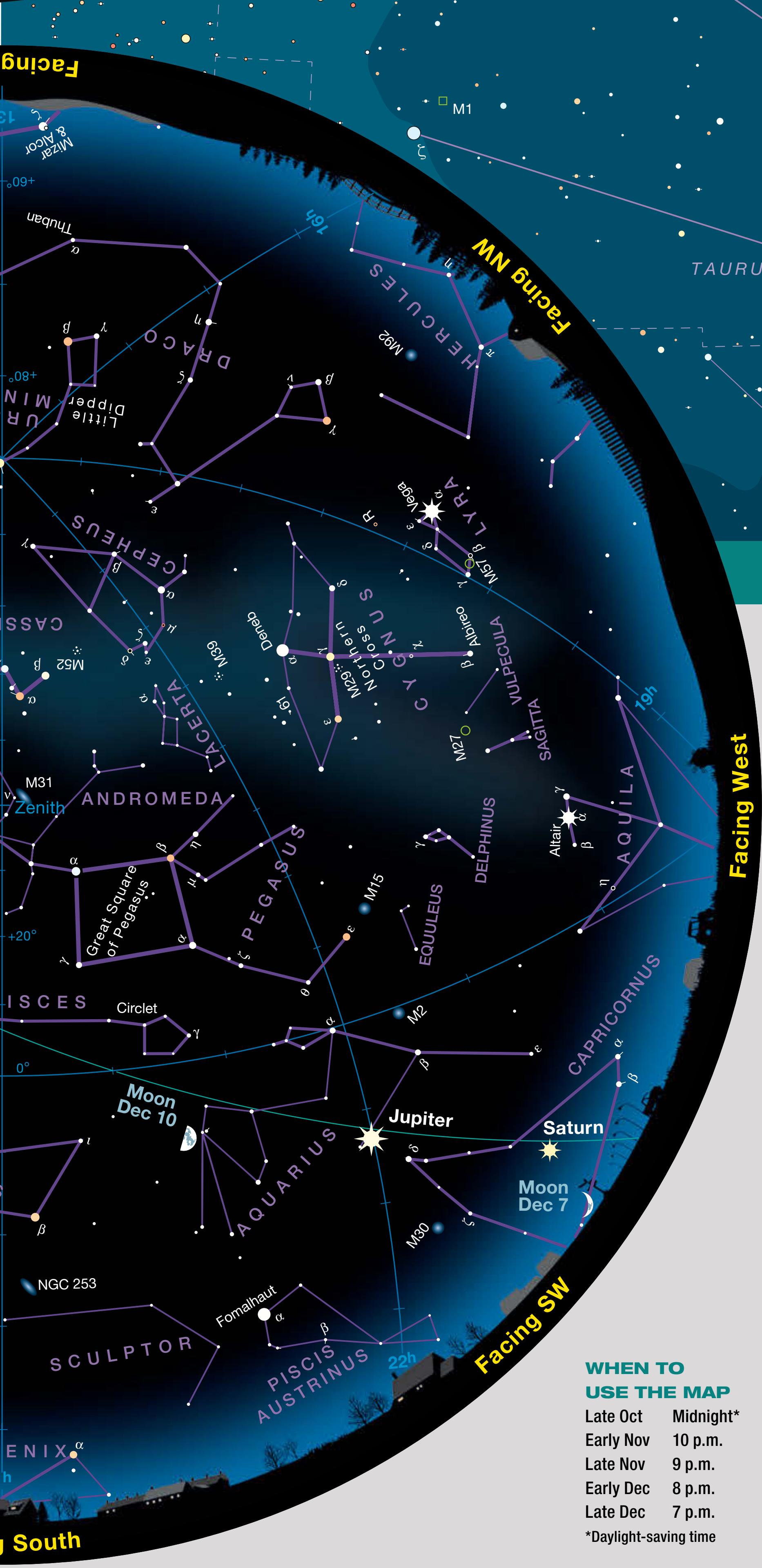
FAVORABLE LIBRATIONS

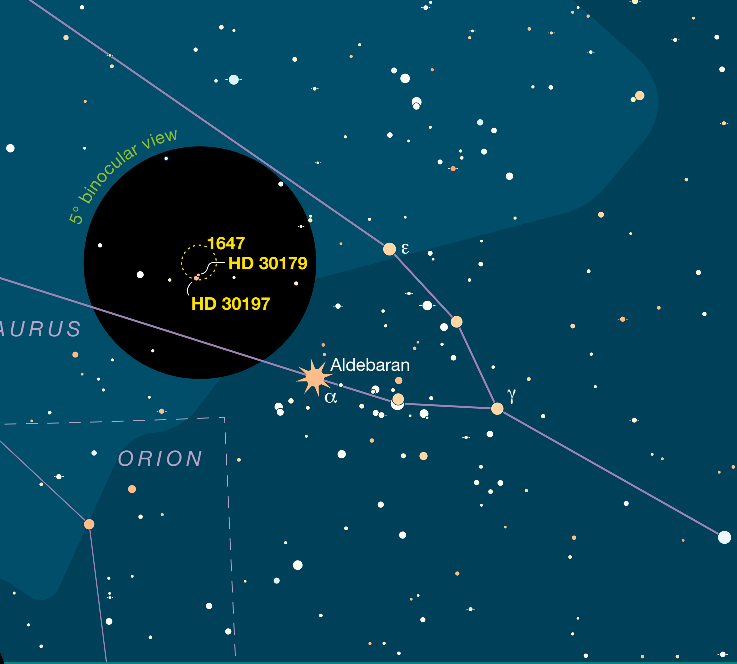
• Bouvard R Crater	December 1
• Zeno Crater	December 7
• Vashakidze Crater	December 10
• Graff Crater	December 26



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.





WHEN TO USE THE MAP

Late Oct	Midnight*
Early Nov	10 p.m.
Late Nov	9 p.m.
Early Dec	8 p.m.
Late Dec	7 p.m.

*Daylight-saving time

Binocular Highlight by Mathew Wedel

Jurassic Ark

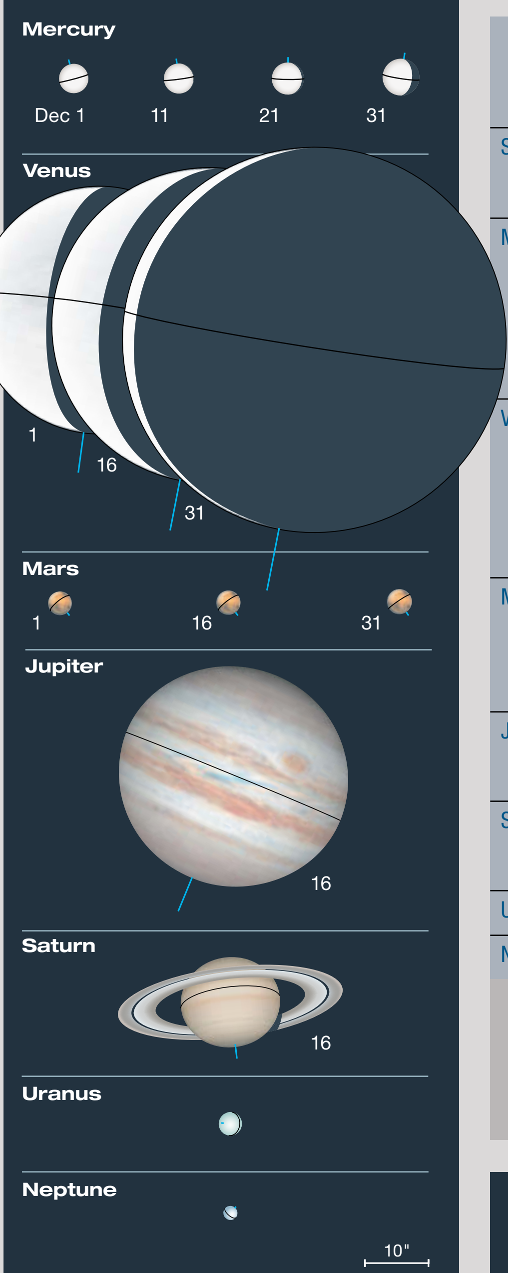
A favorite obsession of mine, both in this column and in my feature articles, is thinking about what was happening here on Earth when various celestial objects formed, or when their light began its journey earthward. It's especially nice when one of those times coincides with a period that I'm researching for my day job as a paleontologist. Which brings us to the open cluster NGC 1647 in the constellation Taurus.

NGC 1647 is located between the horns of the Bull, 3.5° northeast of Aldebaran, or Alpha (α) Tauri. With a magnitude of 6.4, the cluster is visible to the naked eye under clear, dark skies, and it's a wonderful object for binoculars. NGC 1647 contains about 200 stars in total, of which the brightest 30 or so shine at 9th magnitude and are visible in binoculars. My early notes record the cluster as a "vast swarm of faint stars," and I think that description holds up pretty well. On the south edge of the cluster you'll see a fine optical double star formed by HD 30197 and HD 30179. With a separation of 290″, these two *K*-type orange giants are wide enough to be easily split at any magnification.

Recent photometric studies peg the age of NGC 1647 at between 150 and 190 million years old, which means the cluster formed during Earth's Jurassic Period. 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.

■ The incorrigible **MATT WEDEL** will use any excuse to talk about dinosaurs, even in his astronomy column.

PLANET VISIBILITY (40°N, naked-eye, approximate) **Mercury** visible at dusk starting on the 25th • **Venus** shines brightly at dusk all month • **Mars** visible at dawn on all month • **Jupiter** culminates around sunset • **Saturn** visible at dusk and sets in the early evening.



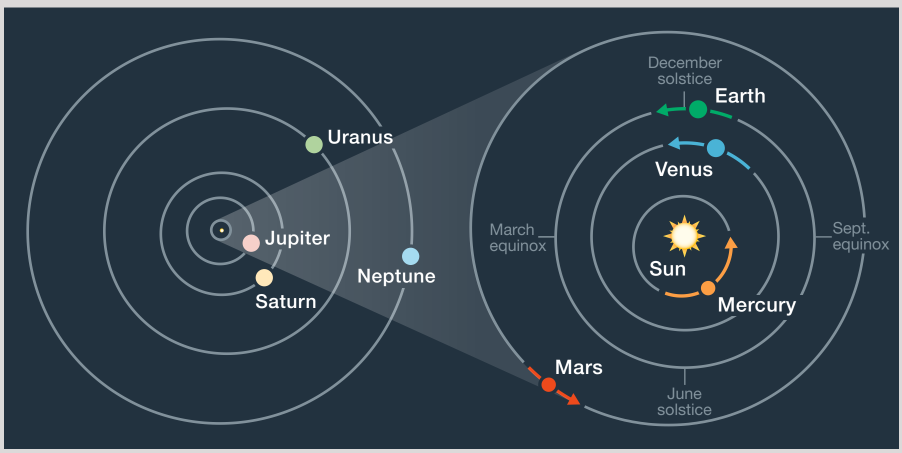
December Sun & Planets

	Date	Right Ascension	Declination	Elongation	Magnitude	Diameter	Illumination	Distance
Sun	1	$16^h\ 27.9^m$	–21° 45′	—	–26.8	32′ 26″	—	0.986
	31	$18^h\ 40.1^m$	–23° 07′	—	–26.8	32′ 32″	—	0.983
Mercury	1	$16^h\ 31.6^m$	–22° 48′	1° Ev	–1.3	4.6″	100%	1.451
	11	$17^h\ 39.6^m$	–25° 07′	7° Ev	–0.9	4.7″	98%	1.421
	21	$18^h\ 49.1^m$	–25° 10′	12° Ev	–0.7	5.1″	93%	1.329
	31	$19^h\ 55.4^m$	–22° 44′	17° Ev	–0.7	5.8″	80%	1.163
Venus	1	$19^h\ 29.3^m$	–24° 50′	42° Ev	–4.9	38.8″	29%	0.430
	11	$19^h\ 48.3^m$	–22° 52′	36° Ev	–4.9	45.6″	20%	0.366
	21	$19^h\ 52.5^m$	–20° 46′	27° Ev	–4.7	53.5″	11%	0.312
	31	$19^h\ 39.4^m$	–18° 49′	14° Ev	–4.3	60.4″	3%	0.276
Mars	1	$15^h\ 14.8^m$	–17° 51′	18° Mo	+1.6	3.8″	99%	2.486
	16	$15^h\ 57.6^m$	–20° 25′	22° Mo	+1.6	3.9″	99%	2.421
	31	$16^h\ 42.3^m$	–22° 21′	27° Mo	+1.5	4.0″	98%	2.346
Jupiter	1	$21^h\ 50.9^m$	–14° 09′	76° Ev	–2.3	38.4″	99%	5.139
	31	$22^h\ 10.0^m$	–12° 23′	51° Ev	–2.1	35.5″	99%	5.555
Saturn	1	$20^h\ 45.3^m$	–18° 53′	60° Ev	+0.7	16.0″	100%	10.383
	31	$20^h\ 56.8^m$	–18° 07′	32° Ev	+0.7	15.5″	100%	10.737
Uranus	16	$2^h\ 34.8^m$	+14° 44′	137° Ev	+5.7	3.7″	100%	18.993
Neptune	16	$23^h\ 25.6^m$	–4° 57′	86° Ev	+7.9	2.3″	100%	29.969

The table above gives each object's right ascension and declination (equinox 2000.0) at 0^h 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.

▲ **PLANET DISKS** have south up, to match the view in many telescopes. Blue ticks indicate the pole currently tilted toward Earth.

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



Seeing the Seven Sisters

One of the sky's finest open clusters has quite a tale to tell.

▲ **ALL THAT GLITTERS** The stars of the Pleiades cluster are moving through space together and passing through a cloud of dust, creating the picturesque haze surrounding the brightest Pleiads in this photo by Alan Dyer.

The Pleiades, or the Seven Sisters as they're also called, is more than just the loveliest star cluster for naked-eye observers. The sight is so distinctive that it has been mentioned in countless legends and great literature throughout history, and it has even appeared in modern advertising.

About two millennia ago, the Druids used the date of the cluster's sunset rising to mark the beginning of their year and the Celtic holiday Samhain, which later evolved into Halloween ("All Hallows' evening"). You may be reading this column around Halloween, but whenever the Pleiades are above the horizon you should have little trouble finding them — so long as your sky isn't washed out by urban light pollution, bright moonlight, or both!

The Pleiades are shown high above the eastern horizon on the Sky Chart presented on pages 42 and 43, which depicts the evening sky at different times from late October to the end of December. At the chart times given, the cluster floats directly above orange Aldebaran and the Hyades — all three sights residing in the constellation Taurus, the celestial Bull. Below Taurus is the low, tilted form of brilliant Orion, with its conspicuous three-star Belt spanning 3°. But unlike the Belt asterism, the Pleiades are a true cluster of stars gravitationally bound to each other as they travel through space.

How far away are the Pleiades? Back in 2009, the International Year of Astronomy commemorated the 400th anniversary of the year Galileo first aimed his telescope skyward. In 2009, estimates pegged the cluster's distance at 400 light-years — a coincidence I took advantage of when I showed the Pleiades to the public. I was able to tell them that the light they were seeing began its journey in 1609, as Galileo was making his monumental observations, Kepler was publishing his first two laws of planetary motion, and Shakespeare was nearing the end of his brilliant career. Now, in 2021, the latest research places the cluster a little farther away, at 446 light-years (see *S&T:* Mar. 2019, p. 26).

The cluster represents the Seven Sisters of Greek mythology, and is so lovely and delicate that it's associated in legends with maidens, doves, or even a mother hen with its brood of chicks. The geometric shape formed by the cluster's brightest stars is most often pictured as a tiny Dipper — a design that will be especially familiar to owners of Subaru cars.

The number of naked-eye Pleiads visible to the person with average eyesight under average sky conditions *may* be seven, but is more likely to be just six. This disparity has led to the legend of "the Lost Pleiad." In his poem "The Good Night" the 19th-century English writer Alfred Austin alluded to the missing star in his beautiful lines, "The Sister Stars that once were seven/Mourn for their missing mate in Heaven."

Part of the reason some observers see fewer than seven stars is the tight pairings of several cluster members. For instance, the stars of the tiny dipper's handle, named for the Seven Sisters' parents, Atlas and Pleione, shine at magnitudes 3.6 and 5.1 but are only about 5′ apart. The bowl of the tiny dipper is formed by stars named for the individual Sisters. Working counterclockwise from 2.8-magnitude Alcyone (the brightest Pleiad) they are: Merope, Electra, Celaeno, Taygeta, Maia, and Asterope, which is a wide double star just north of Maia.

A total of nine Pleiades stars are magnitude 5.6 or brighter, but under excellent sky conditions careful observers can observe several more without resorting to optical aid. The eagle-eyed Stephen James O'Meara has seen 17 Pleiads, and the record is held by the great Walter Scott Houston, who counted 18.

■ **FRED SCHAAF** was able to glimpse 12 individual Pleiads with the unaided eye in his youth.

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

A Big Month for a Small Moon

The year wraps up with a little lunar excitement.

MONDAY, DECEMBER 6

The **Moon** has an eventful month, kicking off this evening with a close encounter with **Venus**. As twilight begins to fade, a thin, earthlit lunar crescent sits about 2½° below left of the brilliant Evening Star. Venus reached its "maximum brilliance" just two days earlier, when it maxed out at magnitude –4.9 — not that its magnitude changes very quickly. So, if you go out and look at Venus and it *seems* brighter than usual, what you're really experiencing is something called *confirmation bias*. Still, there's no denying the planet gleams impressively!

Enjoy Venus while you can, though, because its reign as Evening Star is nearing the end. Throughout December Venus rapidly loses altitude — on the 1st, it sets nearly 3 hours after the Sun, but by the 31st, the gap has closed to a little more than one hour.

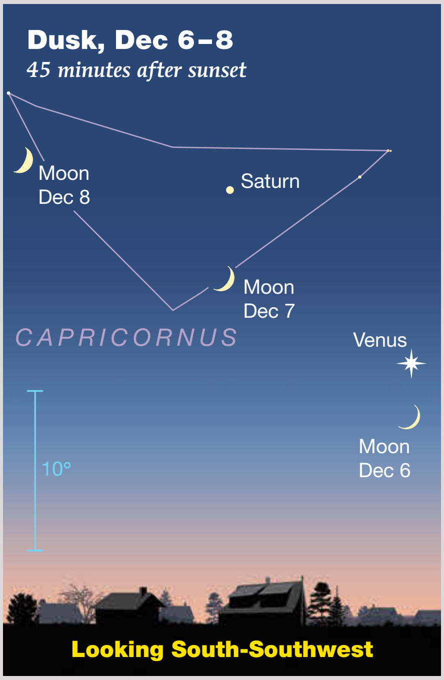
SATURDAY, DECEMBER 18

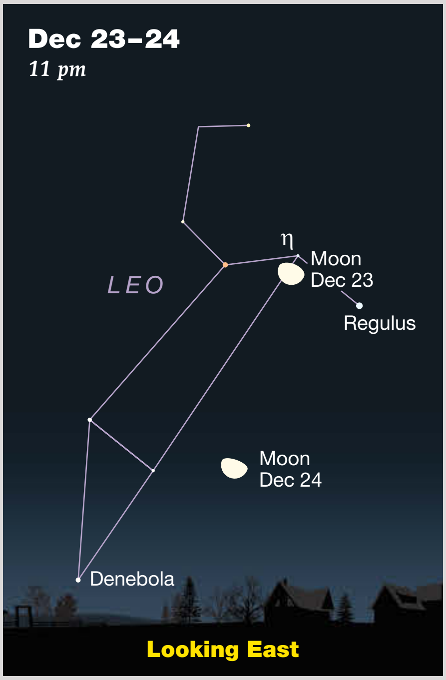
The **Moon** is full tonight at 11:35 p.m. EST. A full Moon is a reliably enjoyable sight — especially when it shines down on a snow-covered landscape. But there are two factors that make this month's full Moon a bit special. First, it occurs just 27 hours after *apogee* — the most distant point in the Moon's elliptical orbit around Earth. Indeed, at a distance of 406,320 km (252,476 miles) this is the Moon's second most distant apogee all year. (The Moon was slightly farther on May 11th, but it was in conjunction with the Sun at the time and thus unobservable.) Thanks to its relatively great distance, we get the smallest full Moon of 2021. Not that that's a "thing," really. Sometimes referred to as a "micromoon," an apogean full Moon is the opposite of its "supermoon" perigean cousin.

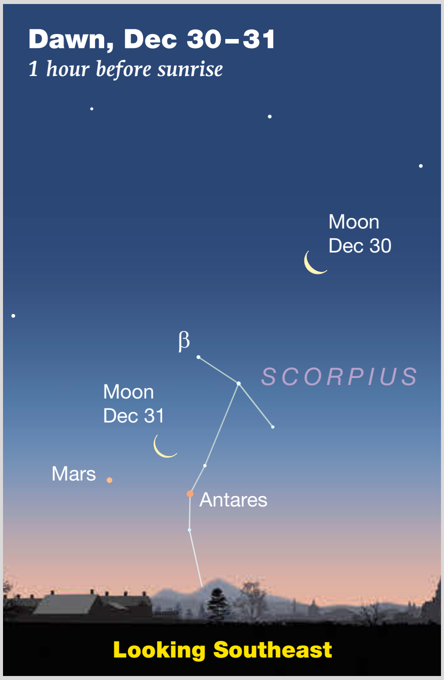
This month's full Moon is also the one that falls closest to the winter solstice. That means the lunar disk is found near the northernmost point on the ecliptic, in Taurus near the Gemini border — just a few degrees from where the Sun will be next June on the solstice. You might notice that the bold shadows cast by the full Moon on this night are short and bring to mind mild summer afternoons even though we're really on the icy cusp of winter.

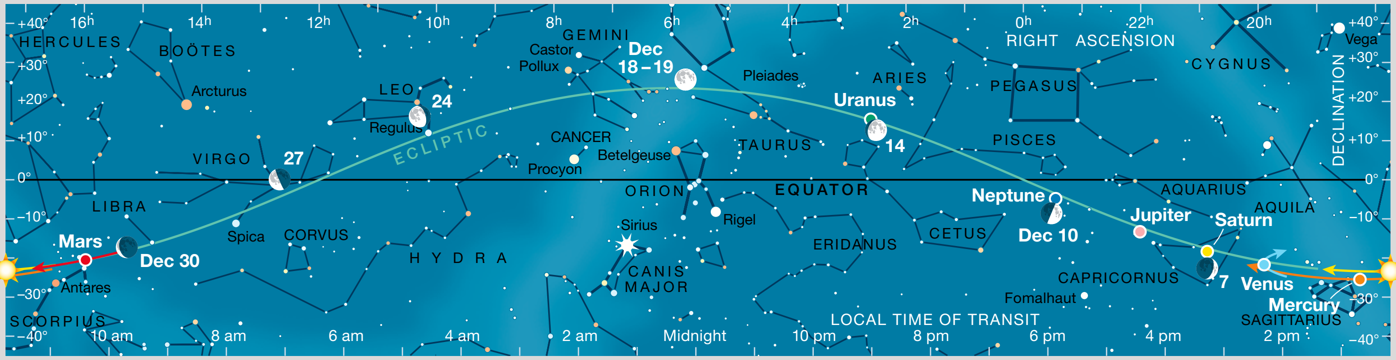
THURSDAY, DECEMBER 23

Late this evening as the waning gibbous **Moon** rises, it's positioned about 4½° above left of **Regulus**, Leo's brightest





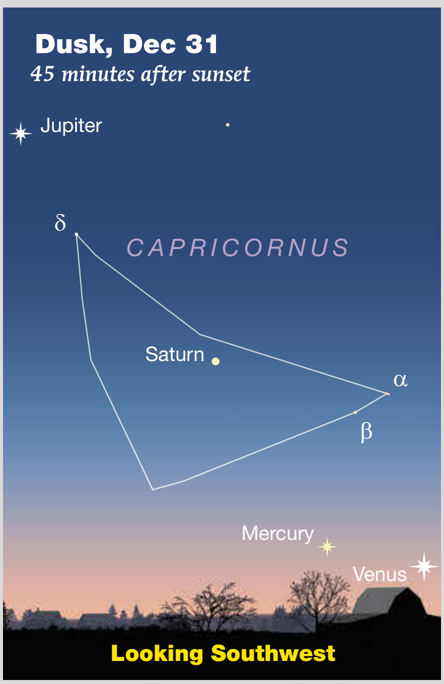




▲ The Sun and planets are positioned for mid-December; the colored arrows show the motion of each during the month. The Moon is plotted for evening dates in the Americas when it's waxing (right side illuminated) or full, and for morning dates when it's waning (left side illuminated). "Local time of transit" 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.

light. That's close enough that both objects can be seen together in the field of view provided by ordinary binoculars. Interesting, sure. But worth braving the chill air of a December night? Perhaps not. However, your binos or (even better) a small telescope might reveal a bonus event. Look closely, and if your timing is right, you may catch the glint of 3.5-magnitude Eta (η) Leonis hovering just off the dark lunar limb.

The specifics of what you have a chance to see depend on where you are. Skywatchers on the East Coast get to witness a complete occultation. They'll see the Moon's bright edge covering Eta, and then later witness the star pop out from behind the dark limb. For observers in New York City, for example, the stellar eclipse begins at 9:50 p.m. EST and wraps up at 10:52 p.m. People at locations in the central part of the continent will miss the coverup but will catch the star's reemergence. From Des Moines, Iowa, Eta's return occurs at about 9:48 p.m. CST. For those in the western half of the U.S. and Canada, you'll just get to see the star attractively positioned to the right of the lunar disk.



TUESDAY, DECEMBER 28

At last, here's an event that has nothing to do with the Moon. Instead, we can appreciate the rise and fall of the two innermost planets. The one gaining elevation is **Mercury**, and the one losing ground is **Venus**. At dusk today they're at their closest. The two planets will be separated by roughly 4¼° but are worlds apart when it comes to brightness — Mercury shines at magnitude –0.7, but Venus is 33 times brighter, at magnitude –4.5. If you're struggling to find Mercury, simply wait a couple of nights. On the 30th and 31st, its elevation will match that of Venus, though they'll be farther apart than on the 28th. This is the last notable event of Venus's current evening apparition. Indeed, this might be one of the last times you see it for a while. Venus is in conjunction with the Sun on January 9th, soon after which it reappears at dawn in its guise as the Morning Star.

◀ 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 blue 10° scale bar is about the width of your fist at arm's length. For clarity, the Moon is shown three times its actual apparent size.

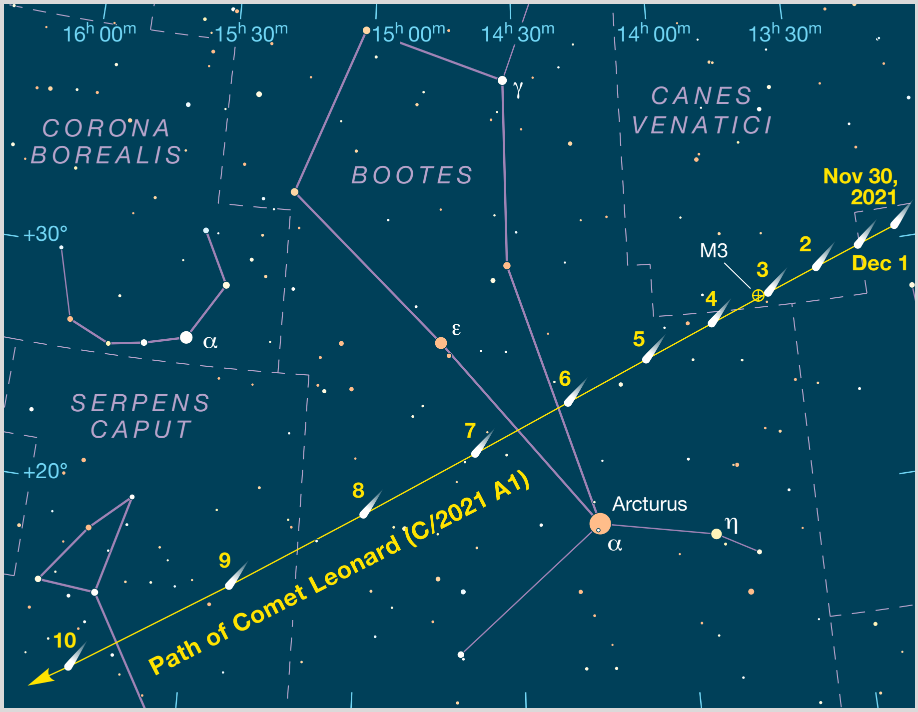
FRIDAY, DECEMBER 31

Try getting up early to make the most of the final day of 2021. Your efforts will be amply rewarded with a pretty dawn conjunction featuring the **Moon** (of course), **Mars**, and **Antares**. The trio form a pleasingly symmetrical triangle in the southeast during morning twilight, with the thin lunar crescent sitting some 3½° from Mars and about 3° from Antares. The Red Planet, still fresh from its October solar conjunction, shines at a relatively faint magnitude 1.5. That's slightly dimmer than nearby Antares, but as the planet's apparition progresses, it will slowly brighten. (The next Mars opposition doesn't occur until December 2022.) By mid-April, Mars should be a good match for 1st-magnitude Antares, but by then the planet's eastward drift will have carried it far from the star and into the constellation Aquarius. For now, you can appreciate their similar hues while the peachy pair are near each other. You can also see why the name Antares means "like Ares" in ancient Greek, remembering that Greek Ares = Roman Mars.

■ Consulting Editor **GARY SERONIK** enjoys each and every full Moon — even the small ones.

Comet Leonard Races Across the Sky

This fast-moving visitor may prove to be the best object of its kind in more than a year.

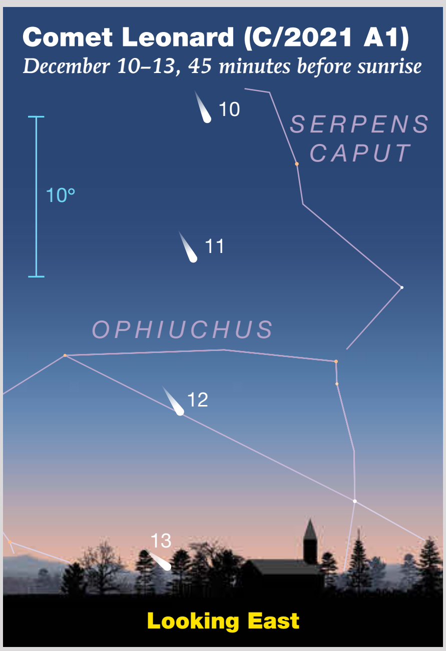


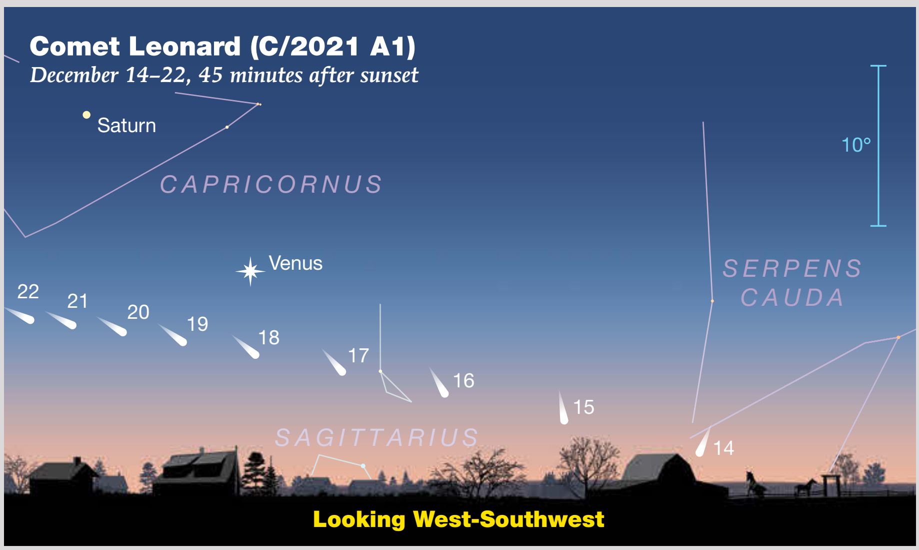
▲ As December begins, Comet Leonard is in Canes Venatici. It will be near the bright globular cluster M3 on the mornings of December 2nd and 3rd, as seen from North America. (The comet's positions are plotted for 0^h UT.)

Many of us have been living off the fumes from Comet NEOWISE (C/2020 F3) in anticipation of the next bright comet. That opportunity will hopefully present itself in December when Comet Leonard (C/2021 A1) could brighten to naked-eye prominence. Astronomer Gregory J. Leonard at the Mount Lemmon Observatory near Tucson, Arizona, discovered the comet exactly one year before perihelion on January 3, 2021, when it was at 19th magnitude.

With any luck the comet might reach magnitude 6.5 in Canes Venatici at the start of morning twilight as the month opens. Leonard then races through Boötes and Serpens where it could become a fine binocular object as it peaks around 4th magnitude during its closest approach to Earth on December 12th. Unfortunately, that's also around the time the comet will lose its battle with bright morning twilight.

Of course, predicting a comet's





brightness is a notoriously tricky business beset with uncertainty. As comet expert Alan Hale notes, "The good news is that it comes close to Earth and will be appearing at a high phase angle, and if it has a reasonably high dust content there could be quite a bit of enhancement due to forward scattering."

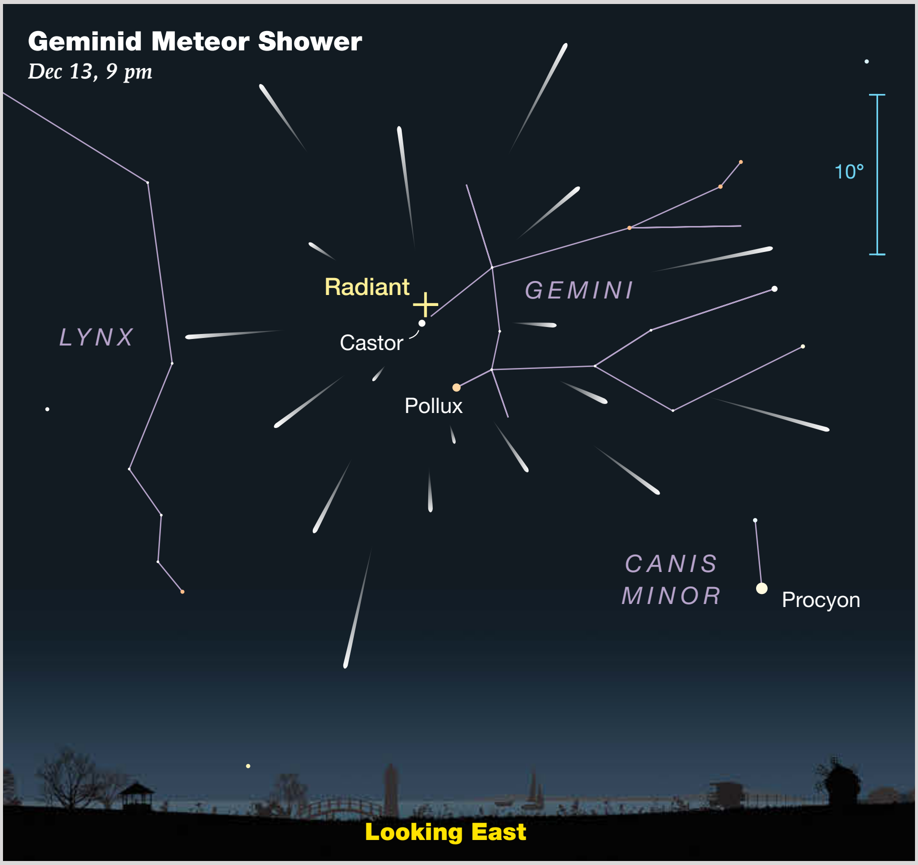
Forward scattering (or *backlighting*) makes dust glow brightly when seen in the same direction as the Sun. However, since most comets don't release the bulk of their dust until after perihelion (which occurs several weeks following Leonard's closest approach to Earth), Hale advises us to temper our expectations.

After December 12th, the comet departs the dawn and pops up low in the southwestern sky after sundown. And it's moving at lightning speed! Between December 12th and 13th, it covers nearly 10° of sky, as it traces a shallow arc across the southwest from Ophiuchus into Sagittarius.

Observers at mid-northern latitudes will struggle to coax Leonard from twilight's glow until later in the month. Near the end of twilight on the 22nd, the comet will shine at 5th magnitude and stand about 5° above the southwestern horizon. It loses another magnitude by month's end as it ducks into Piscis Austrinus.

Highlights of Comet Leonard's apparition include a flyby of the 6.3-magnitude globular cluster M3 on the mornings of December 2nd and 3rd, and at dusk on the 17th the comet sits 5° below Venus. Moonless skies prevail in the morning hours from the 2nd through to the 13th, and in the early evening starting around the 21st.

Comet Leonard may seem in a hurry right now, but it took its sweet time getting here. Aphelion occurred about 35,000 years ago at a distance of 3,500 a.u. Its current visit to the inner solar system has essentially spanned most of modern human history. When the comet next returns, the world will surely have changed beyond recognition.



The Geminids Cup Half Full

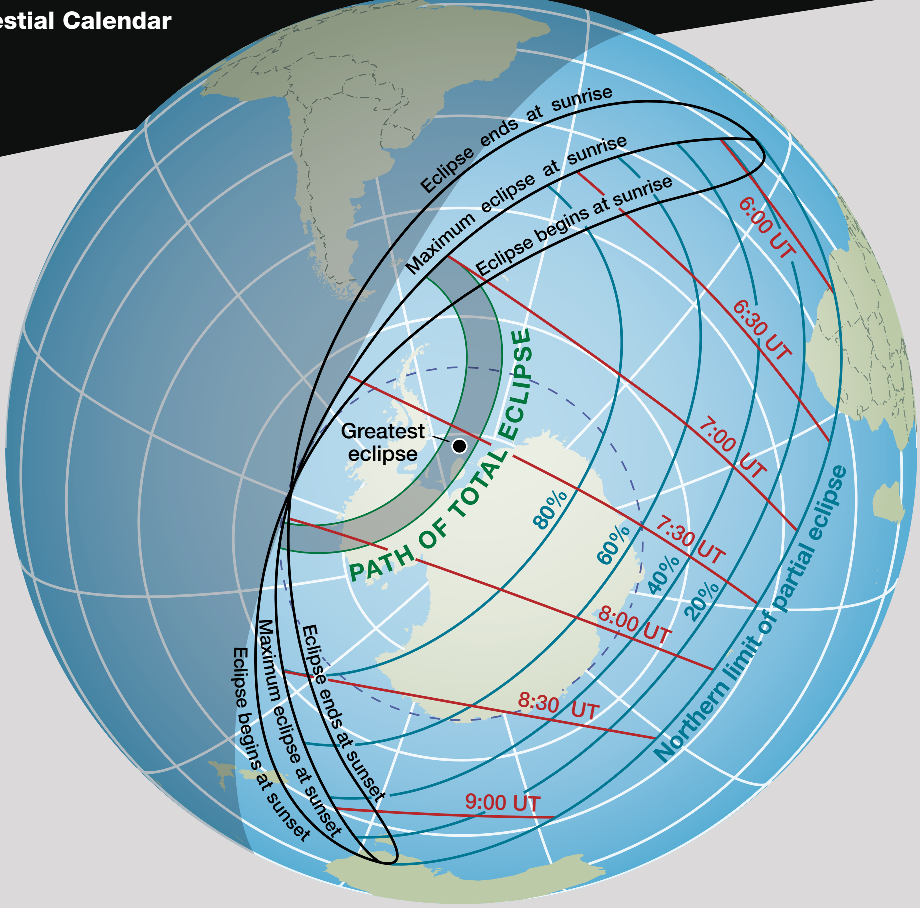
THE STRONGEST ANNUAL meteor shower of the year, the Geminids, peak at 7:00 UT (2 a.m. EST) on December 14th. If you observe after the Moon sets (at around 3 a.m. local time), you might see up to 150 meteors per hour from a dark, rural location and perhaps 30–50 per hour under suburban light pollution.

The shower derives from dust and debris spalled from asteroid 3200 Phaethon during its close approach to the Sun every 1.4 years. Geminids enter the atmosphere at 35 kilometers per second (that's nearly 80,000 miles per hour) — slow enough that they typically don't produce long-lasting ionization trails.

As shown in the chart above, the radiant is located about 2° northwest of Castor and stands 30° high around 9 p.m. local time. Unfortunately, the Moon will be about 77% full and seriously degrade the shower for much of the night. However, if you wait until moonset, you'll have about three hours of darkness before the start of morning twilight. At that time, Gemini will be off to the west and in good view.

Dress warmly, have a hot beverage at the ready, unfold your chaise lounge, and enjoy the display. During lulls in meteor activity, you can always take a few moments to appreciate the brilliant constellations of the winter sky as they sink toward the western horizon.

▲ Dean Rowe photographed this spectacular and colorful Geminid fireball during the 2018 display. Meteor colors are produced when air heats and ionizes atoms from the incoming meteoroid. Each atom emits a characteristic color: Oxygen glows green at the start of the meteor trail, followed farther down by green-glowing magnesium. Calcium lights up purple, and red originates from oxygen and nitrogen in the air itself.



▲ During the early morning hours of December 4th, the Moon's shadow sweeps across the Southern Ocean, South Orkney Islands, and Antarctica. Unlike most eclipses where the shadow moves from west to east, this one will travel from east to west. Touchdown occurs about 500 kilometers southeast of the Falkland Islands. Greatest eclipse of 1 minute 54 seconds occurs just off the coast of Berkner Island in the Weddell Sea at 7:33 UT.

Minima of Algol

Nov.	UT	Dec.	UT
6	15:39	2	11:00
9	12:28	5	7:49
12	9:16	8	4:38
15	6:05	11	1:27
18	2:54	13	22:16
20	23:43	16	19:05
23	20:32	19	15:54
26	17:21	22	12:44
29	14:11	25	9:33
		28	6:22
		31	3:11

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 is approaching the zenith on chilly December evenings. Every 2.7 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

AS DECEMBER GETS UNDERWAY, Jupiter transits the meridian roughly half an hour after sunset and sets late in the evening. That means, the earlier you look, the better the telescopic views should be. On the 1st of the month, the gas giant shines at magnitude –2.3 and presents a disk 38″ across.

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 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 Standard Time is UT minus 5 hours.)

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

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

GREGG DINDERMAN / S&T, SOURCE: FRED ESPENAK

23: 0:03, 09:59, 19:54; **24**: 5:51, 15:46; **25**: 1:42, 11:38, 21:34; **26**: 7:30, 17:25; **27**: 3:21, 13:17, 23:13; **28**: 9:09, 19:05; **29**: 5:01, 14:56; **30**: 0:52, 10:48, 20:44; **31**: 6:40, 16:36

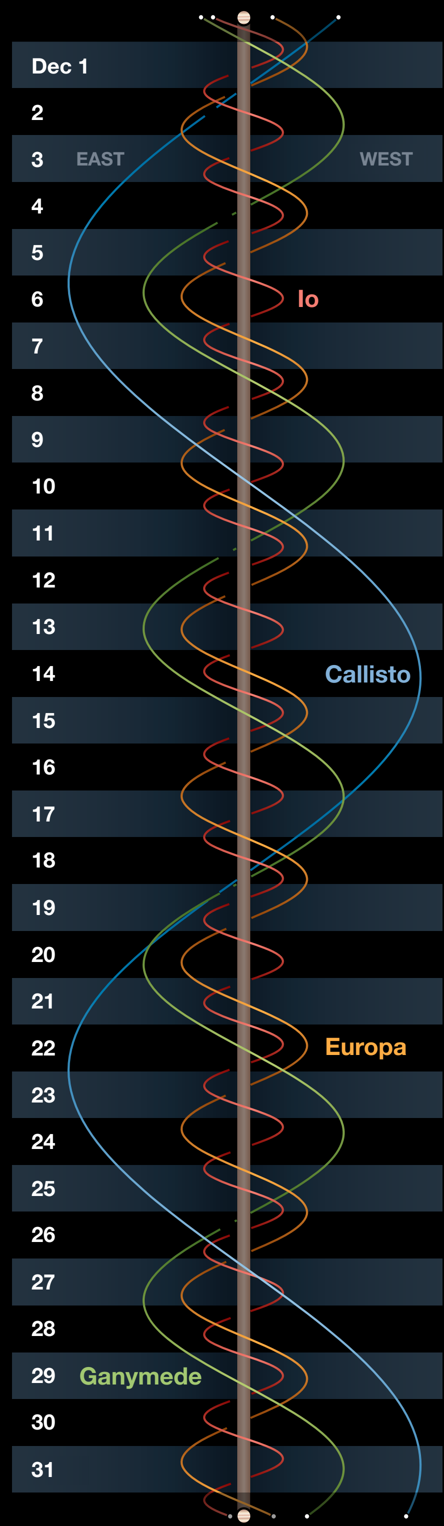
These times assume that the spot will be centered at System II longitude 10° on December 1st. If the Red Spot has moved elsewhere, it will transit 1⅔ minutes earlier for each degree less than 10° and 1⅔ minutes later for each degree more than 10°.

Phenomena of Jupiter's Moons, December 2021

Date	Time	Event
Dec. 1	1:27	III.Tr.E
	3:10	III.Sh.I
	6:40	III.Sh.E
	13:36	I.Oc.D
	17:11	I.Ec.R
	21:37	IV.Oc.D
	22:48	II.Oc.D
Dec. 2	2:13	IV.Oc.R
	4:15	II.Ec.R
	9:59	IV.Ec.D
	10:59	I.Tr.I
	12:15	I.Sh.I
	13:15	I.Tr.E
	14:08	IV.Ec.R
	14:31	I.Sh.E
Dec. 3	8:06	I.Oc.D
	11:40	I.Ec.R
	17:00	II.Tr.I
	19:35	II.Sh.I
	19:50	II.Tr.E
	22:23	II.Sh.E
Dec. 4	5:28	I.Tr.I
	6:44	I.Sh.I
	7:45	I.Tr.E
	9:00	I.Sh.E
	11:53	III.Oc.D
	15:31	III.Oc.R
	17:07	III.Ec.D
	20:39	III.Ec.R
Dec. 5	2:35	I.Oc.D
	6:09	I.Ec.R
	12:10	II.Oc.D
	17:34	II.Ec.R
	23:58	I.Tr.I
Dec. 6	1:13	I.Sh.I
	2:14	I.Tr.E
	3:29	I.Sh.E
	21:05	I.Oc.D
Dec. 7	0:38	I.Ec.R
	6:22	II.Tr.I
	8:54	II.Sh.I
	9:12	II.Tr.E
	11:41	II.Sh.E
	18:27	I.Tr.I
	19:42	I.Sh.I
	20:44	I.Tr.E
	21:58	I.Sh.E
Dec. 8	2:04	III.Tr.I
	5:40	III.Tr.E
	7:12	III.Sh.I
	10:42	III.Sh.E
	15:34	I.Oc.D
	19:07	I.Ec.R
Dec. 9	1:31	II.Oc.D
	6:53	II.Ec.R
	12:57	I.Tr.I
	14:11	I.Sh.I
	15:14	I.Tr.E
	16:27	I.Sh.E
Dec. 10	6:03	IV.Tr.I
	10:04	I.Oc.D
	10:38	IV.Tr.E
	13:36	I.Ec.R
	18:11	IV.Sh.I
	19:43	II.Tr.I
	22:13	II.Sh.I
	22:16	IV.Sh.E
	22:33	II.Tr.E
Dec. 11	1:00	II.Sh.E
	7:27	I.Tr.I
	8:40	I.Sh.I
	9:43	I.Tr.E
	10:56	I.Sh.E
	16:08	III.Oc.D
	19:45	III.Oc.R
	21:09	III.Ec.D
Dec. 12	0:40	III.Ec.R
	4:34	I.Oc.D
	8:05	I.Ec.R
	14:53	II.Oc.D
	20:11	II.Ec.R
Dec. 13	1:56	I.Tr.I
	3:09	I.Sh.I
	4:13	I.Tr.E
	5:25	I.Sh.E
	23:03	I.Oc.D
Dec. 14	2:34	I.Ec.R
	9:05	II.Tr.I
	11:32	II.Sh.I
	11:56	II.Tr.E
	14:19	II.Sh.E
	20:26	I.Tr.I
	21:38	I.Sh.I
	22:43	I.Tr.E
	23:54	I.Sh.E
Dec. 15	6:20	III.Tr.I
	9:56	III.Tr.E
	11:14	III.Sh.I
	14:44	III.Sh.E
	17:33	I.Oc.D
	21:03	I.Ec.R
Dec. 16	4:16	II.Oc.D
	9:29	II.Ec.R
	14:56	I.Tr.I
	16:07	I.Sh.I
	17:13	I.Tr.E
	18:23	I.Sh.E
Dec. 17	12:03	I.Oc.D
	15:32	I.Ec.R
	22:28	II.Tr.I
Dec. 18	0:50	II.Sh.I
	1:18	II.Tr.E
	3:37	II.Sh.E
	9:26	I.Tr.I
	10:36	I.Sh.I
	11:43	I.Tr.E
	12:51	I.Sh.E
	17:04	IV.Oc.D
	20:25	III.Oc.D
	21:38	IV.Oc.R
Dec. 19	0:02	III.Oc.R
	1:10	III.Ec.D
	4:16	IV.Ec.D
	4:41	III.Ec.R
	6:33	I.Oc.D
	8:19	IV.Ec.R
	10:01	I.Ec.R
	17:39	II.Oc.D
	22:48	II.Ec.R
Dec. 20	3:56	I.Tr.I
	5:04	I.Sh.I
	6:13	I.Tr.E
	7:20	I.Sh.E
Dec. 21	1:03	I.Oc.D
	4:29	I.Ec.R
	11:51	II.Tr.I
	14:09	II.Sh.I
	14:41	II.Tr.E
	16:57	II.Sh.E
	22:26	I.Tr.I
	23:33	I.Sh.I
Dec. 22	0:42	I.Tr.E
	1:49	I.Sh.E
	10:39	III.Tr.I
	14:15	III.Tr.E
	15:17	III.Sh.I
	18:47	III.Sh.E
	19:33	I.Oc.D
	22:58	I.Ec.R
Dec. 23	7:02	II.Oc.D
	12:06	II.Ec.R
	16:56	I.Tr.I
	18:02	I.Sh.I
	19:12	I.Tr.E
	20:18	I.Sh.E
Dec. 24	14:03	I.Oc.D
	17:27	I.Ec.R
Dec. 25	1:14	II.Tr.I
	3:28	II.Sh.I
	4:04	II.Tr.E
	6:15	II.Sh.E
	11:26	I.Tr.I
	12:31	I.Sh.I
	13:42	I.Tr.E
	14:47	I.Sh.E
Dec. 26	0:44	III.Oc.D
	4:21	III.Oc.R
	5:12	III.Ec.D
	8:33	I.Oc.D
	8:42	III.Ec.R
	11:56	I.Ec.R
	20:25	II.Oc.D
Dec. 27	1:24	II.Ec.R
	1:54	IV.Tr.I
	5:56	I.Tr.I
	6:25	IV.Tr.E
	7:00	I.Sh.I
	8:13	I.Tr.E
	9:16	I.Sh.E
	12:31	IV.Sh.I
	16:29	IV.Sh.E
Dec. 28	3:03	I.Oc.D
	6:25	I.Ec.R
	14:38	II.Tr.I
	16:47	II.Sh.I
	17:28	II.Tr.E
	19:34	II.Sh.E
Dec. 29	0:26	I.Tr.I
	1:29	I.Sh.I
	2:43	I.Tr.E
	3:45	I.Sh.E
	15:01	III.Tr.I
	18:37	III.Tr.E
	19:20	III.Sh.I
	21:33	I.Oc.D
	22:48	III.Sh.E
Dec. 30	0:54	I.Ec.R
	9:49	II.Oc.D
	14:43	II.Ec.R
	18:56	I.Tr.I
	19:58	I.Sh.I
	21:13	I.Tr.E
	22:14	I.Sh.E
Dec. 31	16:04	I.Oc.D
	19:23	I.Ec.R

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 4 hours ahead of Eastern Daylight 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.

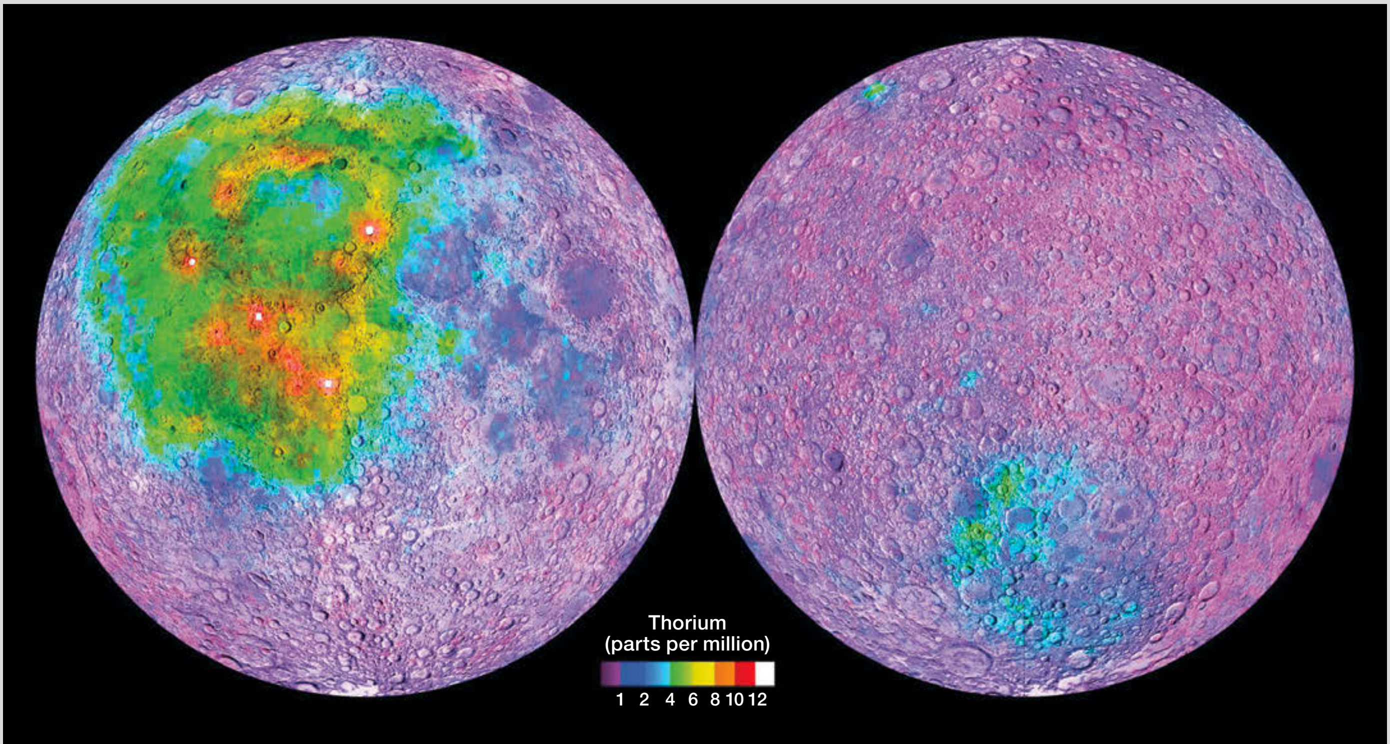
KREEPy Rocks and Terrane

Understanding the Moon requires looking beyond the visible.

The Procellarum KREEP Terrane (PKT) is a 21-year-old discovery that is critical to our modern understanding of the Moon but is hardly known to amateur astronomers. Up until the spacecraft era, our knowledge of lunar geology depended on visual observations and photographs of the lunar surface. Although these are still powerful and important tools, discoveries made using ultra-high-resolution images and the flood of new data from beyond the visible spectrum produced by a host of spacecraft have radically changed what we once thought we knew. A single map can longer depict everything we can glean about our nearest neighbor — that requires the integration of data across multiple disciplines.

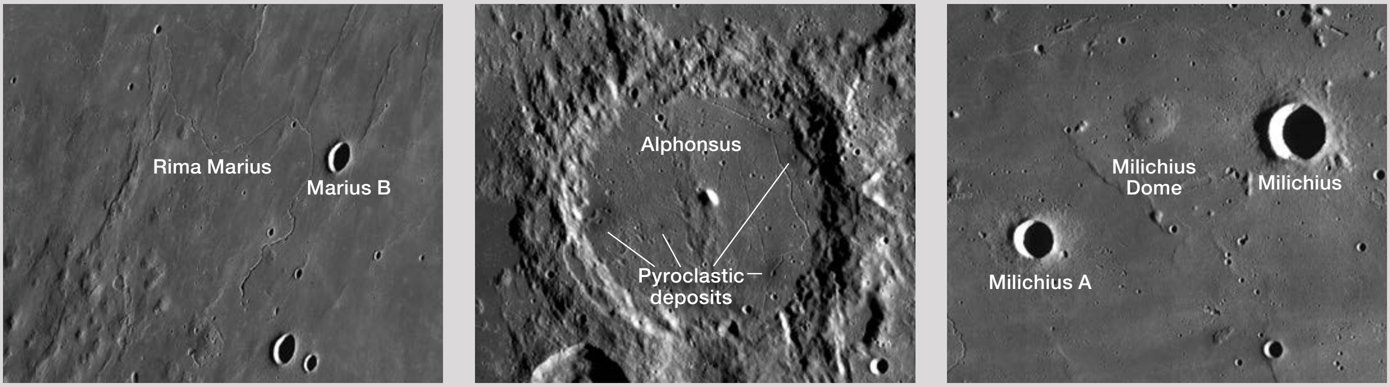
The very first lunar orbiting spacecraft (aptly named the Lunar Orbiter series) accidentally discovered that the strength of lunar gravity isn't homogenous. Mission controllers noticed that the Orbiters were pulled closer to the lunar surface as they passed over maria, demonstrating that there must be more mass beneath their surfaces than is present under the highlands. These *mascons* (mass concentrations) have been mapped with increasing precision ever since this serendipitous discovery.

Following the telescopic photography campaigns in the 1960s that used filters to isolate different parts of the visible spectrum, spacecraft have mapped the Moon across the entire electromagnetic spectrum, revealing the chemical and mineralogical compositions of different lunar materials. The occurrence of the radioactive-element thorium mapped with gamma-ray spectrometers reveals that the interior of the Moon isn't the same everywhere. Other sensors measured thermal, topographical, and magnetization properties — characteristics that are invisible to traditional photography. In addition, the analysis



This map depicts the concentrations of thorium on the lunar surface recorded by NASA's Lunar Prospector. The large colorful area on the nearside (left) is known as the Procellarum KREEP Terrane.

NASA



▲ Sinuous rilles (left) are almost exclusively found in the KREEP terrane, whereas pyroclastic deposits (center) and volcanic domes (right) occur in most nearside maria.

NASA / GSFC / ARIZONA STATE UNIVERSITY (3)

and dating of samples collected during the Apollo missions provided ground truth to accurately calibrate the lunar crater counts used to estimate the ages of maria.

One of the major discoveries from these multitudes of data was of the PKT in 2000 by Brad Jolliff and colleagues at Washington University in St. Louis, Missouri. Scientists had previously discovered basalts, anorthosite-rich highlands materials, and other, less-common rock types from Apollo samples. But they also found an unexpected suite of rocks (called KREEP) rich in certain elements, especially radioactive potassium (atomic symbol K), phosphorous (P), and rare-earth elements (REE) — the so-called incompatible elements that don't bond readily with those in most rocks and so are the last to form when magma solidifies.

KREEP was found in many Apollo samples as brecciated (fragmented) rocks, but also in non-brecciated volcanic rocks in Apollo 15 samples from the **Hadley Rille** area of **Mare Imbrium**. This finding suggests that the source of all KREEP materials is buried in the Hadley Rille region. Presumably, the formation of the Imbrium impact basin brecciated and ejected bits of KREEP basalt, scattering debris all over the Moon. But data from the NASA Lunar Prospector's gamma-ray spectrometer shows that high-radiation levels (as identified by thorium measurements) were almost entirely concentrated in the area covered by **Oceanus Procellarum**, Mare Imbrium, the western half of **Mare Serenitatis**, and the Imbrium ejecta northwest of the crater **Ptolemaeus**. Jolliff and his colleagues recognized that this area is unique and called it the PKT. So have all lunar scientists ever since.

The thorium map shows that the PKT includes most of the maria on the Moon. Only the eastern maria, including **Crisium**, **Tranquilitatis**, **Nectaris**, and **Fecunditatis** are excluded. On the farside there are fewer maria, and only the ones inside the South Pole-Aitken basin have any significant levels of thorium. Another surprising characteristic of the PKT is that, although most of the lunar maria formed between about 3.8 and 3.2 billion years ago, only the basalts in the PKT have crater-count ages as young as 2 to 1 billion years. The PKT is the only area of the Moon that had voluminous quantities of magma for a prolonged period. The older PKT mare rocks appear chemically similar to other mare rocks found over much of the Moon, but the younger lavas that originate in the PKT have nearly twice as much titanium as older rocks outside of the PKT. This means that the source region or processing of the younger magmas had changed since the time of earlier eruptions.

PKT magma also favored the formation of sinuous rilles carved by flowing lava — nearly all of which occur in the PKT. However, domes (another volcanic landform) are common in the PKT as well as elsewhere, such as in the eastern maria, especially Tranquillitatis. Similarly, pyroclastic deposits, such as volcanic ash, are also widespread both in and beyond the PKT, especially in floor-fractured craters.

Models of the various styles of lunar volcanic eruptions by Lionel Wilson at Lancaster University, Lancaster, UK, and James Head, at Brown University, Providence, Rhode Island, help explain these differences. They found that sinuous rilles form when eruption rates and volumes are large, whereas domes (small shield volcanoes) form from small-volume activity. The sinuous-rille distribution may imply that PKT eruptions were generally larger than those in other regions. And the more widespread occurrence of pyroclastic deposits and domes may be explained by noting that the beginning of all eruptions is driven by escaping gases, while the end phases produce smaller eruptions with lavas that flow only short distances and sometimes build up small domes. Pyroclastics are deposited at beginnings of eruptions, and domes form during declining periods, with sinuous rilles occurring any time a lot of magma erupts quickly.

Next time you observe the Moon with your telescope, try to appreciate the impact of the PKT on all aspects of lunar volcanism — each rille, dome, and ash deposit you detect tells you something about local eruption conditions billions of years ago. To fully embrace your role as lunar volcanism explorer, you may want to wear a hard hat and leather boots while observing.

■ Contributing Editor **CHUCK WOOD** sees hints of lunar history every time he views the Moon.

Understanding ISO

Producing high-quality astrophotos with a digital camera means understanding a few key parameters.

▲ For nightscape images like this one, you can usually get good results that are easy to process by shooting with an ISO setting of around 1600 or 3200. If you have an older digital camera, avoid using the lowest ISO settings, which often produce noisy low-light images.

Before digital photography, ISO signified the sensitivity of chemical films. A film with a higher ISO rating has larger photosensitive crystals that are more sensitive to light. Many useful best practices evolved around this fact, incorporating what is called the *exposure triangle*: exposure time, lens aperture, and ISO. These are used to determine the optimal camera settings to get a properly exposed image. Increase the ISO and you can decrease the exposure time or reduce the aperture.

The whole world of photography once revolved around the exposure triangle, and millions of people captured excellent images under many different lighting conditions thanks to a thorough understanding of the relationship among ISO, aperture, and exposure time. Let's set aside the hoops astrophotographers had to jump through to gain some additional film sensitivity for lengthy, low-light exposures and skip to the part where digital cameras showed up and changed everything.

Unlike a film camera, for which you can choose from a variety of films with different ISO ratings, a digital camera has an innate, fixed sensitivity, and there's nothing that can be done to make its sensor more or less responsive to the light reaching it. However, you can still utilize the beloved exposure triangle to produce appropriately brighter or darker images, because a digital camera can *simulate* ISO changes through *digital scaling* — multiplying or dividing the numeric values of the pixels that make up an image. That's right, in today's digital cameras, ISO is fake.

If you shoot in RAW mode (as opposed to JPEG), you can mostly retain the ability to simulate these ISO adjustments yourself after you capture the image — just use your favorite image-editing software. This capability might lead you to believe that it doesn't matter what ISO you shoot. Not quite. There's a fly in the ointment, and that fly is called *noise*.

Know Your Enemy

Let's take a step back to consider how a digital camera works. Light striking the sensor is converted into a small electrical charge, which is then converted into digital signal and processed into

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an image file. Both the collecting of the light and the readout process have their noise contributions.

When it comes to discussing ISO and digital photography, there are three sources of noise that need to be clearly understood. The first is *shot noise*, which is the speckling you see in astro-images that's quite simply the result of there not being enough light — the "signal" — to make a clean, smooth image. Shot noise is actually the absence of light. Think of it as a drizzle of rain leaving splotches on the sidewalk, rather than a downpour that really soaks the pavement. A wide aperture or a long exposure gathers lots of light (rain) and makes for a well-exposed (wet) image. Images taken with short exposures, small apertures, and dim light sources are going to have more shot noise — more gaps between the raindrops.

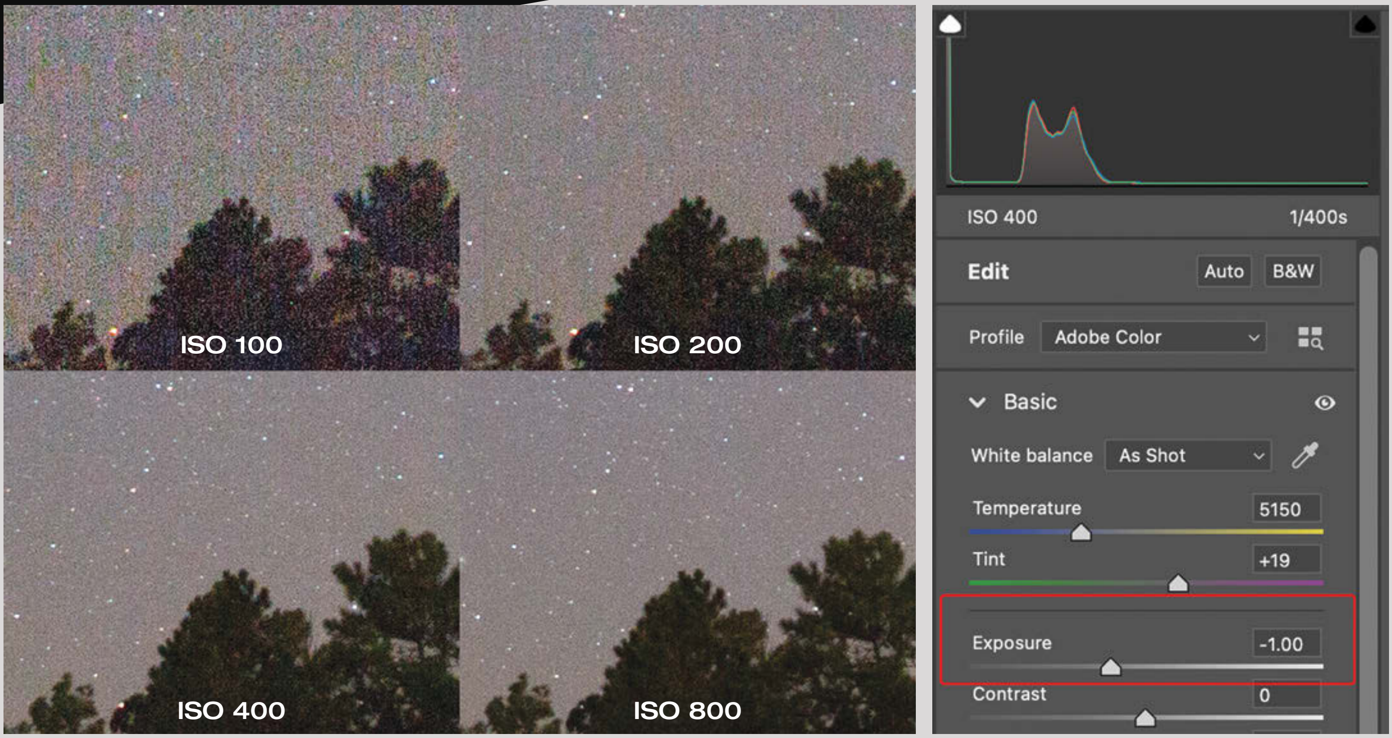
Two other noise sources are *read noise* and *dark-pattern noise*, which come from the image sensor itself and are often lumped together. Read noise is a result of small fluctuations that arise when the image data are read from the sensor. Dark-pattern noise is due to small variations in an image sensor's pixel array and shows up as horizontal or vertical lines and banding in your astrophotos.

Digitally scaling (by changing the ISO setting) sometimes occurs after the data are read out from the sensor and therefore affects both image information *and* the noise equivalently. This can lead to the false conclusion that higher ISOs produce noisier images. In fact, with many cameras, increasing the ISO actually *decreases* the apparent noise!

The reason is that some portion of the ISO range (usually the lower end) is accomplished not with a simple digital multiplier, but by altering the *sensor gain*. This signal amplification is performed *before* the readout occurs, so the dark-pattern noise or read noise don't have as much impact. You could argue that this is the same as increasing the sensitivity of the sensor since it now records fainter objects, but the amount of signal collected isn't actually increased — it's just competing against less noise.

▲ The Horsehead Nebula in Orion is a notoriously difficult visual target but can be captured readily with a digital camera and telescope (or telephoto lens). When imaging deep-sky targets such as this, keep the ISO low enough to preserve as much dynamic range as possible to allow for aggressive processing techniques later.

▼ The vertical structures you see in the noise pattern are a sign that this camera's ISO setting is too low, because an artifact called dark-pattern noise is showing through.



▲ Some digital cameras will use sensor gain to simulate some (but not all) of their ISO settings. To characterize your camera's ISO behavior, shoot several images as described in the text. Then, equalize the brightness of each frame by adjusting the exposure using your favorite RAW processing software. Many cameras do nothing more than the equivalent of this kind of modification internally to mimic ISO adjustments.

Theory aside, the main takeaway is that when it comes to astrophotography, increasing ISO will either reduce the apparent noise in our images or have no noise effect at all.

Practical Considerations

So, what is the best ISO setting for astrophotography? I can't tell you because there is no single answer that applies to every camera. However, you can find out for yourself with a simple experiment and software that allows you to adjust your RAW image files.

Set your camera on a tripod in a dark location (indoors or out) and take a set of RAW images, each made with the same exposure time and aperture setting. To prevent overexposing at high ISOs, set the camera's exposure time and lens aperture so that you get a good, non-clipped image at around ISO 3200. Next, capture a series of images by adjusting only the ISO setting by halves from ISO 3200 down to 100. Finally, use software such as *Adobe RAW* to equalize the exposures for all the images. This means you would double the software's exposure setting from the ISO 1600 image to match the ISO 3200 image and keep doubling all the way back to ISO 100. When you're done, you should have a set of photos resembling those above.

What you may observe, especially with some newer cameras, is that all the images look the same. This is due to something called *ISO invariance*, which means the camera has already been tuned to keep read and dark-pattern noise low via a fixed sensor gain. With such cameras, ISO changes are entirely the result of a mathematical scaling of the image data read off the sensor. With these kinds of cameras, it's best to shoot your astrophotos at low ISOs to preserve your camera's optimal dynamic range (a topic for another day) and just brighten them in post processing. My Canon EOS Ra exhibits this behavior.

You may find, as I did with my older Canon 5D Mark III, that at some point the images start to show read and dark-pattern noise at lower ISO settings. With my 5D, the images are very noisy at ISO 100 but get progressively cleaner until about ISO 1600, where the noise performance stops improving. On this camera, sensor gain is likely employed up until about ISO 1600, and then no further benefit to read or dark-pattern noise is realized. If your camera works this same way, then your ideal ISO is the setting where the noise stops improving — ISO 1600 in the case of my 5D.

So, do I always shoot at the lowest ISO with my Canon EOS Ra? When I'm using a telescope, yes. That's because I often aggressively post-process these kinds of images. For nightscapes, however, the loss of dynamic range from using higher ISO settings is rarely noticeable, so I prefer to shoot around ISO 1600 just to get a good preview on the LCD. Sometimes photography is like cooking — it's okay to season to taste.

■ Contributing Editor **RICHARD WRIGHT** is a software developer by profession, specializing in computer graphics technologies.

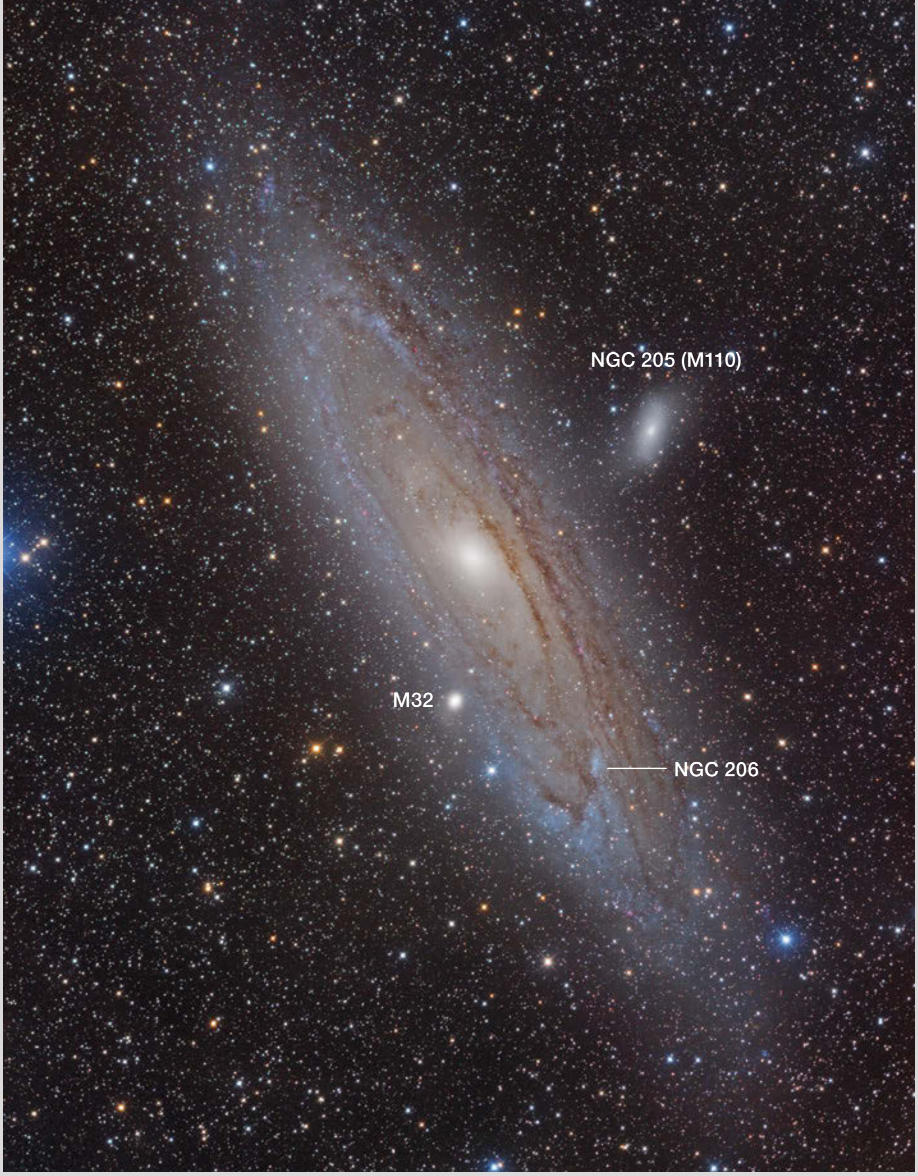
Seeking Stars in Andromeda

Test your limits: See if you can spot individual stars in M31.

Whenever I show the Andromeda Galaxy to the public, I remind each viewer that they're seeing the light of billions of individual stars so far and faint they blend into mist.

Andromeda offers something for everyone. In binoculars and small telescopes, the galaxy's bright nucleus, where stars are most strongly concentrated, stands out from its flattened, elongated disk. Those with small scopes can make out Andromeda's main dark lanes, while those with 10-inch and larger instruments can pick out the galaxy's brightest globular star clusters and stellar associations.

In October 2009, I observed a bright nova just outside the galaxy's nucleus in my 15-inch reflector when it peaked around magnitude 14.9. I could barely contain my thrill at the sight. It was a lucky break. Most novae in M31 never crack 17th magnitude, which is normally beyond my limit.



▲ **MAJESTIC GALAXY** You can espy M31, better known as the Andromeda Galaxy, with the unaided eye under dark skies as a faint smudge. The barred spiral is located at a distance of about 2.5 million light-years. Binoculars and small telescopes begin to reveal detail, while with a bigger backyard telescope you can start to pick out individual clusters and even stars.

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First Encounter

One night, while hunting down globular clusters in the galaxy, I turned the 15-inch on **NGC 206**, M31's largest and brightest star cloud — a 4.2′ × 1.5′ fuzzy knot 40′ southwest of the galaxy's nucleus. The knot's true size is about 4,000 light-years across, making it one of the largest star-forming regions or OB associations in the Local Group of galaxies.

OB associations, named for their type *O* and *B* stars, are loosely organized gaggles of young stars and star clusters born in the collapse of a giant molecular cloud. NGC 206, also known as OB 78, hosts some 300 brilliant, hot blue stars, the youngest of which are just 10 million years old and around 20 times more massive than the Sun.

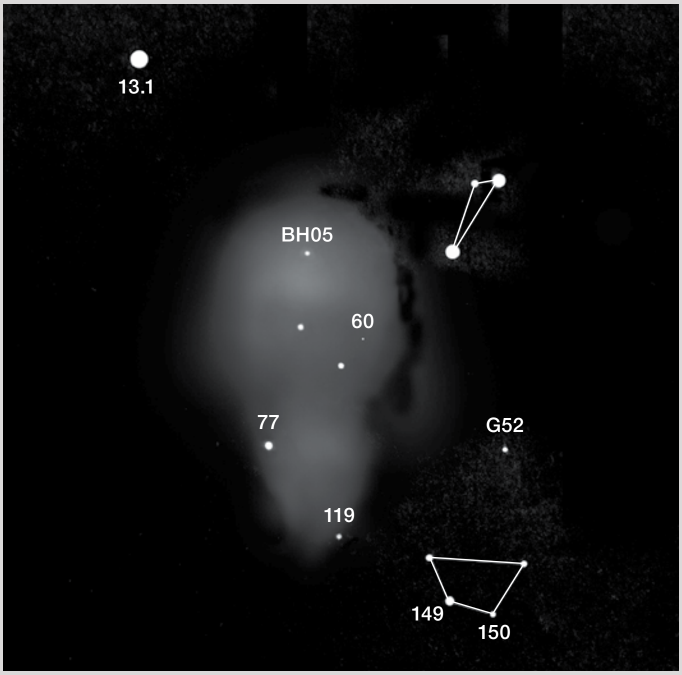
Using a magnification of 142×, I saw NGC 206 as a diffuse, north-south elongated fuzzy patch, brighter and a little clumpy in the north and smoother and fainter in the south. Inspired by photos that showed good resolution of the cloud, I powered up to 357×, allowed my eyes to fully adapt to the darkened field of view, and got the surprise of my life. Stars!

With averted vision, OB 78 revealed flashes of stellar granulation at the limit of vision when the seeing steadied and the scene sharpened. I felt reasonably confident of glimpsing at least hints of resolution after repeated observations. The bigger question was whether I could pinpoint and identify specific cluster members.

Golden Key

In recent years, amateurs have been busy pushing limits both visually and photographically, so it's not surprising that the possibility of resolving individual stars in Andromeda would gain traction.

Stephen Odewahn, research scientist at McDonald Observatory in Texas, examined NGC 206 in the 1980s



▲ **PLUCKING STARS** NGC 206 is a vast and magnificent star cloud located within the spiral arms of the Andromeda Galaxy. Smaller telescopes show it as a faint patch of light slightly brighter than the surrounding haze. Larger instruments reveal its tantalizing grainy texture, the additional cluster BH05, several Milky Way foreground stars and a small number of extremely faint cluster members. Stars that the author observed from Stephen Odewahn's list are labeled.

▲ **DIVING DEEP** This sketch of NGC 206, with north up, was compiled over several nights during the winter of 2020 based on observations made with a 15-inch (38-cm) reflector using magnifications of 357× and 428×. Besides the labeled stars, the author also observed the cluster BH05 and the globular G52, located in the same field. Two small asterisms — a triangle and a trapezoid — will prove useful for keeping your bearings straight while navigating the star cloud.

and published a photometric survey of its brightest stars. While most are hopelessly faint, a half dozen of them between visual magnitudes 14.9 and 17.1 appeared to be within the ken of 12-inch and larger amateur telescopes. It wasn't long before observers began hunting for these elusive stars.

"I never imagined that NGC 206 would get such attention!" wrote Odewahn in an email exchange I had with him. "That project was actually proposed by my future PhD advisor, Gérard de Vaucouleurs." The goal was to calibrate the brightest blue (OB) stars in nearby galaxies and use them as another tool to measure galactic distances. Although this ultimately proved to be infeasible, Odewahn's paper helped to elucidate the distribution of stars by mass within the association.

With photometric data and a photo showing star positions from Odewahn's project, I got to work observing and reobserving the association with my 15-inch scope and confirmed my observations with friends' 18-inch and 24-inch telescopes. I won't say these stars were easy, but the satisfaction at seeing them far outweighed the tired eyes I got doing so.

Reaching My Limit

Several years ago, I positively identified the stars numbered 77, 119, 149, and 150 on Odewahn's list. Then, after two lengthy observing sessions last winter, I made several tentative sightings of Odewahn 60 — a 17.1-magnitude speck at my visual limit. All five are shown in the sketch and photo above.

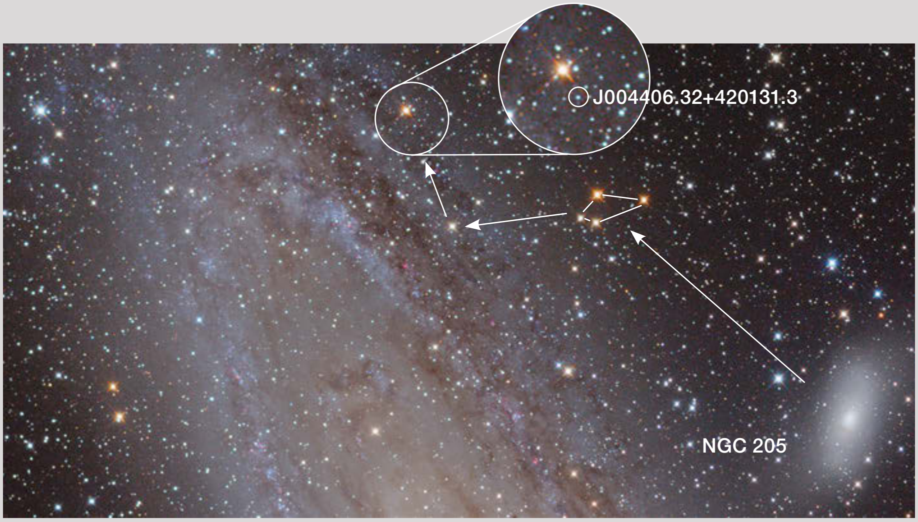
Parsing suns belonging to NGC 206 from Milky Way foreground stars is painstaking work. Most of the association's members are hot and blue, so objects that exhibit that color are good bets for membership. However, all the stars described above — with the exception of 60 — exhibit warmer hues. I would soon discover that this nagging fact would make their association with NGC 206 open to question.

I posted my original observations in an October 2016 blog on the *Sky & Telescope* website. Sometime after publication, amateur astronomer and *Sky & Telescope* contributor Scott Harrington informed me I had inadvertently included several foreground Milky Way stars, which Odewahn had used to measure the precise brightness of his potential OB 78 members.

I weeded those out, including Odewahn 12, which turned out to be a cluster named BH05. It's one of the youngest in both the association and the entire galaxy. A nice surprise!

Harrington also suspected the four stars I recorded might not be part of NGC 206, based on their aforementioned warmer colors. But because the stars were plainly listed as members of the cluster in the paper, I contacted Odewahn for his assessment. In the course of our discussion, he opined, "There is no definitive way, from the photometry alone, to say whether these stars are members." Stars 149 and 150

NGC 206 PHOTO: JIM MISTI; NGC 206 SKETCH: BOB KING



▶ **TWINKLE TWINKLE SINGLE STAR**
Using this annotated image, find your way to Andromeda's brightest supergiant star, J004406.32+420131.3, by starting at NGC 205, one of its satellite galaxies (right). From there, use the helpful asterism (labeled) to navigate to your destination. The prominent star near the supergiant is a 9th-magnitude Milky Way foreground star.

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are "probably field stars." As for 77 and 119, despite their location near the cluster's center, he considered them "a toss-up" because of the color discrepancy.

That left 60 as the only likely member I tentatively saw. Part of me felt crushed, but at the same time I was happy to get a definitive answer. As an observer I'd rather wince and get it right than pretend otherwise. But the story doesn't end there. After all, NGC 206 isn't the only game in town.

Sweet Success!

M31 is home to a number of luminous blue and yellow supergiants, including the yellow supergiant J004406.32+420131.3, also designated M31-004406.32. The paper titled "Yellow Supergiants in the Andromeda Galaxy (M31)" by Maria Drout (currently at the University of Toronto) and her collaborators lists the star as belonging to M31. With a magnitude of 15.6, it's squarely within range of a 12.5-inch or larger instrument.

One especially transparent morning in October 2020, I plotted the star's position on a photograph and star-hopped to its location with my 15-inch. Though quite faint, I found it quickly using magnifications of 357× and 428×. Under ideal conditions even a 10-inch telescope should snag this star.

It appeared like any faint star, but of course it wasn't just *any* star. Good gosh, I was looking at a supersized sun in another galaxy, and it didn't have to explode as a supernova to be visible! I took in the scene and tried to imagine the gulf of time and space that separated my eye and this tiny jewel.

John Martin, associate professor at the University of Illinois (Springfield), worked with colleagues on a project that cataloged the most luminous stars in M31 and M33. It proved an invaluable resource in my star search. During our email exchange Martin provided me with an updated list of stars brighter than 17th magnitude for amateurs seeking some of M31's "softer" targets (see the sidebar above). I plan to work my way through that list in hopes of adding a second or third Andromedan gem to my collection.

When I was a kid, I never imagined that one day I would gaze upon individual stars in the Andromeda Galaxy. But thanks to the work of professional astronomers, amateurs are privy to the deepest recesses of these unimaginably remote objects.

Stars Brighter than Magnitude 17 in M31

While the star names listed at right look cumbersome, they're useful because they actually describe the stars' locations. For example, you'll find J004406.32+420131.3 at right ascension $00^h\ 44^m\ 06.32^s$ and declination +42° 01′ 31.3″. You can use an online atlas such as Aladin Lite (**https://is.gd/AladinLite**) to locate these targets using these designations. Bob would love to hear from you at **nightsky55@gmail.com** if you spot of any of the targets listed!

Mag(v)	Target	J-designation
15.6	M31-004406.32	J004406.32+420131.3
16.0	AF And*	J004333.09+411210.4
16.2	M31-004507.65	J004507.65+413740.8
16.3	M31-004034.82	J004034.82+401825.5
16.4	M31-004247.30	J004247.30+414451.0
16.6	M31-004424.21	J004424.21+412116.0
16.7	M31-004434.65	J004434.64+412503.5
16.7	M31-004518.76	J004518.76+413630.7
16.8	M31-004021.21	J004021.21+403117.1
16.8	M31-004526.62*	J004526.62+415006.3
16.8	Var A1*	J004450.54+413037.7
16.9	M31-004129.31	J004129.31+405102.9

* Indicates Luminous Blue Variable. Target names are from the online catalog of luminous stars listed below.

■ Contributing Editor **BOB KING** likes to meet face-to-face with everything he's read about in astronomy books. He wishes to thank Scott Harrington, Stephen Odewahn, and John Martin for their assistance during the preparation of this story.

FURTHER READING: You'll find Stephen Odewahn's article at **https://is.gd/Odewahn** and Maria Drout and colleagues' paper on yellow supergiants at **https://is.gd/Drout**. Go to **https://is.gd/LuminousStars** for the catalog of luminous stars in M31 and M33 and to **https://is.gd/M31_M33_info** for detailed information and photos.

Capturing Stellar "VOIDS"

These thick clumps of gas and dust make excellent targets for astro-imagers.

Astrophotographers tend to be drawn to the biggest and most colorful objects in the night sky. Emission nebulae, star clusters, and nearby galaxies quickly attract the attention of both novice and seasoned imagers. But there's another, more subtle type of object that can add variety to your growing deep-sky portfolio: dark nebulae.

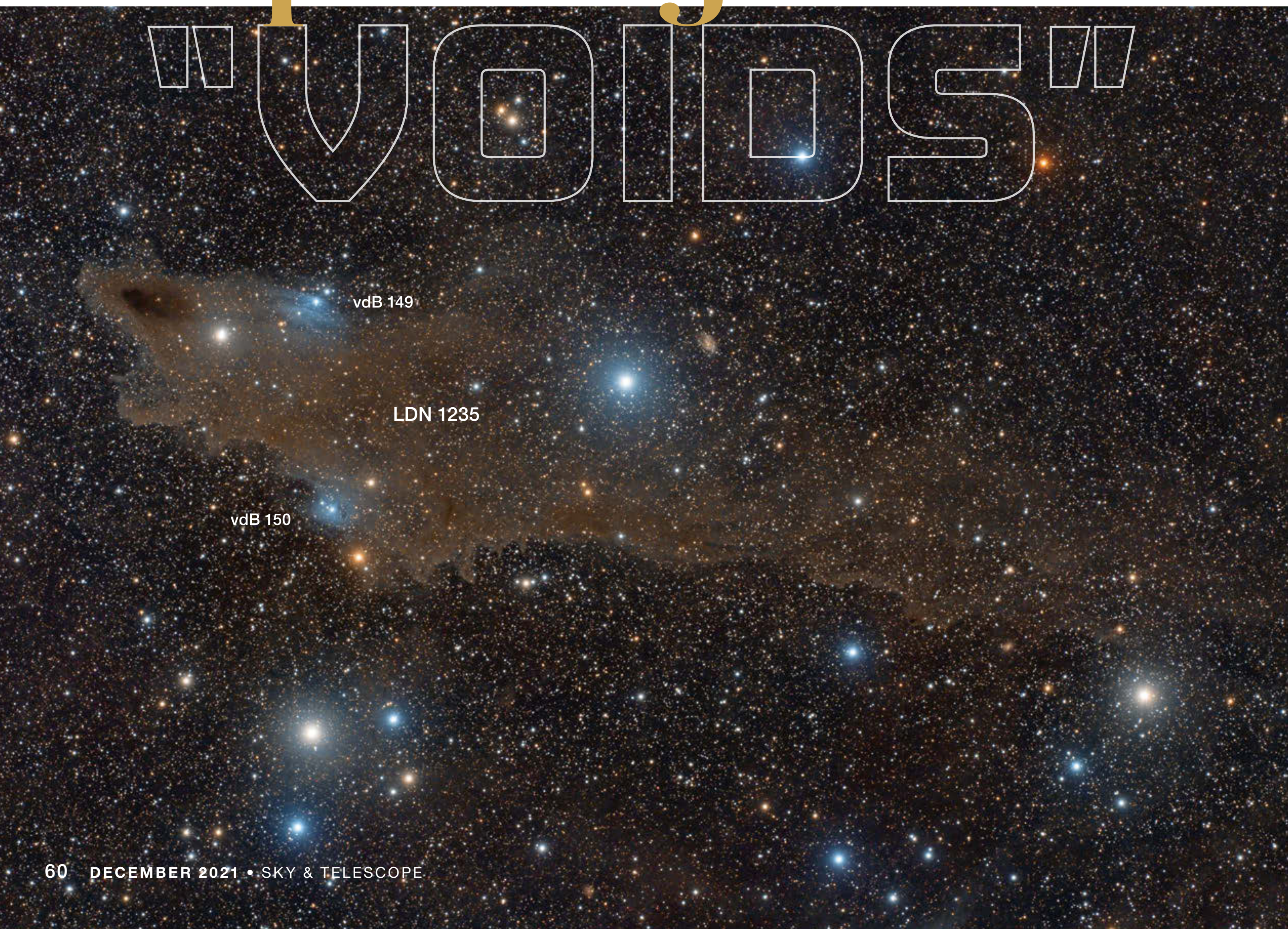
Most dark nebulae are visible in three of the four seasons, with a break during spring when the Milky Way clings to the horizon. From mid-northern latitudes, the best time of year to image these turbid regions is when the Milky Way rides high in the summer, fall, and winter skies.

Dark nebulae are massive interstellar clouds of dust and gas that permeate the Milky Way. Unlike their luminous emission- and reflection-nebulae cousins, many of the finest dark nebulae stand out as starless voids in the rich star fields of the Milky Way, though some are found above or below the galactic plane. Others appear as dark features in front of bright emission and reflection clouds. Here are some of the more interesting dusty targets you can target from mid-northern latitudes.

Fall and Winter Classics

Several large, fascinating dark nebulae lie in Cepheus and are well placed in the autumn and early winter. Let's start about 4½° northeast of Alfirk, Beta (β) Cephei, with **LDN 1235**, sometimes called the Dark Shark. The most opaque part of

▼ **THE DARK SHARK** The same dust that obscures starlight can also reflect it. Light from the Milky Way illuminates the brownish dust in LDN 1235, though the blue reflection nebulae vdB 149 (top) and vdB 150 (lower left) add a different hue (and fins) to the sharky composition.



the cloud makes up the shark's "snout" roughly 10′ northeast of 6th magnitude HD 211300, the shark's "eye." The predator's body appears in long exposures as brownish dust trailing off to the west. Adding to the shark's anatomy are two reflection nebulae, vdB 149 and vdB 150, which some interpret as representing the dorsal and pectoral fins, respectively. This collection of objects fits cozily in a 3½° field with a little room to spare for creative framing.

Another interesting bit of dust lies 1½° south-southeast of Eta (η) Cephei: **B150**, often referred to as the Seahorse Nebula. Brownish dust throughout the field surrounds the denser material that produces the 1° seahorse shape aligned roughly east-west and terminating at 8.5-magnitude HD 198300. A wide-field telescope and camera combination producing at least a 1½° field is necessary to frame this target.

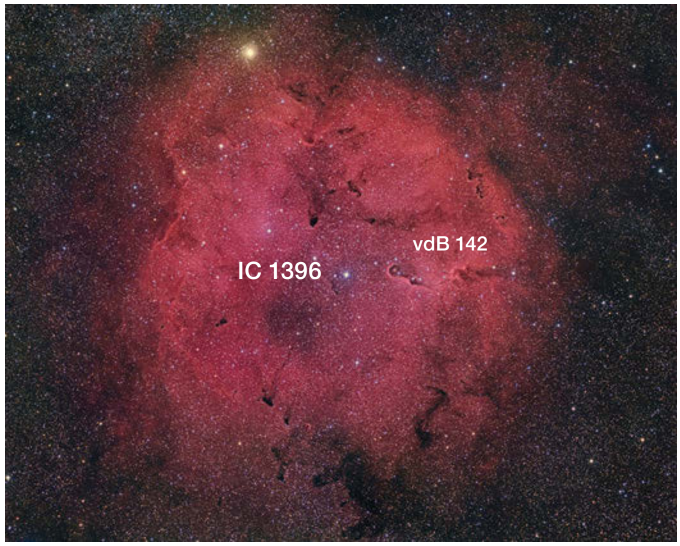
Returning to Alfirk, aim 3⅓° southwest for **NGC 7023**, the Iris Nebula. This complex structure contains reflection, emission, *and* dark nebulae each having its own designation. Just 6′ northeast of the reflection component is the prominent dust of **LDN 1174**, while ½° to the south is a group consisting of **LDN 1173**, **LDN 1172**, and **LDN 1170**. These are just a few of the many dusty structures revealed in long exposures of this region (more can be found in the August issue, p. 18).

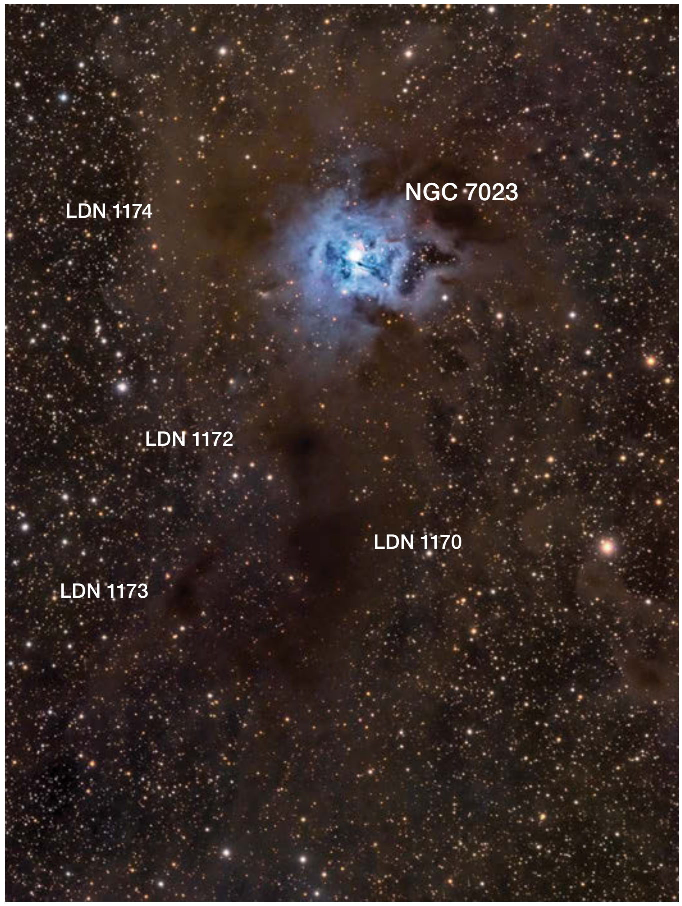
Before moving on from Cepheus, I can't resist slewing slightly more than 1° southwest from 4th-magnitude Mu (μ) Cephei, the Garnet Star. That's where the large, faint emission nebula **IC 1396** resides. This sprawling object covers a 2°-wide, roughly circular patch of sky and is riddled with thick clumps of dark nebulosity. The best known is **vdB 142**, the Elephant's Trunk Nebula, located just west of the center of IC 1396. The Elephant's Trunk also contains a small, bluish reflection component, which landed it on van den Bergh's catalog of reflection nebulae. The entire IC 1396 complex is an excellent target for large and small telescopes alike; small, wide-field instruments with a 2½° field of view will frame the entire nebula, while large telescopes are better suited for close-ups of vdB 142 and other nearby silhouetted knots of dust.

Skipping southeast over to Orion, you'll find some of the best-known dark nebulae of the winter Milky Way. Orion houses such a treasure trove of glittering deep-sky objects that perhaps the darker features have escaped your notice.

The most striking of these for imagers is **B33**, the famous Horsehead Nebula, located ½° south-southeast of Alnitak, the easternmost star of Orion's Belt. This distinct pillar of cosmic dust billows in front of the glowing nebulosity of IC 404. Just 15′ east-northeast of Alnitak lies **NGC 2024**, the Flame Nebula, with its back-illuminated dust lanes giving the appearance of a match that's just been struck. Both NGC 2024 and B33 comfortably fit within the same 1° field. These two objects are among the most frequently imaged dark nebulae in the winter sky (see page 25).

Found 2½° northeast of Alnitak are the dark tendrils winding through reflection nebula **M78**. Aside from its network of opaque dust, I've always found M78 interesting





▲ **KNOTS AND TRUNKS** *Top:* The large emission nebula IC 1396 in Cepheus hosts several dark components. Particularly interesting for imagers with large scopes is vdB 142, seen at right, which also contains a small, bluish reflection nebula.

▲ **EXOTIC FLOWER** *Above:* Composition is important when attempting to include as much of the dust surrounding the Iris Nebula (NGC 7023) as possible in the frame. Orient the long axis of your camera north to south and place the bright reflection nebulosity towards the top of the frame in order to include dark nebulae LDN 1173, 1172, and 1170.

ALL IMAGES COURTESY OF THE AUTHOR

◀**A BIT OF EVERYTHING** The combination of emission, reflection, and dark nebulosity in M78 makes it challenging to image but rewarding when you pull it off successfully.

Fall-Winter Dark Nebulae

Object	Type	Size	RA	Dec.
LDN 1235	Dark	100′ × 40′	$22^h\ 15^m$	+73° 25′
B150	Dark	60′ × 3′	$20^h\ 50.6^m$	+60° 18′
NGC 7023	Reflection	18′	$21^h\ 00.5^m$	+68° 10′
LDN 1174	Dark	37′	$21^h\ 02.6^m$	+68° 12′
LDN 1173	Dark	5′	$21^h\ 04.7^m$	+67° 42′
LDN 1172	Dark	6.8′	$21^h\ 02.7^m$	+67° 42′
LDN 1170	Dark	32′	$21^h\ 01.7^m$	+67° 37′
IC 1396	Emission	2.8° × 2.3°	$21^h\ 39.1^m$	+57° 30′
vdB 142	Dark / Reflection	1′	$21^h\ 37.1^m$	+57° 29′
B33	Dark	6′ × 4′	$05^h\ 40.9^m$	−02° 28′
NGC 2024	Dark / Reflection	30′	$05^h\ 41.9^m$	−01° 51′
M78	Emission / Reflection	7′ × 6′	$05^h\ 46.7^m$	+00° 03′
NGC 2237-39	Emission	80′ × 60′	$06^h\ 32.3^m$	+05° 03

Angular sizes are from recent catalogs. Right ascension and declination are for equinox 2000.0.

because it contains structures of so many different colors and brightnesses. But these attributes make it a challenging target to process.

Moving east-northeast about 12° to Monoceros you'll come to **NGC 2237**, **NGC 2238**, and **NGC 2239,** which together make the Rosette Nebula, a large emission nebula complex roughly 1½° in diameter (see image on page 27). Standing out in stark contrast along its north and west sections are a meandering series of dark knots of dust. The most prominent of these appears as a jagged, three-vane structure almost due north. Each of these dark clumps of dust is slowly evaporating due to hot stellar winds emanating from the young stars of open cluster NGC 2244 in the center of the nebula. The Rosette looks great when photographed through most any telescope — imagers with wide-field instruments can frame the entire complex, while those using large scopes can focus their attention on the complex strands of dust.

Lazy Summer Nights

The summer Milky Way features some of the most majestic dark nebulae found in the sky. Most obvious is the massive complex of dust found in Ophiuchus, northwest of the galactic center. Here lies a sprawling collection of opaque dust and gas roughly 10° in circumference known collectively as the **Dark Horse Nebula**. The Dark Horse is most recognizable as a walking horse with its head bowed low if you present the image with east at the top. The horse doesn't have an official designation, but individual parts of it do. Its hind legs are made up of **B78**, also known as the Pipe Nebula (a large, 7°-wide nebula itself), and **B72**, the S-shaped Snake Nebula found within the horse's torso. You can record this entire collection of nebulae with a full-frame camera and lens of about 100-mm focal length, though smaller components like B78 require a field of at least 8° to adequately frame both the Pipe's stem and bowl. The Snake Nebula is framed best with about a 1° field of view.

Moving about 9° east into Sagittarius, we find M20, the Trifid Nebula. While we usually think of the Trifid as an emission and reflection nebula complex, it owes its nickname to dark nebula **B85**, appearing as a triad of dusty gashes dividing up the emission component. Messier 20 is a colorful target with many small-scale features that beckon imagers with large telescopes, but it also looks great in wide-field astrographs, particularly when framed to include its popular neighbor M8, the Lagoon Nebula, just 1⅓° south-southeast.

Following the Milky Way north into Aquila we come to another silhouetted molecular cloud with a familiar appearance. With a little imagination, the two dark nebulae **B142** and **B143** appear like an interstellar letter E. Use a field of at least 1.5° to frame it comfortably and be sure to orient your camera so that its long axis is directed north to south. Only 2° west-northwest is **LDN 673**, a fascinating dark nebula consisting of wide, tentacle-like dark structures. This object can be a challenge to photograph due to 6th-magnitude HD 181383, which lies just 20′ to the northwest. Careful framing is required to avoid reflections or scatter from the star that would detract from your composition.

Northern Nebulae

I can't overstate the beauty of the dark structures found around the galactic center. However, there are plenty of great dark nebulae targets further north, around and within the Summer Triangle formed by the bright stars Vega, Deneb, and Altair.

Perhaps the most familiar lies about 2½° east-southeast of Deneb, in Cygnus. The prominent dust lane that separates **NGC 7000**, the North America Nebula, from **IC 5070** and **IC 5067**, the Pelican Nebula, doesn't have an official name, though it makes up the nebulous continent's Gulf of Mexico. Both the North America and Pelican nebulae neatly fit in a 4° field of view.

Another emission nebula subdivided by dark nebulae is **IC 1318**, sometimes called the Butterfly Nebula. The glowing wings of this celestial insect span the 2° directly east

▲ **HOST WITH THE MOST** The opaque lanes of Barnard 85 give M20, the Trifid Nebula, its memorable name.

▲ **TWISTED TENDRILS** *Left:* Dark nebula LDN 673 in Aquila appears as a complex tangle of blackness spanning roughly ½°. *Right:* Barnard 142 and 143 together make up Barnard's E, though inky B142 is denser and more prominent against the background star field.

of 2nd-magnitude Sadr, Gamma (γ) Cygni, and is, in my opinion, one of the prettiest fields in the summer sky.

Imaging Strategies

Dark nebulae are, well, dark. Often they appear either slightly brighter or fainter than the background sky. They are invariably low-contrast and require careful post-processing to reveal their subtleties. Apart from those that appear in front of emission nebulae, these opaque objects are best imaged with one-shot-color cameras or monochrome detectors equipped with LRGB filters. They respond well to modern light-pollution filters, as well as the exotic multi-bandpass filters designed for DSLRs. When using a light-pollution filter, be sure to compensate for the filter's reduced light transmission by increasing your exposure time. Dark nebulae in front of emission regions are also excellent targets for those imaging through narrowband filters.

Since dark nebulae are set against dense Milky Way star fields, the appearance of the individual stars has a major impact on the overall aesthetics of your image. Try to retain as much star color as possible during processing. My approach is similar to that for star clusters (*S&T:* July 2021, p. 35).

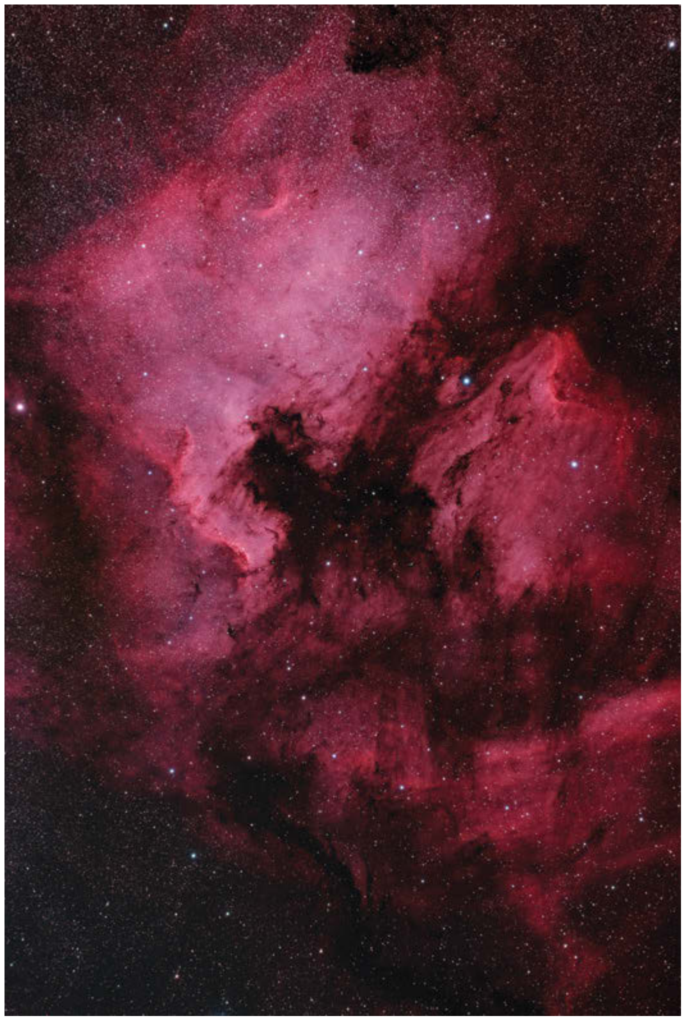
Any time the Milky Way is visible in your sky, you won't have to look far to find a dark nebula that suits your specific imaging setup. They come in all sizes and help reveal the three-dimensionality of our home galaxy. Best of all, many can be captured in a few hours with a one-shot-color camera, allowing you to take advantage of those brief breaks in the clouds. So what are you waiting for? Come on over to the dark side.

■ Contributing Editor **RON BRECHER** often targets nebulae, star clusters, and galaxies from his backyard observatory in Guelph, Ontario, Canada.

Summer Dark Nebulae

Object	Type	Size/Sep	RA	Dec.
Dark Horse Nebula	Dark	10° × 10°	$17^h\ 21.0^m$	–21° 07′
B78	Dark	7°	$17^h\ 30.0^m$	–26° 00′
B72	Dark	10′	$17^h\ 23.0^m$	–23° 32′
B85 (M20)	Emission / Dark	28′	$18^h\ 02.6^m$	–23° 02′
B142	Dark	60′ × 30′	$19^h\ 40.7^m$	+10° 30′
B143	Dark	50′ × 39′	$19^h\ 41.5^m$	+11° 00′
LDN 673	Dark	50′ × 15′	$19^h\ 20.9^m$	+11° 16′
NGC 7000	Emission	2.0° × 1.7°	$20^h\ 58.8^m$	+44° 20′
IC 5067/70	Emission	80′ × 70′	$20^h\ 47.8^m$	+44° 22′
IC 1318	Emission	50′ × 30′	$20^h\ 21.0^m$	+39° 54′

Angular sizes are from recent catalogs. Right ascension and declination are for equinox 2000.0.



▲ **BUTTERFLY WINGS** *Top:* Emission nebula IC 1318 (left) is divided by a thick dust lane into two fairly symmetrical "wings".

▲ **DARK GULF** *Above:* The dark nebula between NGC 7000, the North America Nebula (left), and NGC 5067/5070, the Pelican Nebula (right), helps to give both objects their namesake shapes.

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Gift Guide: Astronomy Books for Kids of All Ages

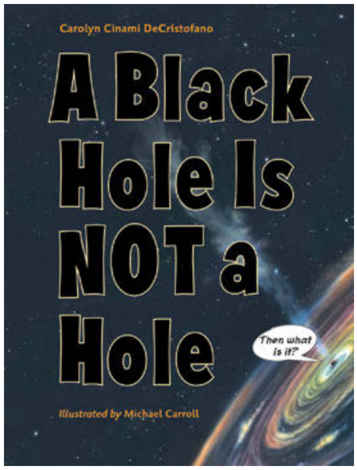
The holiday season is a wonderful time to share your passion for astronomy with younger generations, whether kids or grandkids, nieces or nephews. The following illustrated children's books serve as beautiful introductions to celestial wonders — not to mention more down-to-earth values such as unconditional love and persistence in the face of challenges.

We've selected these books for their appeal to both children *and* adults. After all, when a book becomes a bedtime favorite, you'll want to love it, too (especially when you're reading it for the hundredth time)! The books run a gamut of styles, from lyrical to playful, their illustrations sometimes in bold colors or softer pastels, and the reading levels also range from toddler to pre-teen.

Full disclosure: I've test-run these books multiple times with a small sample pool (my kids: 2½, 6, and 9 years old). So consider this selection kid-tested, parent-approved!

■ MONICA YOUNG is *Sky & Telescope*'s News Editor.

A BLACK HOLE IS NOT A HOLE (UPDATED AND EXPANDED EDITION)



Carolyn Cinami DeCristofano, illustrated by Michael Carroll
Charlesbridge, 2021
80 pages
ISBN 9781570917844
$18.99, hardcover

Suggested age range: 9–12

THIS BLACK HOLE PRIMER is sure to pull in — and hold — the attention of preteens, cover to cover. The writing is clear and dynamic enough that adept younger readers may dive in, too, though they may not fully take in the more abstract topics.

With apt analogies and dashes of humor, author Carolyn DeCristofano explores the counterintuitive nature of black holes. She uses easy-to-understand analogies to tackle complex concepts, from the finite speed of light to spacetime and general relativity, in a tone that's conversational but never pedantic. Even adults not familiar with the topic might find this book to be a useful introduction!

Actual photos of star-forming regions, galaxies, and, of course, a certain now-famous black hole (*S&T:* Sept. 2019, p. 18) accompany the text. Other illustrations include diagrams and artist's conceptions ranging from the funny to the fantastic. There's also plenty of white space, which helps gives readers the headspace to bend their minds around the topics. Speech bubbles and sketches pepper the white space, lending some punches of kid-appreciated humor.

Advances in black hole science over the past decade have demanded revisions to the book, which was first published in 2012. The author and illustrator have obliged with updates and expansions, including a full chapter on the Event Horizon Telescope's silhouetted image of the supermassive black hole in the nearby galaxy M87.

MARS! EARTHLINGS WELCOME

Stacy McAnulty, illustrated by Stevie Lewis
Henry Holt and Co., 2021
40 pages
ISBN 9781250256881
$18.99, hardcover

Suggested age range: 4–8

"IF YOU THINK PARTIES on Earth are fun, just you wait!"

In the latest book of the Our Universe series, author Stacy McAnulty and illustrator Stevie Lewis make Mars come to life as a "classy — not gassy" world that wants to be the first planet to host human guests.

Kid-friendly facts are packed into every page in witty ways that keep the story from going dry (unlike Mars, of course, which went dry long ago). Readers will get a tour of the most marvelous places to visit and learn why Mars is red (and no, it's not because it's hot). *Mars!* also recalls some of the more interesting robotic visitors — but what the planet really wants is a visitor with a heartbeat, i.e., you!

Curiously, the book doesn't mention Curiosity (or Perseverance, though given the book's release date that might have been a matter of timing). However, the Mars Exploration Program does get a callout in the appendices, which also include a quiz, a timeline, and interesting facts.

Bold illustrations, made with colored pencil and digital techniques, work together with the lively text to make this Red Planet a world kids will want to get to know.

THE STUFF BETWEEN THE STARS: HOW VERA RUBIN DISCOVERED MOST OF THE UNIVERSE

Sandra Nickel, illustrated by Aimée Sicuro
Abrams Books, 2021
48 pages
ISBN 9781419736261
$18.99, hardcover

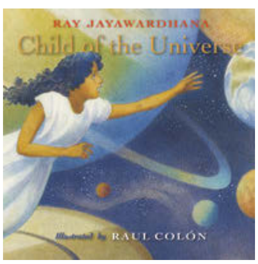
Suggested age range: 6–9

VERA RUBIN (1928–2016) fell in love with astronomy through her bedroom window, watching one star after another cross the frame. Today she is revered as the "mother of dark matter," the astronomer who found convincing evidence of the universe's missing mass. But the path along the way was far from straight or smooth.

In Sandra Nickel's expressive recounting, older children experience Rubin's perseverance in the face of challenges — but also her sheer joy in inquiry and discovery. Watercolor, ink, and charcoal drawings depict scenes from Rubin's life in dreamlike images that evoke the idea of memories. Additional details about her life can be found in the back.

To be clear: This isn't a book only for girls. While much of the story centers on a woman making her way in what was (and in some ways, still is) a man's world, my sons engaged fully with the story, following Rubin's challenges as well as her ultimate successes. And the final chapter isn't yet written: We still don't know yet what dark matter is. Mysteries remain, to be unraveled by "the adventurous scientists of the future."

CHILD OF THE UNIVERSE



Ray Jayawardhana, illustrated by Raul Colón
Penguin Random House, 2020
40 pages
ISBN 9781524717544
$17.99, hardcover

Suggested age range: 2–6

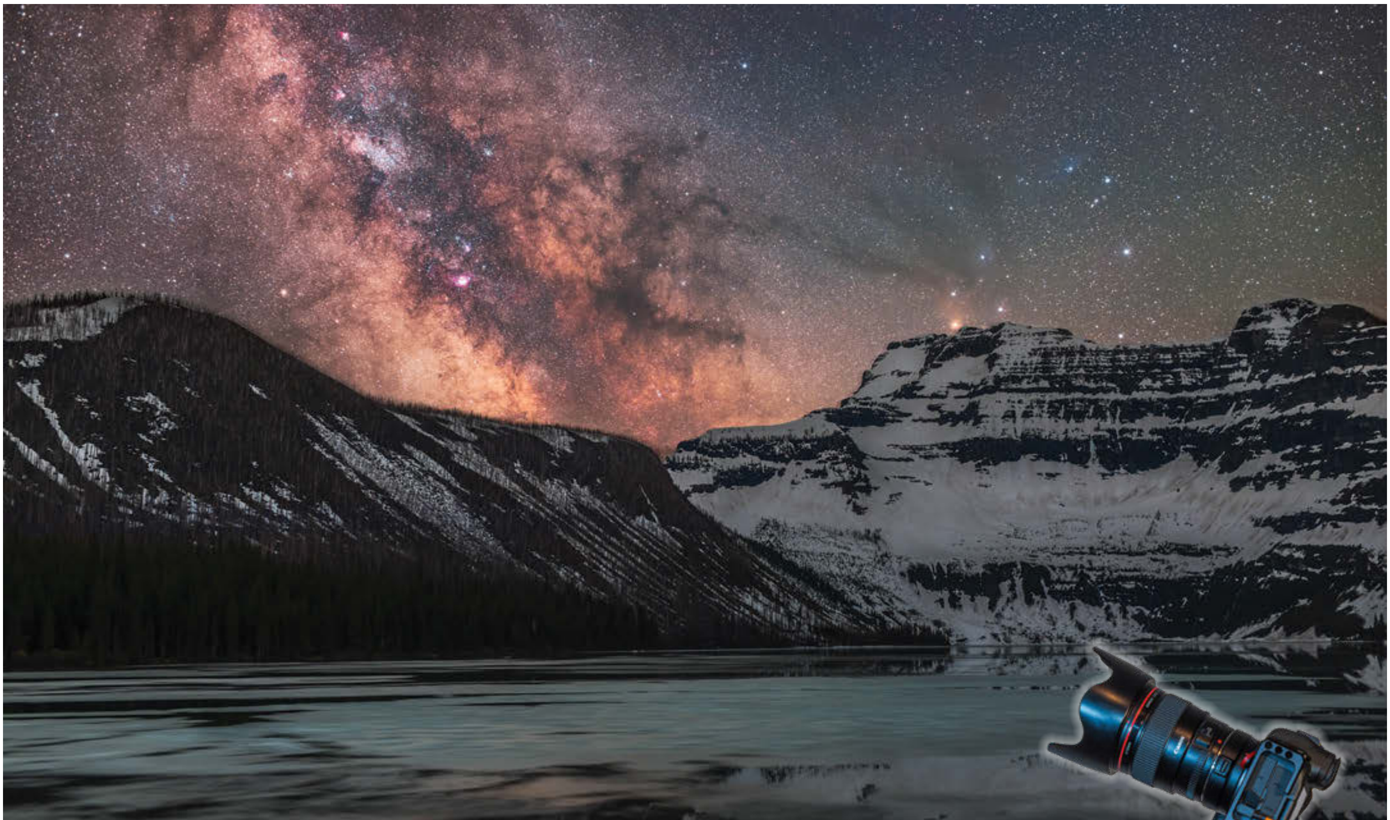
IN THIS BEDTIME STORY, a father tells his daughter of his love for her, a story so universal it transcends the pair sitting in a darkened bedroom gazing at the Moon. "My father says I am made of stars," the story begins. What follows is a lyrical connection between this one special child and the vastness of the cosmos.

Author and astronomer Ray Jayawardhana studies other worlds, which informs the poetry and art in his picture-book debut. His "star-stuff" tale is comforting because it grounds the child in who they are while linking them to the larger universe — their smile of galaxies, their eyes that reflect the stars. From there, the child's imagination soars past the bedroom walls and toward the wilder worlds that might be out there.

The steady rhythm of the two-line verses engaged my younger kids, and the beauty of the words made them a pleasure to read aloud. But the words are only part of the story: Raul Colón's colored-pencil fantasies drawn over watercolor washes act like a countermelody to the verses. The dynamic illustrations tell of exploration and the delight of discovery.

Testing the Move-Shoot-Move Tracker

Does this compact, low-cost device make tracking astrophotos and time-lapse sequences easy?



▲▲ The little Move-Shoot-Move tracker is designed for packing on treks to backcountry sites to shoot nightscapes without trailed stars. This is a stack of four 2-minute tracked exposures of the sky blended with two 8-minute untracked exposures capturing the foreground, all made with a 35-mm lens.

▲ The basic setup used to capture the scene includes the MSM tracker with its optional equatorial wedge and polar-alignment laser, and a ball head for aiming the camera.

ALL PHOTOS PROVIDED BY AUTHOR

Move-Shoot-Move Tracker / Time-Lapse Rotator

Basic Tracker: $199; Equatorial Wedge: $88.98; Laser Pointer: $35; Polar Scope: $69.98; Phone Mount: $24.98; Alyn Wallace V and Z Platforms: $39 each. Bundled kits available at package prices.
moveshootmove.com

What We Like

Compact and lightweight

Easy alignment with laser pointer

Basic time-lapse functions

What We Don't Like

Unreliable tracking accuracy

Mechanical slippage at connection points

Confusing mounting and alignment options

IF SOCIAL MEDIA ALGORITHMS know you're an astrophotographer, then chances are you've seen your newsfeeds punctuated by ads for this little device. The Move-Shoot-Move (MSM) offers functions for motion-control time lapses and for tracking the sky during long exposures of the Milky Way. I tested a unit sent to me in May 2021 from China by the Move-Shoot-Move company.

The MSM is offered either by itself or bundled with a dizzying array of packages. I opted to test the unit with several accessories necessary for typical tracked nightscape and time-lapse astrophotography.

Mounting the MSM

The unique selling points of the MSM are its low price and small size. The MSM is a box 10 centimeters (4 inches) long and only 3.5 cm (1.4 in) thick. It slips into a camera bag or pocket, making it easy to pack for hiking to nightscape sites.

The MSM is powered by an internal lithium-ion battery that lasted up to nine hours at room temperature. In the field on colder nights, expect to get one or two nights of shooting (the specs promise five hours of use). Users can also power the MSM with an external 5-volt battery.

The body has three bolt holes to choose from for mounting to a tripod. This is potentially a source of confusion for beginners, despite the MSM's instruction sheet. In star-tracker mode, the MSM should be mounted on one of its narrow sides using the ¼-20 threaded hole. It can also be mounted on the larger surface of its back using the threaded ⅜-inch socket. This is how I usually attached the MSM to my tripod, because it allowed me to take advantage of the back's larger, textured surface to grip the tripod's mounting plate.

Polar Alignment for Tracking

The device and company name "Move-Shoot-Move" comes from the device's time-lapse mode, which ironically is the function that most buyers are least likely to use. Instead, it's the device's suitability as a lightweight star tracker that will be of greatest interest to *S&T* readers.

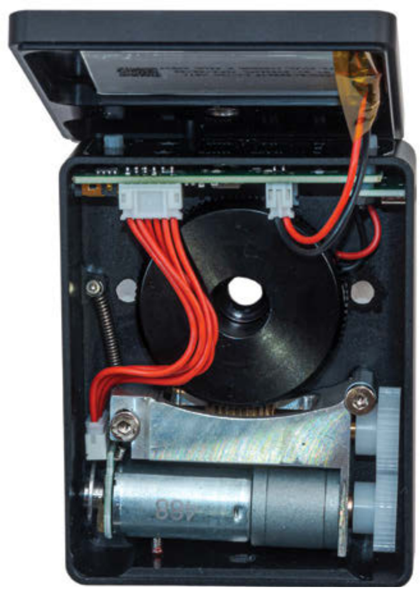
All trackers designed for long-exposure, night-sky photography require polar alignment. For those in the Northern Hemisphere, finding Polaris with the naked eye isn't the issue; it's placing Polaris in the relatively confined field of its polar-alignment scope. MSM also offers an optional right-angle viewfinder to reduce your contortions while polar aligning.

A better option, in my opinion, is MSM's optional green laser pointer, which makes the task quick and easy for beginners and experienced astrophotographers alike. In the Northern Hemisphere, adjust whatever you have the MSM mounted on (a tripod head or MSM's optional wedge) to aim the laser at Polaris. Polar alignment is achieved in moments, all without the neck craning and back straining to look through a polar scope. But as you might guess, there are caveats to using the laser.

First, the 5-milliwatt (mW) model supplied with my test MSM was not collimated — the laser beam was not exiting the housing parallel to the axis

▲ One option is to mount the MSM on its narrow side as shown here. The laser (bottom left) and polar scope (left) clamp to the side of the tracker. While the wedge makes polar alignment easier, under a load it can slip down in altitude with the slightest touch to the adjustment knob.

of the body. Fortunately, the laser has two tiny hex screws that allow the user to adjust the aim of the beam in the X and Y axes. You accomplish this by aiming the laser at a distant wall and tweaking the adjustments until the pro-



▲ *Left:* The base price includes the tracker, hot-shoe-to-rotator cord, USB-C charging cable, adapter bushings, and hex wrenches seen at left. The laser, polar-alignment scope, and wedge (at right) are recommended options. The ball head is one the author already owned. *Right:* Inside the unit's solid metal housing lies a tiny motor, a 1¾ inch-diameter plastic drive gear, and a spring-loaded brass worm gear driven by two plastic spur gears.

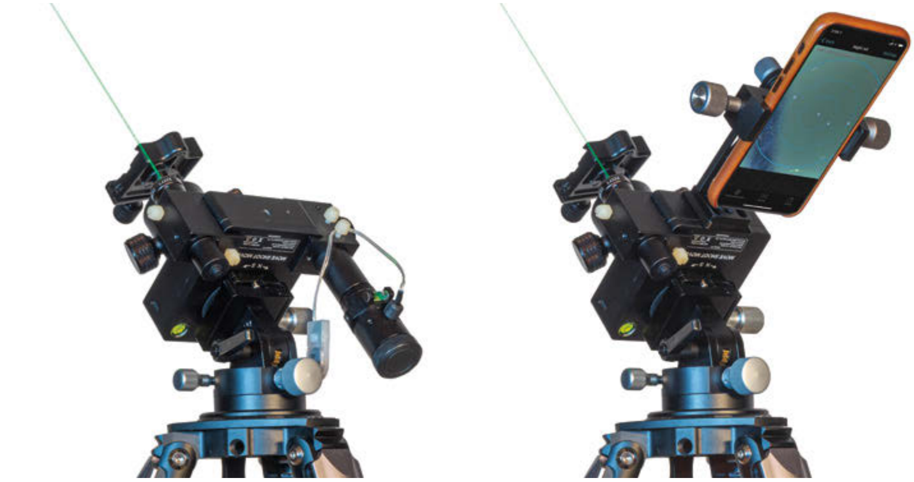
jected beam remains stationary as you rotate the laser in its mounting bracket. You can also wrap tape around the laser housing to help eliminate any play it has within the bracket.

Once I had the laser collimated, I soon learned to trust its accuracy. Its ease of use made it quick to polar align each time I moved around a scenic site seeking different compositions. (As a tip, it's possible to shine a laser through any optical polar scope, to aid in coarse polar alignment.)

Second, it might not be legal to use a 5-mW green laser where you reside, or even to import one into your country. Australian customers, for example, are advised to buy the optical polar scope (Version B), which has a reticle marked for use with the 5th-magnitude southern pole star, Sigma Octantis.

My polar scope (Version A) came equipped with an illuminated reticle with an inner circle for placing Polaris and an outer circle for Sigma Octantis. For users in either hemisphere, MSM offers an interesting alternative for polar alignment: a sturdy bracket for holding a smartphone loaded with an app to polar align. The one I found worked best is *PhotoPills* (**photopills.com**), a popular app among nightscape photographers for planning shoots, using its NightAR mode. You adjust the aim of the MSM so the app's grid of the celestial pole falls in the center of the phone screen (see photo at top of facing page).

In testing from my home in Canada, I found app-based alignment worked well enough for short exposures made with wide lenses. In the Southern Hemisphere, the app would get you close enough to the south celestial pole so that you could home in on it more accurately by using the optical polar scope. Apps allow rough polar alignment during daylight, or from sites where the pole is not visible.



▲ *Left:* While the green laser is the easiest way to polar align, the optical polar-alignment scope (attached to the right of the device) serves as a backup. While the laser's unique 3.7-volt battery is rechargeable, no charger is supplied. *Right:* A third polar-alignment option is to use a smartphone placed in the optional phone mount.

▼▶ With the correct interval (set at the camera) combined with one of the MSM's higher preset speeds, a time lapse can follow the sky while the camera pans across the scene. For time lapses, the MSM mounts horizontally, here on a third-party leveling head, with the included sync cable connected to the camera's hot shoe. A user-supplied intervalometer controls the sequence. The MSM's control panel appears the right way up only in this mode.

Tracking Performance

The Move-Shoot-Move is rated to carry up to a 3-kilogram (6.6-lb) load — a figure that from my testing I'd judge as optimistic. However, even a DSLR with a hefty wide-angle lens usually doesn't weigh more than 2 kg. The issue isn't so much weight as it is the focal length of the lens. As the focal length increases, so does the need for accurate tracking. Trailed stars from mistracking gears and mechanical slippage are far more apparent with telephotos than with wide-angle lenses.

In shooting several sets of dozens of 1- and 2-minute exposures with an

▲ The laser, once collimated, proved accurate, though it may not be legal to own or operate in some countries. Here it's shown aimed at the north celestial pole, just above Polaris on this spring night. The optional phone mount with the author's smartphone running the *PhotoPills* app also proved a coarse but reliable method of polar alignment.

85-mm lens and the camera aimed east, south, and west, I found the failure rate (the percentage of unacceptably trailed images) to lie between 15% and 60%. Sometimes the MSM tracked very well; often it did not. There was no consistent pattern, though the ratio of good-to-bad frames seemed better with the MSM mounted on its back (as seen at top of facing page) rather than on its side.

Using 135-mm and 200-mm lenses (both of which fall within the advertised limits for focal length and weight for the MSM), I found the failure rate of trailed frames in 60- to 90-second exposures to be as high as 75%. I wouldn't recommend the MSM for anyone with ambitions to shoot deep-sky objects.

To be fair, the MSM is advertised first and foremost as a portable nightscape tool, for use with more forgiving wide-angle lenses. Using a 24-mm lens and the MSM mounted on its back, I made sets of 1- and 2-minute exposures. The resulting yield was better, with only 20% to 30% of frames trailed to some extent. Some of the bad frames were at the start of a sequence, when the MSM's gears sometimes took a few minutes to engage and begin tracking.

By comparison, in two sets of 40 2-minute exposures with the same 24-mm lens and camera on the Sky-Watcher Star Adventurer Mini (one of the MSM's closest competitors), every frame was usable. (See the December 2017 issue, page 58, for my review of the Sky-Watcher tracker.)

Time-Lapse Functions

As noted earlier, the Move-Shoot-Move tracker's namesake feature is its time-lapse mode. This feature allows users to shoot a sequence of still images that are later assembled into movies in which the camera pans slowly across a scene while the foreground and sky change over time.

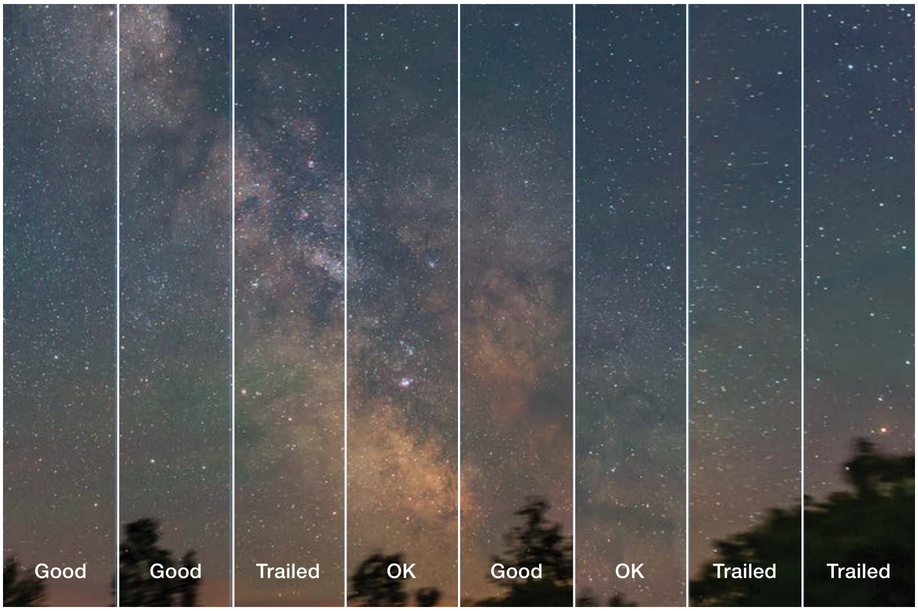
For shooting time lapses, the MSM is mounted horizontally on its other large surface, so its rotating circular platform attaches to a tripod, with the main body of the MSM on top, to turn with the camera. What's now the top surface has a bubble level and arrows showing which way the MSM will turn when set to the North or South direction. These tend to baffle some users but serve a valuable purpose in the time-lapse configuration.

▲ The Alyn Wallace V plate allows the camera to be turned by hand from frame to frame parallel to the horizon while the MSM tracks the sky, allowing for tracked nightscape panoramas.

The hot-shoe-to-rotator cord is necessary in time-lapse mode to send a signal to the MSM drive that initiates movement after each exposure.

When shooting time lapses, the MSM turns by a tiny increment between each frame when the shutter is closed. It shoots, moves, then shoots, moves, etc. This prevents the ground from blurring during long exposures at night. How much the MSM moves between each shot is governed by the four hard-wired speeds selectable on its backlit control panel. In all, the MSM worked quite well for time lapses, serving as a low-cost unit for someone getting started.

A sample 4K video of test time lapses, along with my written tutorial on how to calculate time-lapse sequences with the MSM, is available at **vimeo.com/theamazingsky/msmtest**.



▲ This set of images shows blow-ups of eight consecutive 2-minute exposures captured with a 24-mm lens. While the success rate is better than with a telephoto lens, some images still show trailing.

chance of a camera slowly twisting during a shoot, or worse, coming loose and flopping down.

Those in the Southern Hemisphere have to be especially cautious, because as the camera rotates to follow the sky it turns in the direction that will also unscrew it from the MSM if the load shifts too far to the west.

Accessory Platforms

An optional extra that many buyers select is one of the platforms designed by engineer-turned-astrophotographer and popular vlogger Alyn Wallace. His V or Z hinged-metal plates provide a level platform to mount the camera, essential for shooting tracked panoramas. They work very well for that intended purpose. The V plate simply adjusts the camera's angle, while the Z plate also raises the camera higher away from the MSM.

But I found shooting with the V platform between the MSM and ball head added another point of flexure. While they do lock down solidly, the camera and lens mounted on these plates can bounce like diving boards under most any load. They also tend to twist ever so slightly as the load shifts. Sequences taken on the V plate often showed worsening trailing as the camera rotated to the west and the load became unbalanced.

Unless you intend to shoot tracked panoramas, when one of the Alyn Wallace plates is a great addition, I suggest avoiding them. They add weight and potential instability.

Even without a V or Z platform in the stack, there are several single-point connections between the equatorial wedge, MSM, and camera that can come loose during a night's shoot. Other trackers minimize single-point screw-on connections, so there's less chance of a camera slowly twisting during a shoot, or worse, coming loose and flopping down.

Recommendations

While the promise is a device that is simple to use, my impression from testing, borne out by the many pleas for help on the Move-Shoot-Move Facebook group, is that the little tracker can be troublesome for beginners to use. Its options for mounting and polar alignment, the choice of purchasing and use of its many accessories, and the minor fixes users are advised to apply, all prompt many questions.

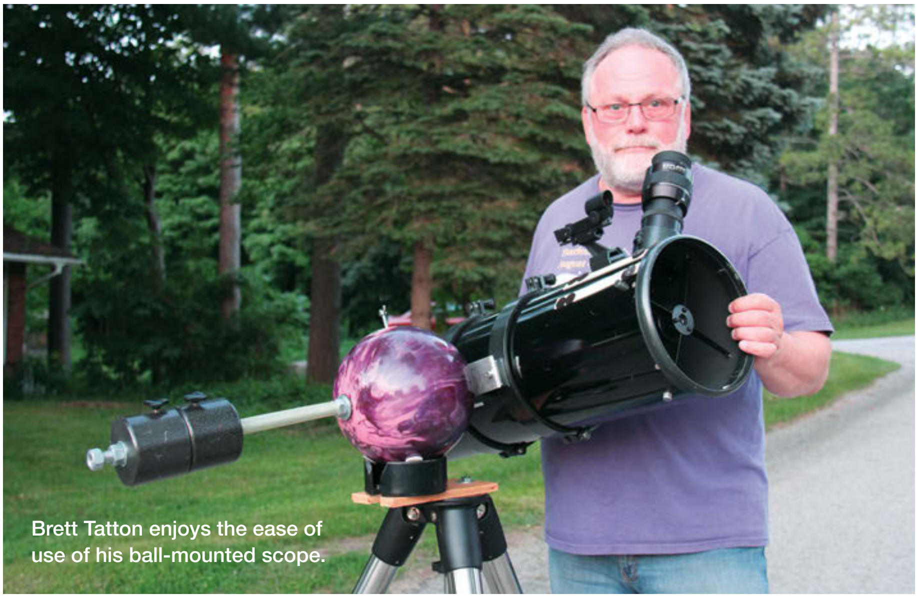
The MSM is undeniably light and compact — traits that might be paramount for you. I have friends who climb mountains to shoot their nightscapes, for whom every ounce in their backpack counts. As a portable tracker the MSM can produce good results if you restrict it to very wide-angle lenses and practice with it before a critical outing to get used to its shortcomings. Even then, take lots of shots. Don't pack up until you've inspected your images to ensure you have enough that are well tracked to make up a set for stacking or a panorama.

■ Contributing Editor **ALAN DYER** is co-author with Terence Dickinson of the revised fourth edition of *The Backyard Astronomer's Guide*, available at bookstores everywhere.

▼ This photo comprises a set of six tracked images of the sky taken with the configuration shown on the previous page, blended with another set taken with the MSM motor off to record the foreground.

Bowling Ball Mounts, Take 2

A closer look at an innovative spherical mount.



Brett Tatton enjoys the ease of use of his ball-mounted scope.

A SPHERE IN A CRADLE is arguably the simplest, most convenient way to mount a telescope. It enables easy one-axis movement in any direction, even straight overhead and near the poles, and it allows for comfortable eyepiece placement as well.

Bowling balls are ready-made for spherical mounts. In our July 2018 issue I featured several bowling-ball mounts, but I focused mostly upon the tracking system that their builder, Doug Arion, made for them. Inspired by that column, Brett Tatton, of Port Elgin, Ontario, Canada, has come up with a great design, so in this installment let's look at how he made the mount itself.

The basic concept behind the bowling-ball mount is simple: Attach the telescope to one side of the ball and stick a counterweight out the other side to balance it. Set the ball in some kind of cradle, and you're done.

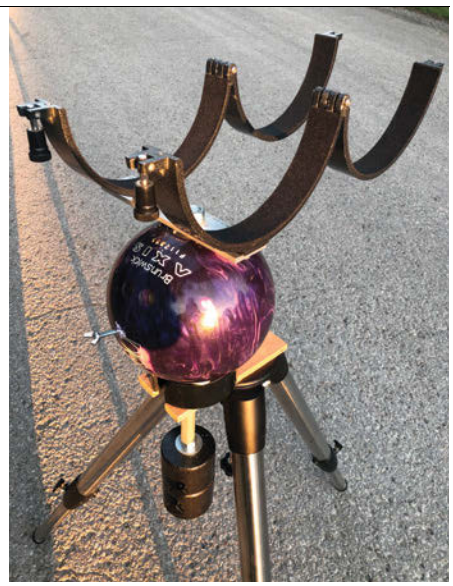
First, of course, you need a bowling ball. A trip to the local lanes yielded Brett a bright purple one for free. (Brett thanks Port Elgin's Sunset Bowling for their generosity.) He used a long ⅝-inch wood bit in a large drill press to extend the thumb hole all the way through, and he bought a length of ⅝-inch Ready Rod (long, fully threaded rod) for the transverse shaft. He ran it through the ball and bolted it to a flat metal plate that the telescope's tube rings mount to.

This brings up a happy coincidence: If you're currently using a Newtonian scope on an equatorial mount — one of the most ungainly, awkward setups known to mankind — you're in great shape to do a bowling-ball conversion. You already have the tube rings! If you have a Dobsonian, you can either make or buy tube rings or you can bolt the tube box to the transverse shaft.

When you run the rod through the ball, put a big rubber O-ring on either side and add a pair of big washers outside the O-rings. Now snug a nut up against the ball from the long side, pressing the O-rings against the ball. That'll mate the curve of the ball to the flat washers and keep the shaft from turning inside the ball. (If the shaft turns, friction on that axis won't match friction in other directions, so the scope will be harder to aim.)

Put a counterweight or two on the other end of the shaft and secure them in place with nuts, too. Another advantage for those of you moving from equatorial mounts: You have ready-made counterweights. But you can

▼▶ By moving the cradle off to the side and cutting a slot in the pipe end cap (left), Brett enabled the counterweight to hang straight down while attaching and removing the telescope (right).



ALL IMAGES COURTESY OF BRETT TATTON

◀ A thick O-ring on either side prevents the shaft from turning independently from the ball. Cover the rod's exposed threads with a plastic hose.

easily make them with barbell weights or even concrete-filled plastic bottles. Remember the principle of leverage: The longer the shaft the less weight you need — but the more awkward it will be. You can cover the exposed rod threads with a length of garden hose or any kind of tubing that fits.

The ball needs to sit in a socket of some sort that will let it glide smoothly in any direction. I've heard of people using dog bowls, but Brett found that a 4-inch pipe end cap works even better. The bottom is nice and flat and can be mounted atop a tripod with the equatorial head removed. Felt pads on the edge of the pipe cap allow the ball to move with a buttery-smooth "Kriege and Berry" feel.

Brett at first mounted the pipe cap directly atop the tripod head, but the unbalanced ball/weight assembly hopped off the pipe cap without the OTA attached. So he offset the pipe cap sideways between two of the tripod legs and cut a slot in the side of the cap so the counterweights can hang straight down. That lets him set the ball and weights into the socket, then set the scope into the tube rings and close them up with ease. Once the scope is in place, he's balanced and ready to observe.

What do you gain by making this conversion? As Brett says, "There are some nice improvements in ergonomics and utility." No Dob's hole, for one. Nor any gimbal lock near the North or South poles. Easy eyepiece height adjustment. Smooth, single-axis tracking in any direction. Until you've tried a ball mount, you have no idea how user-friendly the observing experience can be.

■ Contributing Editor **JERRY OLTION** is convinced that once people recognize the simple elegance of ball mounts, they'll eventually come 'round.

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RECLINING HUNTER

Matt Harbison

The constellation Orion abounds with nebulosity. The huge emission nebula Sharpless 264 (left) surrounds the "head" of the hunter. At right, Barnard's Loop cradles the hunter's belt and the nebulous gems IC 434 and the Great Orion Nebula, M42. At top right, above the bright star Rigel, floats IC 2118, the Witch Head Nebula. North is to the left.

DETAILS: *William Optics FLT 132 Triplet refractor with QHY 16200A camera. Mosaic of 200 panels, each totaling 2.4 hours through Astrodon LRGB filters.*

▷ A SPLASH OF SPOTS

Chris Schur

Dark sunspots stand out against the complex granules of the Sun. Its lighter penumbras give sunspot AR 2860 the semblance of planet-size ink droplets splashed on a sheet of parchment.

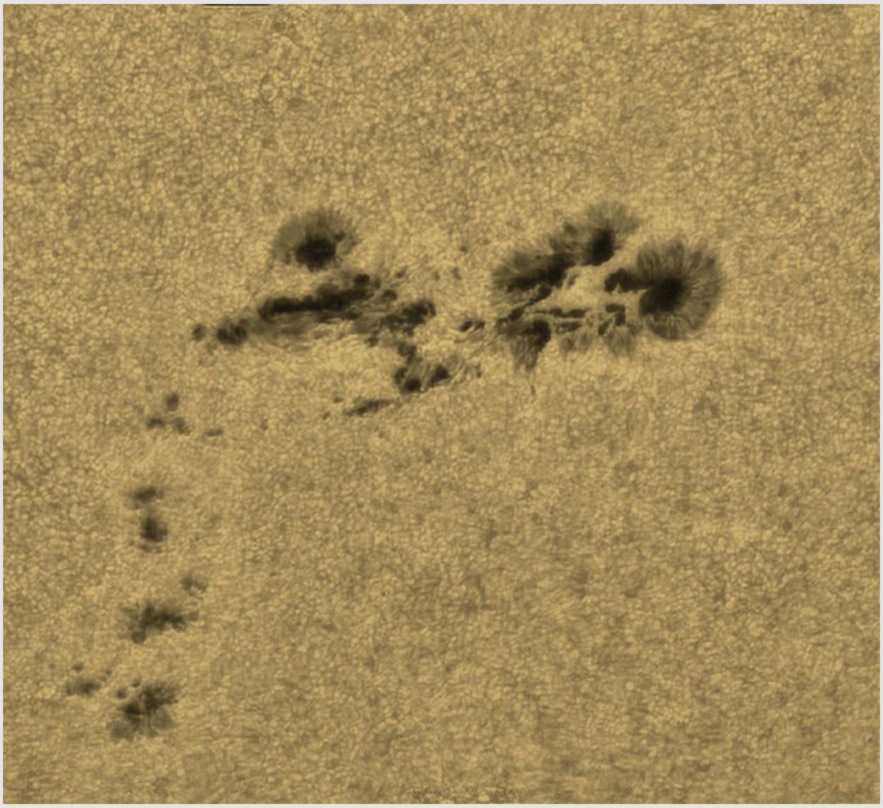
DETAILS: *Explore Scientific AR152 Doublet refractor with Imaging Source DMK51AU02 video camera. Stack of several 1/100-second frames through a solar filter.*

▽ KODACHROME BASIN

John Vermette

Utah's Kodachrome Basin State Park lives up to its photographic namesake in this 36-image nightscape. Orange Antares sits just above the horizon to the right of our galaxy's center (right). The Andromeda Galaxy shines at lower left.

DETAILS: *Canon EOS 6D camera and Rokinon 24-mm lens. Total exposure: 9 minutes per panel at f/1.4, ISO 3200.*



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The Art of Sidewalk Astronomy

A veteran offers some hard-won tips on how to perform it successfully.

WHEN I FIRST STARTED doing sidewalk astronomy, I'd stand in the town common on Saturday afternoons with my solar telescope and ask people strolling by if they'd like to look at the Sun. I might as well have had a placard around my neck reading "Creepy Guy" as I watched mothers drag their children away. So I made a sign explaining what I was up to and what visitors would see.

I've learned a lot more since then. For starters, once you have a sign, where do you take it? The answer to that question is anywhere and everywhere! Libraries and museums, outdoor concerts and farmer's markets, near the exit of a Walmart — any place with lots of people is good for outreach. I once got permission to set up in the middle of the New York State Sheep and Wool Festival, and it worked out very well.

Campgrounds are my favorite site to inspire new stargazers. You can spend more relaxed time there with folks, including kids, who are sponges that often soak up astronomy as fast as you can dish it out. Just be careful not to treat them like children: You may be surprised how much some of them know about space! Altogether, if over the course of a weekend I get just one child excited about astronomy, I've succeeded in my mission.

When sharing your telescope with the public, safety is essential. For solar-viewing with strangers, I always carry a roll of blue painter's tape to secure my filters so there's no way someone can accidentally remove them. The tape also helps to protect the filters, which I've found don't bounce when dropped on sidewalks or other unforgiving surfaces.

▶ The author cherished his friendship with the "father of sidewalk astronomy," John Dobson, seen here showing off one of his homemade solar telescopes in downtown Portland, Oregon, in 2003.

GARTH ELIASSEN / GETTY IMAGES

What hardware to bring? Day or night, choose any equipment you aren't afraid to have manhandled. I'll never forget the time I asked a kid to hold one of my treasured Nagler eyepieces, and he dropped it in the mud. After that I started wearing clothes with lots of pockets. As for scopes, Edmund Scientific's classic red Astroscan is a kid magnet and nearly indestructible.

Typically I bring a mix of refractors and reflectors so I can describe the difference between them. To display how the light path travels through each design, I have laminated diagrams. I also put out a pair of cheap binoculars on a tripod to show how magnification differs between binos and scopes.

To demonstrate Earth's rotation, I make sure I have at least one scope with tracking, and, while keeping the magnification up, I ask visitors to observe the Moon through the eyepiece as I shut off the drive. They're often stunned at how quickly our satellite drifts out of view.

> I'll never forget the time I asked a kid to hold one of my treasured Nagler eyepieces, and he dropped it in the mud. After that I started wearing clothes with lots of pockets.

If you have to park far from your outreach site, a wagon comes in handy. I bought a Radio Flyer EZ Fold wagon, which holds two scopes plus handouts and snacks. I also keep a 55-gallon garbage bag rolled up by each scope. If it starts to rain, I can quickly cover all my gear. Always bring soft cloths and a lens-cleaning pen. You'd be amazed how many people want to stick their finger or even their eyeball right into your eyepieces. Lastly, for nighttime observing, don't forget your red LED flashlight and laser pointer (if you use one).

I hope, if you're not doing it already, that you'll consider joining the ranks of sidewalk astronomers. The warm feeling you come away with from sharing your love of astronomy with other people makes it all worthwhile.

■ **ALAN RIFKIN**, a retired technical consultant, passed away in November 2019, just four days after turning in a draft of this article. His fee will go in his memory to the Springfield, Massachusetts STARS club (**https://is.gd/STARSclub**), of which Rifkin was once president.

Omne Trium Perfectum

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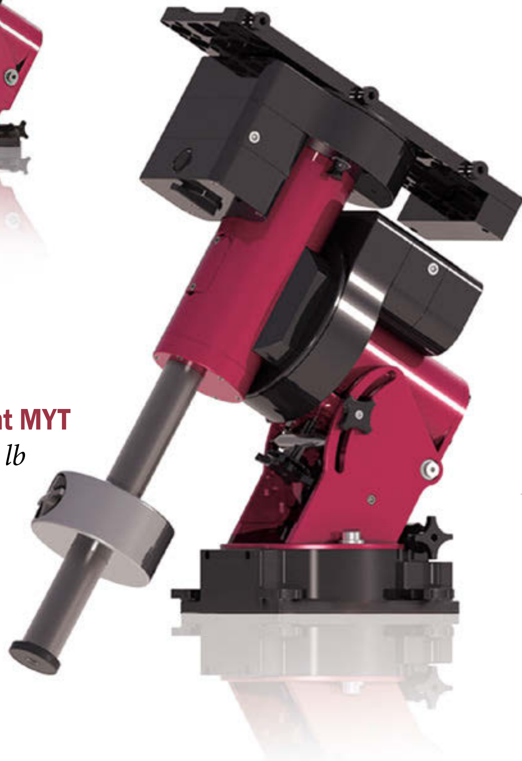

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