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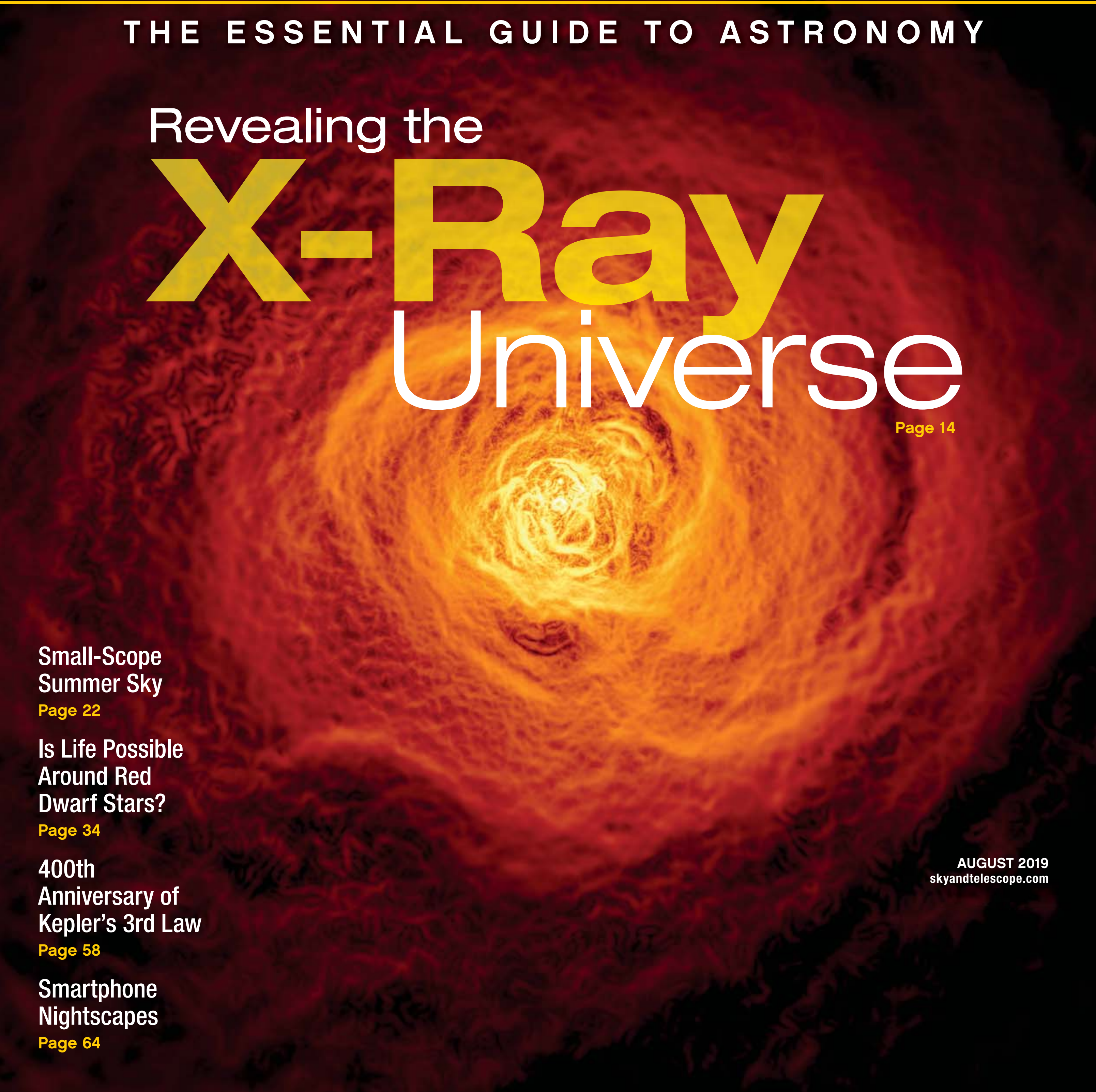
SKY & TELESCOPE

THE ESSENTIAL GUIDE TO ASTRONOMY



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AUGUST 2019
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Apollo 11 Specifications:

F.L.:	11mm
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Eye Relief:	19mm
F.S. dia. (effective):	16.2mm
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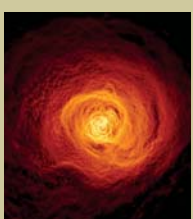

X-rays reveal swirling hot gas in the Perseus galaxy cluster.

PHOTO: NASA / CXC / GSFC / S. A. WALKER ET AL.

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A Feast for the Eyes

FORTUNATELY FOR ASTRONOMY, light comes in many flavors. If we could observe celestial objects and events only in the visible light our eyes can perceive, we'd miss so much of what is on offer out there. It would be like tasting only sweet foods but not salty, bitter, sour, or savory. How limited our palate would be!

But what our eyes can't picture, our instruments can. They can capture and focus low-energy radio, microwave, and infrared photons as well as high-energy ones such as ultraviolet, X-rays, and gamma rays. Through our ingenuity, light from the entire electromagnetic spectrum has become viewable to us.

X-ray astronomy, for one, has come leaps and bounds since its start in the early 1960s, as News Editor Monica Young details in our cover story on page 14. One striking measure of this is that, between the launch of the first focusing X-ray telescope aboard a sounding rocket in 1965, and the launch of the Chandra X-ray Observatory in 1999, the sensitivity of X-ray telescopes improved 100 million times.

In this composite image of the galaxy NGC 3079, X-rays appear in pink and purple and optical data in orange and blue.

X-RAY: NASA / CXC / UNIVERSITY OF MICHIGAN / J-T LI ET AL, OPTICAL: NASA / STSCI

X-rays are emitted when matter has been heated to temperatures in the millions of degrees, or when particles have been accelerated to relativistic speeds. By allowing us to "see" this high-energy light, X-ray space telescopes like NASA's Chandra and the European Space Agency's XMM-Newton — both 20 years old this year — enable us to witness events and objects in some of the universe's most extreme environments.

We can discern, for example, multi-million-degree gas strands around ultra-dense neutron stars or stellar black holes, whose wickedly strong gravity has yanked the gas from a companion star. We can see the crescent-shaped shock front from a supernova, where the force from what was an unimaginably violent explosion has compressed interstellar gas so quickly as to leave it glowing in X-ray light.

X-ray astronomy helps us address fundamental questions. One example involves the superhot gas that permeates galaxy clusters, the largest structures in the universe. Studying these nebulous forms aids astronomers in tackling what Riccardo Giacconi, the father of X-ray astronomy who died in December, called "one of the most interesting open questions of modern cosmology" — namely, how structure developed and evolved in the early universe.

X-rays can shoot right across the cosmos, yet Earth's atmosphere absorbs them. Imagine: After traveling for millions of years, they're stopped at the last nanosecond! But we get around that barrier with X-ray space telescopes, which spread out a celestial smorgasbord for our delectation and investigation.

Peter

Editor in Chief

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Last Look from Yerkes?

▲ Al Bellg got a look through the 40-inch refractor at Yerkes Observatory on September 26, 2018, the last clear night for public observation.

As a mutual 65th birthday present, my childhood astronomy buddy Al Bellg arranged for the two of us to tour and view at the 40-inch refractor at Yerkes Observatory in Williams Bay, Wisconsin. It turned out to be the very last clear night for public observation before the observatory ceased public operations. We brought our own 40-mm and 50-mm eyepieces to view Saturn and the Saturn Nebula, and we used the focuser ourselves.

While driving home, we remarked on how simple that giant scope was to operate: It uses setting circles, and the process of finding objects is totally manual. We were tickled to watch our host, a graduate student in astronomy at the University of Chicago, grasp the wooden handlebars and swing around the monstrous but finely counterbalanced tube to center objects for viewing, using a 6-inch finder.

Wouldn't amateur astronomy clubs line up for a series of "rental" nights to use the scope? Could management of Yerkes Observatory be shared by a consortium of amateur groups, perhaps with a local college physics department (there are two within 35 miles) keeping the keys and instituting a training program for representatives of the participating clubs? We'd love to see it happen!

Steve Marshall • Milwaukee, Wisconsin

Research and You Will Find

The letter titled "Problems at Home" (*S&T:* May 2019, p. 6) expressed concern that money is wasted on space exploration and, in particular, SETI research, which the writer believes "have little value or relevance to Earth and its inhabitants. . . ." I strongly disagree.

During fiscal year 2018, the U.S. federal government spent around $4.1 trillion. Less than half of one percent of that went to NASA and essentially zero to the SETI Institute, an organization funded mainly by private contributions. Space research has already yielded vast tangible benefits. Can you imagine going back to a world without GPS, telecommunications, or weather satellites? Finding even bacterial extraterrestrial life would be an astounding scientific breakthrough; finding intelligent extraterrestrial life would be the greatest discovery in the history of humanity.

That letter reminded me to make a donation to the SETI Institute.

Bruce Flamm
Riverside, California

Sinusoidal Tendencies

You may have gotten this question many times previously, but please explain again: Referring to the planetary almanac (*S&T:* May 2019, p. 44, for example), why does the path of the ecliptic appear to be sinusoidal? Does the projection or development of the path of the ecliptic from the surface of the celestial sphere onto the plane of the paper result in this geometry?

William Woods
Weyers Cave, Virginia

Roger Sinnott replies: *Both the celestial equator and the ecliptic are great circles. But, as you note, distortion occurs in the rectangular projection when a spherical surface is flattened out onto a sheet of paper. If the equator is made to be a straight line, the ecliptic becomes roughly sinusoidal. It would also be possible to plot the ecliptic as a straight line, but then the equator would become sinusoidal.*

There is another type of projection, the gnomonic, in which all great circles are straight lines. But in this case there is extreme distortion in scale across the chart, and less than one hemisphere can be shown on a gnomonic map. It is, however, preferred by those who observe and plot meteor showers. Each meteor's track is simply a straight line.

All's Well with Caldwells

As we approach the 25th anniversary of the Caldwell catalogue, I'd like to take a moment to thank a small but vocal group of curmudgeons for their whirlwind of negative publicity that has only helped vault the Caldwell objects into mainstream use. The Astronomical League's Caldwell Observing Program is thriving. Astronomy apps and Go To databases identify Caldwells by default. The public requests target views by "C" number at outreach events. Even the redoubtable Wikipedia highlights Sir Patrick's gems. Quite an impressive run for a list of post-Messier suggestions that started as a single *Sky & Telescope* article (Dec. 1995, p. 38).

Stephen Saber
Rock Island, Illinois

More Optical Mishaps

Bill Dellinges's letter (*S&T:* June 2019, p. 9) reminded me of a time when I imaged the crystal-clear sky all night with Amherst College's 18-inch Clark refractor. As dawn approached and I enthusiastically gathered up my plates for development, I couldn't find the lens cap anywhere. Eventually I located it perched safely atop the telescope's tube.

After throwing away the undeveloped plates, I headed home.

Harold Heaton
Damascus, Maryland

In winter, my favorite first look after collimating my 12.5-inch truss Dob is the Double Cluster, where I view the small semicircle of stars a friend has coined the "Cowboy Asterism" (the semicircle is his head, and the bright star beneath it is the medallion in his string tie). One night I had the hardest time picking out the asterism. I first thought perhaps transparency was worse than it appeared, then I began to wonder if something was wrong with my eyes.

COURTESY OF STEVE MARSHALL AND AL BELLG

Before purchasing a commercial Barlowed laser collimator, I had been using a cardboard laser collimation target I would slip over the bottom end of the focuser tube. As it turned out, I had forgotten to remove it and was trying to view the Double Cluster with an eyepiece stopped down to 6-mm aperture!

Steve Emert
White Bear Lake, Minnesota

Found in Space

Great article on Alpha Centauri (*S&T:* Apr. 2019, p. 34). This star and the 1960s television show *Lost in Space* — the Robinsons were headed there — were what first got me interested in astronomy. I tried to find out all I could about it, which wasn't easy back then. But in the Army and on guard duty one night on the Big Island of Hawai'i, I spotted it. That was the only time I've ever seen it. I'd love to see it through a telescope, but at this point in my life, that looks unlikely. I hope you'll keep us posted on any planet discoveries in that system. We may need to send the Robinsons out there someday if we screw up Earth!

Ed Bailey
Daniels, West Virginia

Another Amateur Discovery

Congratulations to Giuseppe Donatiello on his discovery of a dwarf galaxy (*S&T:* Mar. 2019, p. 9). His keen-eyed observation reminds me of another amateur who has, more recently, also discovered a previously unknown galaxy.

In 2017 Rick Steiling, a member of my local club, the Astronomical Society of Eastern Missouri, discovered a faint smudge on one of his images of the NGC 2655 field. With the help of fellow club member Dan Crowson and much sleuthing, Rick was finally able to verify that he had discovered a hitherto unknown low-surface-brightness galaxy. He and Dan published a paper in *Research Notes of the AAS* (Apr. 24, 2018), which became one of the most downloaded papers in American Astronomical Society journals in 2018. For the article, see **https://is.gd/steilingfind**. To read a discussion of the potential importance of Rick's discovery, see **https://is.gd/mzs5Zk**.

Bill Sheehy
Chesterfield, Missouri

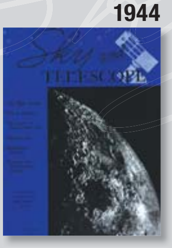
FOR THE RECORD

- While Juno was the first spacecraft to image Jupiter's poles (*S&T:* May 2019, p. 16), other spacecraft have come close to its polar perspective. Ulysses flew on a solar polar orbit, so it too flew over Jupiter's poles, though at a greater distance and without a camera. The Pioneer mission also flew by but at a more oblique angle that prevented seeing the poles themselves.

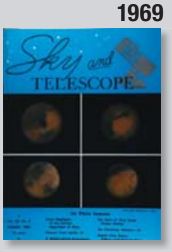
SUBMISSIONS: Write to *Sky & Telescope*, 90 Sherman St., Cambridge, MA 02140-3264, U.S.A. or email: letters@skyandtelescope.com. Please limit comments to 250 words; letters may be edited for brevity and clarity.

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

1944



1969



1994

◖ August 1944

Moon Rockets? "There are many experts who believe . . . that the day may not be far distant when we shall be exploring outer space in person — possibly 500 years from now, possibly in 1,000 years. Some think it may come even sooner than that, after the war perhaps, when men's minds will turn once more to the peacetime utility of rockets and rocket ships. Perhaps, they say, before some now alive have died, rocket-liner trips to the moon may be a common daily performance. This is wild supposition, not scientific statement. But there are those who believe it."

Marian Lockwood was an early columnist for Sky & Telescope *and its predecessor,* The Sky.

◖ August 1969

Gravitational Waves "If the results of a delicate experiment by Joseph Weber of the University of Maryland have been correctly interpreted, gravitational radiation reaching Earth from space has finally been detected. . . . He uses two or more detectors [600 miles apart, each being] a one-ton aluminum cylinder about five feet long, with piezoelectric crystals bonded to its surface. . . .

"Dr. Weber's report covers an 81-day monitoring period. During this interval, more than 17 significant coincidences were recorded."

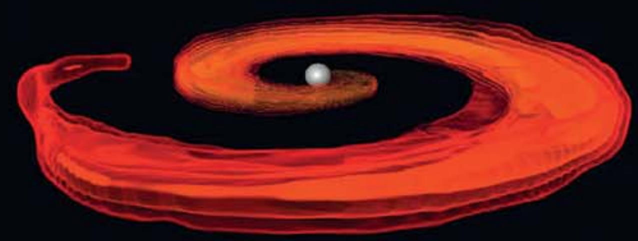
Weber's results were never confirmed, but many astronomers credit him with founding the field of gravitational-wave detection. He died in 2000. The first true waves were picked up in 2015 from the faraway merger of two black holes, probably in the south-circumpolar sky. (See also a related item, next.)

◖ August 1994

Gamma-Ray Bursts "About once a day an explosion somewhere in space produces an intense blast of gamma rays that is detected by Earth-orbiting or interplanetary spacecraft. We don't know what causes these bursts or where they are produced. They do not appear to generate radiation in any other energy range. . . . Gamma-ray bursts remain among the most baffling phenomena in astronomy. . . .

"There are good reasons to reject all of the proposed solutions to the gamma-ray burst enigma. Adherents of any one model find it easier to critique rival theories than to defend their own. Most researchers remain agnostics, awaiting some observation or theoretical development that will crack the case. . . . It is humbling that we do not know the distance scale of the burst sources to better than 10 orders of magnitude."

Charles Meegan was lamenting more than two decades of failed efforts to understand gamma-ray bursts (GRBs). But his Compton Gamma Ray Observatory team finally, in 1997, linked them to potent explosions in remote galaxies. In 2017 a GRB coincided with gravitational waves detected when two neutron stars merged in Hydra.



This simulation frame shows a black hole (gray sphere) devouring a neutron star.

GRAVITATIONAL WAVES

LIGO and Virgo Find Possible Black Hole–Neutron Star Crash

ONLY TWO MONTHS INTO a new observing run, gravitational-wave observatories have announced 13 new candidate signals — one of which could turn out to be a black hole swallowing a neutron star.

Major improvements to both the Laser Interferometer Gravitational-wave Observatory (LIGO) in the U.S. and the Virgo instrument near Pisa, Italy, have made all three detectors far more sensitive to ripples in spacetime. And beginning with the third observing run, which goes from April 2019 to April 2020, LIGO and Virgo are announcing gravitational-wave signals as they happen — that is, before the sources themselves are fully vetted and confirmed as real. Finding electromagnetic radiation from these candidate events is crucial to understanding them, and immediate announcements allow astronomers to observe the sky near candidate sources at once.

Of the 13 candidates announced as of May 24th, 10 appear to be black hole mergers, while two others seem to be neutron star crashes. The most tantalizing, though, is a possible mashup between a black hole and a neutron star. (These categories are preliminary and await further analysis.)

While black hole pairs aren't expected to produce light, astronomers do expect inspiraling neutron star pairs — or a neutron star spiraling into a black hole — to flash across the electromagnetic spectrum. No counterparts have been announced so far, but investigations are still under way.

Unfortunately, one of the detectors — LIGO Hanford — was briefly offline when the signal from the first neutron star merger arrived on April 25th. All three detectors working together can narrow the field to hundreds of square degrees, but with Hanford out of commission the sky area to comb through expanded to 10,000 square degrees. All detectors were online when the second such merger was detected.

Meanwhile, the signal from the black hole–neutron star collision, which came on April 26th, was weak. "It's like listening to somebody whisper a word in a busy café," says LIGO spokesperson Patrick Brady (University of Wisconsin, Milwaukee). "It can be difficult to make out the word or even to be sure that the person whispered at all. It will take some time to reach a conclusion about this candidate."

Despite the challenges involved in following up on gravitational-wave signals, early efforts are promising. "We do have one tantalizing candidate remaining for which the jury is still out," says Mansi Kasliwal (Caltech). "We are collecting more information, and I hope to be able to say more soon."

Regardless, 13 candidates in two months is an auspicious start. The team had expected to find a few black hole mergers per month; however, with only a single neutron star collision observed in 2017, predictions for the rate of these less-massive mergers had ranged from one per month to one per year. As of the end of May, we've already seen two neutron star mergers; if things keep going this way, we can expect to see many more.

■ MONICA YOUNG

Find out how amateurs can participate in LIGO research by visiting https://is.gd/proamLIGO.

THE MOON

Apollo-era Data Reveal the Moon's Tectonic Activity

A NEW LOOK AT OLD SEISMIC DATA gathered during the Apollo missions reveals that young active faults might be the source of shallow moonquakes.

When the Apollo astronauts deployed seismometers on the lunar surface, they revealed 28 shallow, but sometimes surprisingly powerful, quakes between 1969 and 1977. A new study appearing May 13th in the journal *Nature Geoscience* links these quakes to current tectonic activity on the Moon.

As the Moon loses heat from its interior, it shrinks and its surface wrinkles. Thrust faults form where the brittle crust breaks: One side of the break slips downward while the other side goes upward, a process that creates steep slopes, or *scarps*, typically tens of meters high.

Even though these faults cover most of the lunar surface, they had largely gone undetected until 2010,

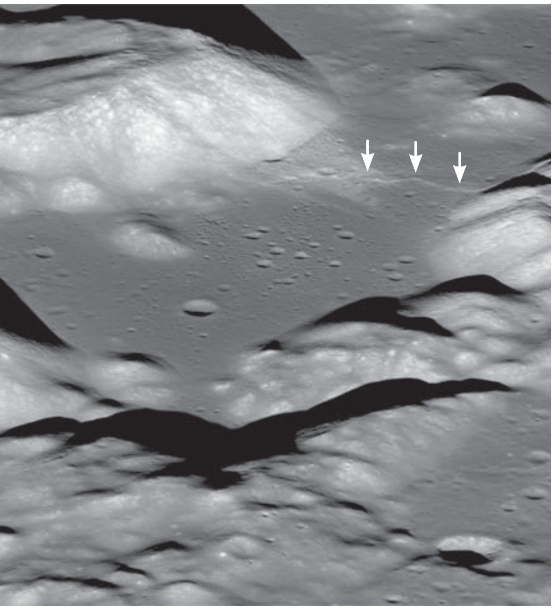
MILKY WAY

Omega Centauri Is Losing Its Stars

ASTRONOMERS HAVE DISCOVERED a stream of stars pulled from Omega Centauri, the largest and most brilliant globular cluster around the Milky Way — and perhaps the remnant of a one-time dwarf galaxy.

Omega Centauri is unusually luminous and massive. What most puzzles astronomers, though, is that its stars separate into multiple populations, suggesting that the cluster came together over billions of years instead of all at once. These peculiarities have led some astronomers to suggest that this globular might actually be the remains of a galaxy that came too close to the Milky Way. As it was

A. TONITA, L. REZZOLLA & F. PANNARALE



▲ Apollo 17 astronauts Eugene Cernan and Harrison Schmitt zigzagged their rover up and over the Lee-Lincoln fault scarp (arrows) that cuts across the Taurus-Littrow Valley.

when NASA's Lunar Reconnaissance Orbiter started systematically mapping the surface at high resolution. Thomas Watters (Smithsonian Institution) and colleagues estimate that the scarps are younger than 50 million years old.

But are the faults these scarps are associated with still active today? The researchers used a new computer algorithm to better estimate the locations of the quakes' epicenters, and their analysis revealed that eight of the quakes were centered within 30 kilometers (19 miles) of a fault scarp. Moreover, six of these quakes occurred during *lunar apogee*, when the Moon's elliptical orbit takes it farthest from Earth. (In fact, 18 of the 28 shallow shakes occurred close to apogee.) The connection with apogee is important, because that's when Earth's tidal pull per lunar surface area is largest. This gravitational stress is what can cause the faults to slip, resulting in the tremors observed.

Brigitte Knapmeyer-Endrun (University of Cologne, Germany), who was not involved with the current study, agrees the result is statistically significant. If the results pan out, they'd point to a Moon that is still tectonically active more than 4 billion years after its formation. The results could also have practical implications for lunar exploration, such as avoiding high-risk areas when planning permanent structures.

■ JAVIER BARBUZANO

IN BRIEF

Beresheet Crash-lands on the Moon

Israeli company SpaceIL attempted to land Beresheet (Hebrew for "in the beginning") on the Moon on Thursday, April 11th. Launched on February 22, 2019, the Beresheet mission took six weeks to reach the Moon, using a series of orbital boosts that elongated its orbit for capture by the Moon's gravity on April 4th. While the first phases of the descent went off without a hitch, the lander began having trouble with its main engine. Although the team was able to re-establish contact and restart the engine at an altitude of about 150 meters (490 feet), it was too late. Final telemetry showed that the lander was still going 1,080 m/s (2,400 mph) when it slammed at a low angle into the lunar surface. The Lunar Reconnaissance Orbiter later imaged the crash site at the edge of Mare Serenitatis. Beresheet cost only $100 million to build and was funded mostly by private donors. Beresheet 2.0 is now under way, and Peter Diamandis of the XPRIZE foundation has already pledged $1 million toward the new mission's development.

■ DAVID DICKINSON

torn apart by our galaxy's gravity, most of its stars would have streamed away, looping around the galaxy. Rodrigo Ibata (University of Strasbourg, France) and colleagues reported new evidence for this theory April 22nd in *Nature Astronomy*: the long-sought detection of a stellar stream belonging to Omega Centauri.

The European Space Agency's Gaia satellite provides precise distances to and movements of more than a billion stars. When stars that are near one another also move together — especially if they're outside the galactic disk — they're probably part of a stellar stream. To find these stellar groupings, Ibata's team used a computer algorithm called *Streamfinder* to pick out more than a dozen new streams.

One of these, dubbed Fimbulthul (for one of the 11 rivers that coursed through the primordial void in Norse mythology), contains 309 stars across 18° on the sky. The researchers calculated the stellar orbits, which take the stars as close as 5,000 light-years to the galactic center and as far as 21,300 light-years — remarkably similar to Omega Centauri's orbit. Moreover, the range of heavy-element abundances detected in Fimbulthul's stars is consistent with stars in the globular. Computer simulations show that Fimbulthul could be the trailing arm of stars that our galaxy's gravity has pulled from Omega Centauri.

The researchers acknowledge that their computer simulations are still simple and not a perfect match to the data. Future plans include working on more realistic models to better understand the Fimbulthul stream's origins.

■ MONICA YOUNG

Omega Centauri

MOON: NASA / GSFC / ARIZONA STATE UNIV.; OMEGA CENTAURI: ESO / INAF-VST / OMEGACAM / ACKNOWLEDGEMENT TO A. GRADO, L. LIMATOLA / INAF-CAPODIMONTE OBSERVATORY

COSMOLOGY

Astronomers Find Universe's First Type of Molecule

ASTRONOMERS OBSERVING NEARBY interstellar space have finally detected helium hydride (HeH^+), the first molecule to form in the early universe. Rolf Güsten (Max Planck Institute for Radio Astronomy, Germany) and colleagues report the find in the April 18th *Nature*.

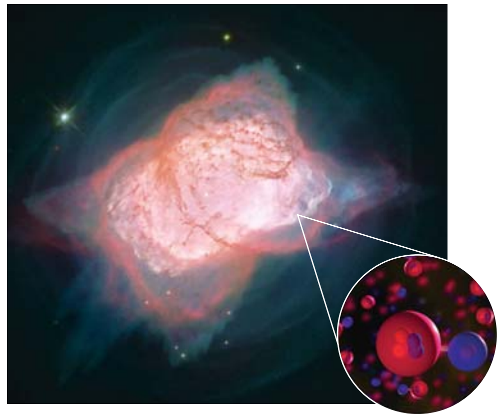
The early universe contained mostly hydrogen and helium, so it's perhaps unsurprising that its first molecule would be helium hydride. But of all the elements, helium requires the most energy to remove an electron — it's no easy feat for it to combine with another atom. Indeed, the ion didn't survive long even in the unique conditions of the early universe, but it played a brief but important role. Its destruction gave rise to molecular hydrogen (H_2), which eventually permeated galaxies and star-forming reservoirs. The existence of HeH^+ is thus instrumental to understanding early chemical evolution.

Yet for years, astronomers tried — and failed — to detect the molecule. Although it was created in a lab in 1925, its fragility makes it rare in the natural world. Astronomers in the 1970s realized they might find the molecule newly created in nearby plasmas, but a definitive detection eluded them.

So Güsten and colleagues took to the skies. They flew with the Stratospheric Observatory for Infrared Astronomy aboard a modified Boeing 747, soaring above the infrared-absorbing lower atmosphere (*S&T:* Apr. 2015, p. 60) to observe a planetary nebula named NGC 7027. The nebula is an ideal target because the blazingly hot 600-year-old white dwarf at its center emits ultraviolet radiation that strips electrons off hydrogen and helium atoms alike. The spherical region where helium is ionized is slightly larger than where both hydrogen and helium are ionized; in this outer region, ionized helium is able to bond with neutral hydrogen to make helium hydride in a thin shell around the star. Using the German Receiver for Astronomy at Terahertz Frequencies instrument, Güsten and colleagues detected radiation from the ion at 149.137 microns.

Having finally discovered HeH^+, the team also studied the formation and destruction mechanisms of the molecule that kick-started cosmic chemistry.

■ **MONICA YOUNG**



▶ Astronomers found helium hydride molecules *(inset)* in the heated gas of the planetary nebula NGC 7027.

EXOPLANETS

Solar System "Twin" Is Missing Infant Jupiters

EXCEPTIONAL NEW IMAGES of the LkCa 15 system, a young, Sun-like star once thought to host multiple gas giant protoplanets, show that these particular planets probably don't exist after all.

LkCa 15 has excited astronomers ever since interferometry and direct observations of hydrogen gas flows turned up evidence of up to three gas giants being born in the protoplanetary disk of gas and dust around the star (*S&T:* Aug. 2012, p. 20). These putative planets orbit inside the large outer disk, having presumably cleared out the inner region. Since LkCa 15 is only a couple million years old, the same age as our Sun was when Jupiter and Saturn took shape, the discovery promised insights into the birth of a solar system.

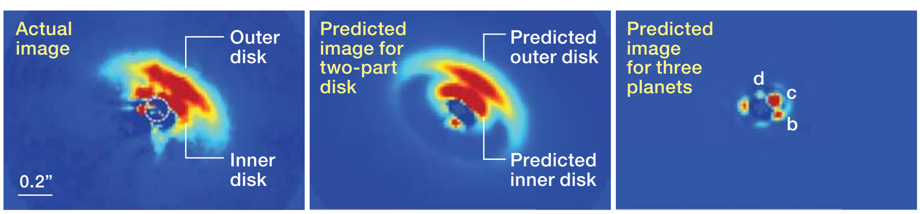
But Thayne Currie (NASA Ames Research Center) and colleagues are throwing those claims into question with a new study to be published in the *Astrophysical Journal Letters*. The team used the Subaru Coronagraphic Extreme Adaptive Optics system at the Subaru Telescope to take a sharper image of the LkCa 15 system than ever before obtained.

The resulting view doesn't show any baby Jupiters; instead, it shows an inner disk in addition to the outer one. Starlight scattered off the inner disk has the same brightness as the signals previously attributed to protoplanets.

Keck Observatory images taken in 2009 and 2017 confirm that this bright arc remained in the same place over the years. If the light were coming from unresolved planets, the arc would have rotated around the star.

Nevertheless, Kate Follette (Amherst College), who was not involved in the new study, thinks the data still support the existence of at least one protoplanet, and Currie agrees: "I think it's very clear that there are planets around the star. They're just fainter than we previously thought." Distinguishing infant planets from the disk they're born in will continue to be a challenge.

■ **STEVEN MURRAY**



▲ *Left:* A new image of LkCa 15 reveals two arcs of light. *Middle:* A theoretical model with an inner and outer disk reproduces the arcs. *Right:* Another theoretical model shows what the image would look like if the innermost arc were actually multiple planets.

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STARS

Astronomers Use Asteroids to Measure the Stars

ASTRONOMERS USUALLY GLEAN information about an asteroid's shape and size during an *occultation*, when the rock briefly blocks a background star. Now, astronomers are using occultations to measure the stars themselves.

The four 12-meter telescopes that make up the Very Energetic Radiation Imaging Telescope Array System (VERITAS) in Arizona are designed to watch for the faint blue flashes of Cherenkov radiation, produced when gamma rays crash into Earth's atmosphere. But Wystan Benbow (Center for Astrophysics, Harvard & Smithsonian) and colleagues instead decided to try using the telescopes to measure stellar diameters during asteroid occultations. They published the results April 15th in *Nature Astronomy*.

▼ This artist's concept exaggerates the diffraction pattern of a distant star as it's occulted by an asteroid.

When an asteroid passes in front of a star, the edges of the shadow it casts are lined by so-called *diffraction fringes*, where light waves interact to alternately boost or cancel the signal. So, immediately before and after an asteroid blocks out a background star entirely, the star's brightness will vary in a predictable way. The VERITAS telescopes' large collecting areas and incredible time resolution enable astronomers to distinguish these small changes in brightness from the blurring effect of Earth's atmosphere. By comparing the observed fringes to those from a true point source, Benbow's team inferred the diameters of two stars.

First, the asteroid 1165 Imprinetta passed in front of the 10.2-magnitude star TYC 5517-227-1. In this proof-of-principle observation, the astronomers used VERITAS to snap 300 images a second, pegging the star's angular size at 0.125 milliarcsecond. Given its distance of 2,700 light-years, that's equivalent to between 9 and 12.9 times the Sun's diameter. From its size, and follow-up observations to measure its spectrum, the researchers conclude the star must be a red giant.

A second chance for the team came when the asteroid 201 Penelope swept in front of 9.9-magnitude star TYC 278-748-1. This time VERITAS captured 2,500 images every second, giving an angular size of 0.094 milliarcsecond. At the star's distance of 700 light-years, it must have a girth about twice the Sun's. A spectrum confirms the star is in the Sun's G class.

The uncertainty in asteroid orbits makes predicted paths uncertain, too, so observing asteroid occultations with large, unportable telescopes is difficult. Nevertheless, the researchers figure, any telescope capable of observing a 10th-magnitude star should see on average about five occultations per year.

■ DAVID DICKINSON

IN BRIEF

First Marsquake Detected

After two months of science operations, Insight's Seismic Experiment for Interior Structure (SEIS) picked up its first clear quake. Insight Principal Investigator Bruce Banerdt (NASA JPL) announced the detection on April 23rd at the annual meeting of the Seismological Society of America. The trembling may have originated from heat loss from the Martian interior, or it could have come from a meteorite impact that reverberated inside the planet. The signal lasted around 10 minutes and had a magnitude of 2 to 2.5, a shaking so slight that humans wouldn't have felt it if it had happened on Earth. SEIS has recorded three other signals that could also be marsquakes, but researchers are still working to rule out other possible causes. Depending on how many of these tentative signals are confirmed as real, the data collected so far suggest that SEIS may see 5 to 18 marsquakes per year.

■ JAVIER BARBUZANO

Chang'e 4 Explores the Farside of the Moon

Since China's Chang'e 4 spacecraft landed in Von Kármán Crater on January 3rd (*S&T:* Apr. 2019, p. 9), its Yutu 2 rover has been measuring the spectra of sunlight reflecting off the crater floor and the huge South Pole-Aitkin basin in which the crater resides. In the May 16th *Nature*, Chunlai Li (Chinese Academy of Sciences) and colleagues report the spectral fingerprints of olivine and low-calcium pyroxine, two minerals that probably originated in the lunar mantle. The presence of mantle material is expected; scientists figured that the impact that carved out the largest and oldest basin on the Moon would have penetrated the crust and excavated the mantle beneath it. However, this is the first time a mission has actually sampled mantle material. The find sheds light on the mantle's composition — which may contain the two minerals in equal parts — and, ultimately, on the nature of the magma ocean that once enveloped the Moon.

■ MONICA YOUNG

The Origin of Saturn's Inner Moons

At least five of the small moons dancing among Saturn's rings likely formed as icy ring material built up around tiny cores. That's the scenario favored by Bonnie Buratti (Jet Propulsion Laboratory) and colleagues March 28th in *Science*. The scientists came to this conclusion using images and other data taken by the Cassini spacecraft as it whizzed close by the moons Pan, Daphnis, Atlas, Pandora, and Epimetheus five times between December 2016 and April 2017. The flybys were part of the "Ring-Grazing" phase of the spacecraft's final orbits. The observations show that the moons have low density and porous surfaces. These properties support the idea that the moons were created by the buildup of icy ring material, perhaps around the shards of an earlier moon that broke up near Saturn. Ridges around the equators of Pan and Atlas, which give them a ravioli-like appearance, are also likely accreted ring material.

■ CAMILLE M. CARLISLE

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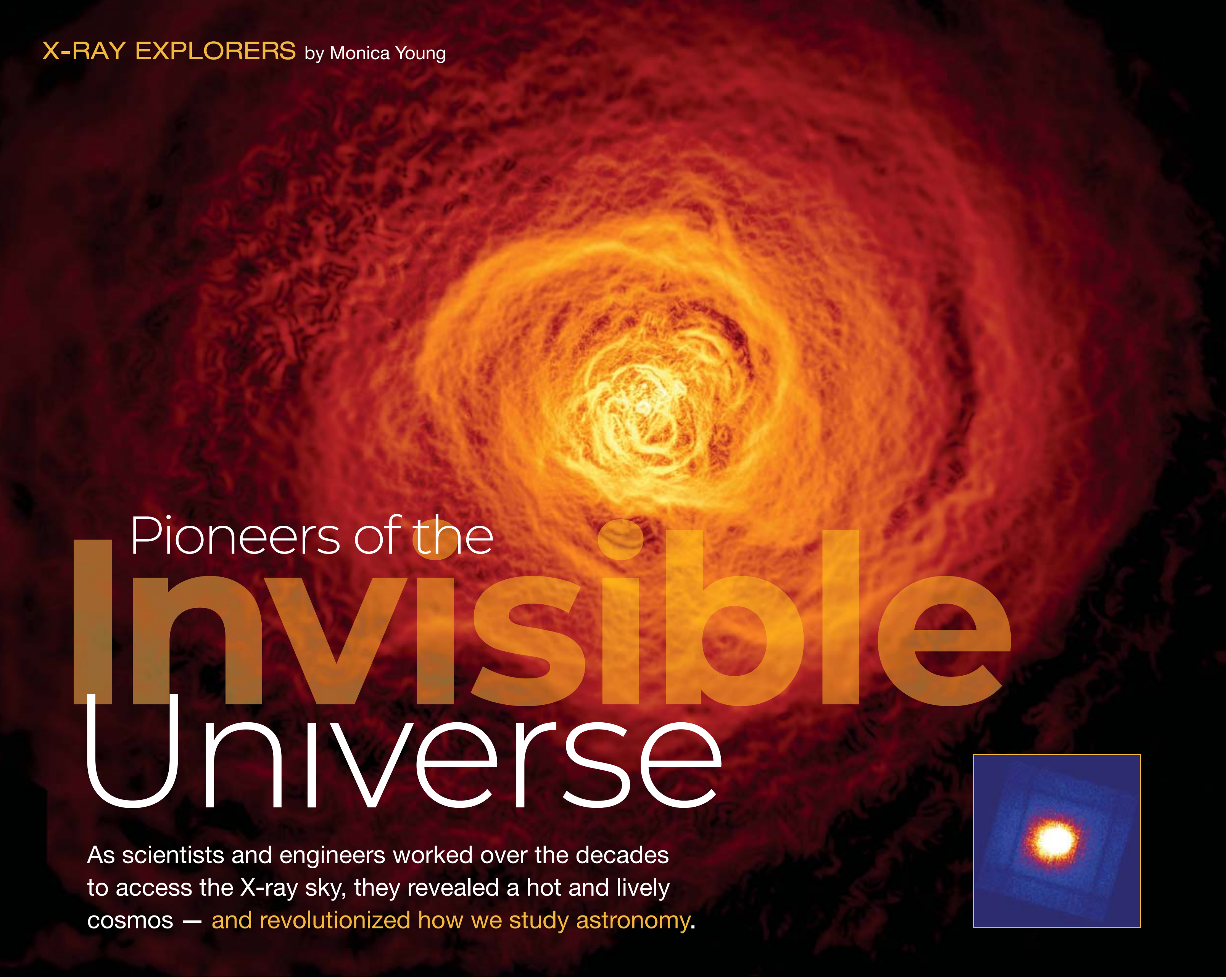
 by Monica Young



Pioneers of the Invisible Universe

As scientists and engineers worked over the decades to access the X-ray sky, they revealed a hot and lively cosmos — and revolutionized how we study astronomy.

▲ **PERSEUS CLUSTER** After the Uhuru satellite first detected hot gas swirling within galaxy clusters, the Einstein Observatory imaged the blob of gas within Perseus (*inset*). Ultimately, Chandra revealed intricate details that are helping astronomers probe the cluster's history.

PERSEUS BY CHANDRA: NASA / CXC / GSFC / S. A. WALKER ET AL.; PERSEUS BY EINSTEIN: NASA

Walk outside tonight and you'll see stars twinkling in their constellations, while planets wander predictably through the star field. Only the occasional nova or eclipse mars the seemingly immutable heavens.

But what if we swapped this tame view with X-ray vision? Hot and violent sources would flare across the sky; Aristotle would never have spoken of immutability under such a sight.

Fortunately for philosophers (and for life itself), Earth's atmosphere has long shielded against doctrine- and DNA-destroying X-rays. Humanity had graduated to space before we realized what we were missing. The first hints of an X-ray-emitting universe came from rocket and balloon observations of the Sun, starting in 1949. But solar emissions were so weak — a million times fainter than visible light — that to see even nearby stars, detectors would have had to be a thousand times more sensitive. Scientists doubted other cosmic X-ray sources could be observed. In fact, NASA rebuffed scientist Riccardo Giacconi (then at American Science & Engineering) when he submitted a proposal for a rocket to observe X-rays from across the sky.

Undeterred, Giacconi reworked his proposal for the U.S. Air Force. The solar wind, he argued, could fluoresce off the Moon with possible impacts on communications. The Air Force accepted his proposal and in 1962, after two failed attempts, Giacconi and his team finally launched an Aerobee rocket from White Sands Missile Range in New Mexico.

The rocket flew above 80 kilometers (50 miles) — where the atmosphere thins enough for X-rays to pass through — for all of 5 minutes and 50 seconds. But during that brief time, it caught something: a bright X-ray source nowhere near the Moon, dubbed Scorpius X-1 for its location on the sky.

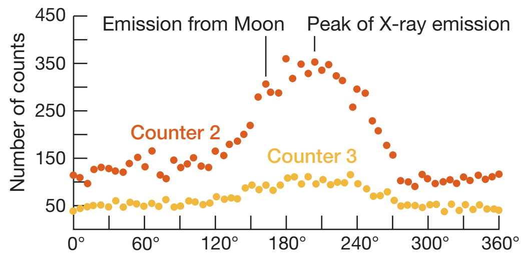
Turns out, Sco X-1 is the brightest enduring X-ray source outside the solar system. But the rocket launched by Giacconi's team might easily have missed it: A big chunk of sky was hidden behind Earth during the nearly six minutes the rocket was aloft. The discovery was fortunate indeed for Giacconi, as it played a key role in winning him the 2002 Nobel Prize in Physics. But it was even more fortunate for X-ray astronomy, galvanizing the field as well as the imagination. "It was pretty hard to explain [Sco X-1] by anything except something that you didn't expect to find," says former Chandra X-ray Center director Harvey Tananbaum (Center for Astrophysics, Harvard & Smithsonian).

Over the next six decades, X-ray astronomy kept growing, albeit sometimes in fits and starts. As more instruments took to space, the data that came back helped confirm theorists' wildest imaginings — X-rays provided crucial evidence for the existence and physics of neutron stars, black holes, dark matter, and more. "There's a whole range of activity in the universe that would have been completely unknown to us without X-ray astronomy," says Peter Kretschmar (European Space Agency). Yet even as 2019 sees the triumphant 20th anniversaries of the Chandra X-ray Observatory and the XMM-Newton satellite, astronomers are still struggling to maintain their space-based window on the X-ray universe.

Revealing the X-ray Sky

Year	Number of X-ray sources
1962	1*
1965	10
1970	60
1974	160
1980	680
1984	840
1990	8,000
2000	340,000
2010	780,000
2017	1,250,000

*Excluding the Sun.
Data source: NASA's High Energy Astrophysics Science Archive Research Center



▲ **DISCOVERY** Riccardo Giacconi and his team launched an Aerobee rocket and, in addition to solar fluorescence off the surface of the Moon, the second proportional counter onboard detected X-rays streaming from a source identified as Scorpius X-1. The third counter, which was pointing in another direction, saw a pervasive background of X-ray photons. (The first counter failed and isn't shown.)

Freedom: Satellites Take to the Sky

Not long after the first discoveries, scientists began craving more than the few minutes of observing time that a rocket could grant them. Giacconi led the team at AS&E as they began to build a dedicated X-ray satellite — this time with NASA funding.

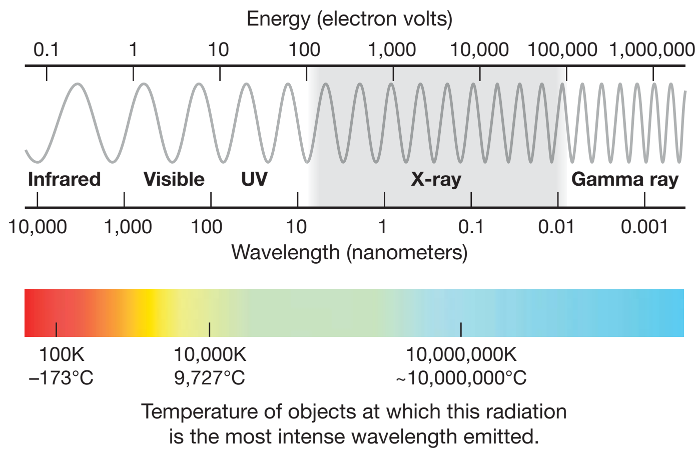
The project, officially known as Small Astronomical Satellite A, would contain two sets of *proportional counters* to scan the sky and pinpoint X-ray sources to within a few arcminutes. These proportional counters consisted of beryllium casings surrounding interiors that were filled with argon gas. An X-ray photon that penetrated the tube's thin beryllium windows would collide with an argon atom and initiate an avalanche of ion-electron pairs proportional to the photon's energy. Combined with a star tracker that told scientists which way the satellite was pointing, the proportional counter could record X-rays by their position on the sky.

The just-graduated Tananbaum joined the team in 1968, when the field of X-ray astronomy was only six years old. He accompanied equipment to the launch site off the coast of Kenya, an equatorial location where Earth's rotation boosts rocket speed. With the rocket due to launch shortly after midnight, Tananbaum followed the crew's progress via a computer on the mainland, six miles from the rocket platform. He was waiting to perform a last equipment test about half an hour before launch.

"They're counting down, and they go into a hold, they're checking something on the rocket," he recalls. "There's limited information flowing, and the Sun comes up and it's starting to get warm. . . . Temperatures inside the payload are going up and up." High heat and humidity were threatening the mission before it could make it into space. The platform crew had to decide: scrub or launch.

The decision was quick — the count jumped from T minus hours to T minus minutes. "And bingo, it launches," Tananbaum chuckles. That day, December 12, 1970, happened to fall on Kenya's independence day, and Giacconi renamed the mission Uhuru (Swahili for freedom) in the country's honor.

Before long, computer screens showed so-called "X-ray stars" seething on the sky. Some varied predictably in their



▶ **X-RAY VISION** Rather than using wavelengths, astronomers typically refer to X-rays in terms of their energy, given in units of electron volts (eV) or, more often, kiloelectron volts (1,000 eV, or 1 keV). Uhuru, for example, used proportional counters to detect X-rays in the range from 2 to 20 keV. Nowadays, XMM-Newton sees X-rays between 0.1 and 10 keV. Some instruments, like Integral, go to even higher energies, catching both X-rays and gamma rays (3 to 10,000 keV).

DISCOVERY OF SCO X-1: R. GIACCONI ET AL. / *PHYSICAL REVIEW LETTERS*
1962; ELECTROMAGNETIC SPECTRUM: GREGG DINDIERMAN

emissions, such as Centaurus X-3: This source brightened and faded every 4.8 seconds, while its average brightness went up and down over a roughly two-day period. Others, like Cygnus X-1, varied randomly but hugely on time scales as short as a tenth of a second, implying that whatever was radiating was extremely small.

At first, scientists had no idea what could be powering these strong X-ray sources. “While you’re trying to figure it out, discovery at that point is challenging,” Tananbaum says. “It’s not just exhilarating, I mean; it’s very frustrating.”

Kretschmar thinks part of the struggle was philosophical. “The astronomy community was maybe not fully believing that black holes and neutron stars would really exist,” he says. Some scientists especially opposed the idea of black holes. “A lot of this was marginal, at the fringe of science,” Kretschmar adds.

But understanding dawned quickly. Cen X-3’s regular, seconds-long pulsations are a signature feature of pulsars, spinning neutron stars detected in X-rays rather than radio. The source’s longer, two-day variation comes about because the pulsar is in an eclipsing binary system.

▲ Riccardo Giacconi hangs out with the Uhuru flight spare.

▼ **UHURU** Before the spacecraft could be shipped to Kenya for launch to space, it underwent preflight tests at the NASA Goddard Space Flight Center (*left*, shown with Project Manager Marjorie Townsend and a colleague). An artist’s concept (*right*) shows the spacecraft in flight.

Cygnus X-1 proved more of a puzzle; there was no predicting its tumbles up and down in brightness. The biggest clue appeared when astronomers combined Uhuru data with visible-light observations, which showed a blue supergiant star orbiting the X-ray source every 5.6 days. The short period implied an enclosed mass at least 10 times the Sun’s — too massive for a white dwarf or neutron star. Soon, Cygnus X-1 became the poster child for the existence of black holes.

All in all, Uhuru cataloged several hundred X-ray sources, tracking some of them for years. It was a remarkable achievement considering the onboard data recorder failed after only six weeks: For most of its time in space, the mission could only transmit data in real time, as it was flying over ground stations. Then a key component of the star tracker, which determined where the satellite was looking at any given time, burned out after inadvertently crossing the Sun. Christine Jones (then a Harvard graduate student conducting research at AS&E) found a workaround, using the spacecraft’s magnetometers to localize sources. Nevertheless, after two years the mission was on its last legs.

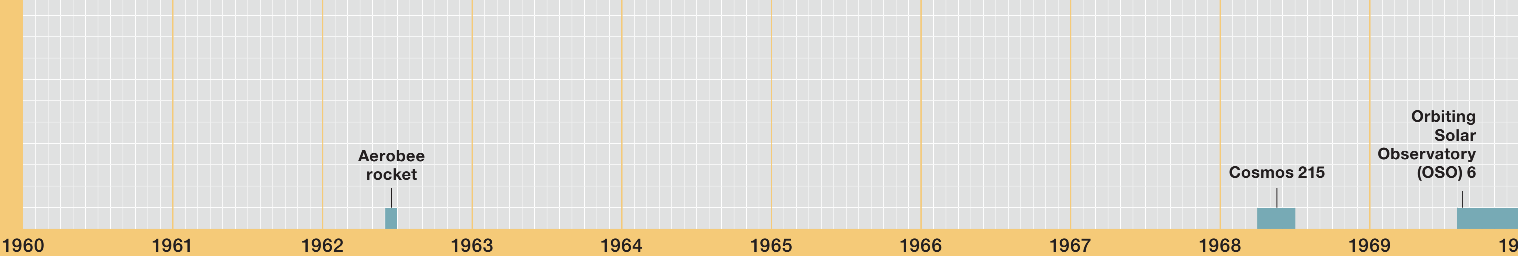
Fortunately, other missions were on their way. Ariel V, a British-American satellite launched in 1974 from Kenya, was equipped with higher sensitivity, a better ability to pinpoint sources, and, ultimately, a lifetime twice as long as Uhuru’s.

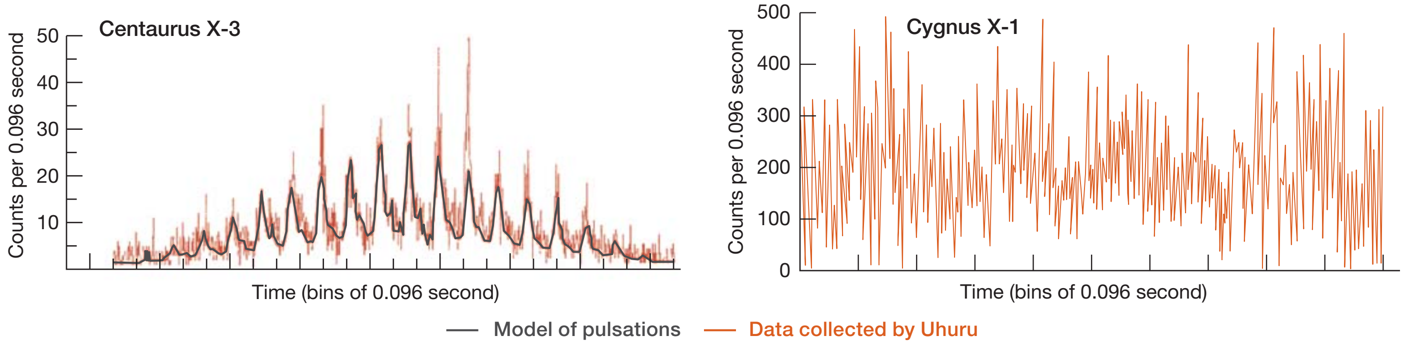
That same year, Martin Elvis (now at the Center for Astrophysics, Harvard & Smithsonian) joined the Ariel V team at Leicester University, UK. He started his graduate studies just as many of the astronomers left for Kenya’s warmer and sunnier weather. “But it was incredibly lucky for me,” he says. He recalls spending his student days monitoring the basement printer as data began coming back. “I remember watching the plots come out. We’d have these pen plotters that would do this ‘djj djj djj,’ drawing little boxes on the sky on very long rolls of paper. . . . You’d see these one-dimensional scans of the sky, a little histogram going around 360°, and you’d see sources popping up.”

“We found not just new sources but new *types* of sources,” Elvis adds. “We’d publish one after another — oh, we found a distant cluster of galaxies; oh, we found an active galaxy!”

GIACCONI: CENTER FOR ASTROPHYSICS, HARVARD & SMITHSONIAN; UHURU PRE-FLIGHT: NASA; UHURU ARTIST CONCEPT: SMITHSONIAN ASTROPHYSICAL OBSERVATORY; TIMELINE INFOGRAPHIC: TERRI DUBÉ, SOURCE: JONATHAN MCDOWELL

THE EVOLUTION OF X-RAYS Over the decades, astronomical X-ray explorations have advanced from relatively short-lived projects to decades-long missions. With the exception of the galvanizing 1962 rocket flight, this graphic shows only orbital X-ray missions.





▲ **HEARTBEAT & CHAOS** Uhuru detected regular pulsations from Centaurus X-3 (*left*), which flashed every 4.8 seconds. (The overall intensity also changes in this plot, but it is an artificial effect: The spacecraft was rotating, so its detector's response increased and then decreased as it rolled over the source.) Cygnus X-1 (*right*), on the other hand, exhibited large, random variations on incredibly short time scales.

Among its discoveries, Ariel V provided a crucial measurement of the curious X-ray blobs first discovered in Uhuru data. The bright blobs had already been identified with galaxy clusters, but the new observations revealed the emission's source: huge clouds of million-degree gas trapped by the clusters' gravity. Ultimately, these X-rays would play a key role in exploring the nature of dark matter and dark energy.

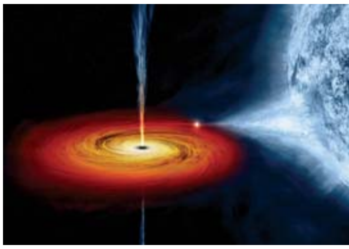
From Counting to Seeing

Both Uhuru and Ariel V viewed the X-ray universe with proportional counters, but such devices have limited sensitivity and ability to pinpoint source locations. What X-ray astronomy needed was a telescope — an optic that could focus incoming X-rays.

The trouble is, high-energy photons don't reflect off most materials; they penetrate them. At best they can reflect at *grazing incidence* angles, skipping off a material like a smooth pebble across a pond. That makes focusing enough X-rays to make a decent image a difficult prospect.

A 1952 design by German physicist Hans Wolter showed how to focus X-rays by allowing them to graze off of not just one but two specially shaped mirrors. Wolter didn't pursue the design once he realized it was impractical for X-ray microscopy, but Giacconi and Bruno Rossi (then at MIT) saw its greater value for telescopes. Even as Giacconi continued to build conventional proportional counters over much of the next two decades, he worked behind the scenes on plans for the very first X-ray telescope: the Einstein Observatory.

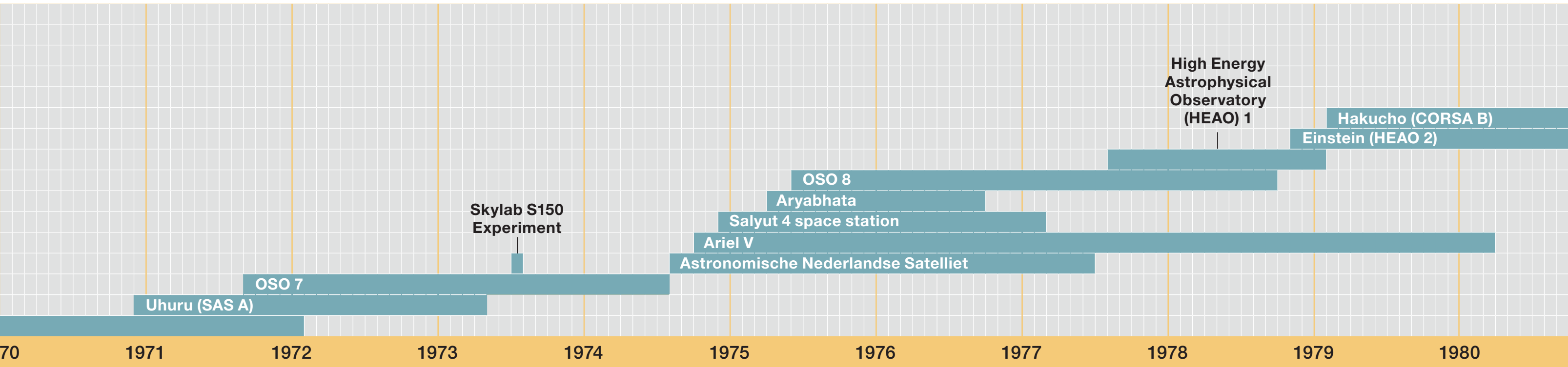
Launched on November 13, 1978, Einstein carried four Wolter-type mirror pairs nestled within each other to focus a greater number of photons. For the first time, astronomers could view details in the X-ray universe on the level of a few arcseconds, nearly equivalent to the focus of large, ground-based optical telescopes. Einstein resolved turbulent structure in supernova remnants and hot blobs of gas in galaxy clusters. Moreover, the space telescope was 100 times more sensitive to X-rays than Ariel V, opening a new window on fainter (and often farther) objects. The number of sources jumped from hundreds to thousands.



▲ **CYGNUS X-1** A giant blue companion star orbits the X-ray-emitting source Cyg X-1 — the poster child for the existence of black holes.

Within months the Einstein telescope had solved a mystery remaining from the 1962 rocket flight: Unlike the dark night sky, the X-ray sky is bright no matter where you look. Where do all of these X-rays come from? Some scientists suggested that hot gas filled the space between galaxies and clusters; others argued that couldn't be, or the universe would collapse under its own weight. But as Einstein discovered more and more sources, it found increasing numbers of *active galaxies* at fainter luminosities and greater distances. It soon

CENTAURUS X-3 AND CYGNUS X-1 LIGHT CURVES: H. TANANBAUM / INTERNATIONAL ASTRONOMICAL UNION SYMPOSIUM NO. 55, 1973 (2); CYGNUS X-1 ARTIST CONCEPT: NASA / CXC / M. WEISS



became clear that what appeared to be a diffuse X-ray background was actually emission from many individual active galaxies that remained too faint to be seen.

Stars provided another, unexpected source of X-ray emission. "If it were up to me," Tananbaum admits, "we might never have looked at stars." But a few astronomers insisted, and Einstein ended up spotting emission from normal stars far more powerful than that from the Sun. The find established an entirely new field, the study of stellar atmospheres.

Then in 1980, disaster struck. The spacecraft temporarily lost the use of a gyro used to help point the telescope on the sky; multiple attempts to utilize a solar sensor to control the spacecraft pointing consumed large amounts of propellant. "It was pretty desperate," Elvis says. "[Einstein] lost a year of its mission." While the malfunctioning gyro was eventually restored, the spacecraft ran out of fuel a few months later.

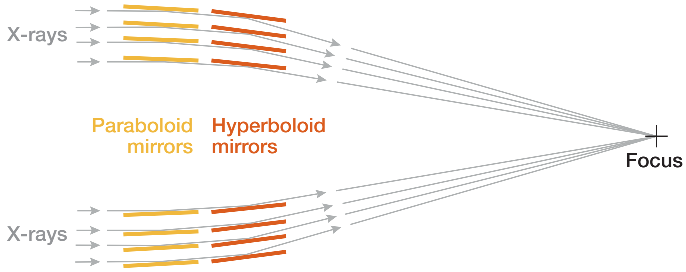
▲ **ARIEL V LAUNCH** The Uhuru and Ariel V satellites both took off from the Italian San Marco launch platform, located off the coast of Kenya.

Still, with 2½ years in space and more than 5,000 targeted observations, the observatory had imaged everything from comets to quasars. After Einstein, Elvis says, it became clear: "Everything emits X-rays. You can't do astronomy without X-ray astronomy."

Gearing Up

In 1976, before Einstein even flew, Giacconi and Tananbaum had submitted a proposal to NASA for a new X-ray telescope to succeed it, one that would be longer-lived and higher-performing. NASA approved and the mission — ultimately named the Chandra X-ray Observatory — was projected to launch in the 1980s. However, technological challenges, budget struggles, and political meanderings caused more than a decade delay.

From a technical standpoint, cutting, grinding, and especially polishing the X-ray-reflecting mirrors posed the biggest challenge. The mirrors had to be extremely smooth, with bumps no more than a few atoms high; otherwise, X-rays would smash into the bumps instead of skipping off the surface. (For comparison, a human hair is roughly 500,000 atoms wide.) By the end of 1991, the team of scientists and engineers had finally proven the technology they needed.

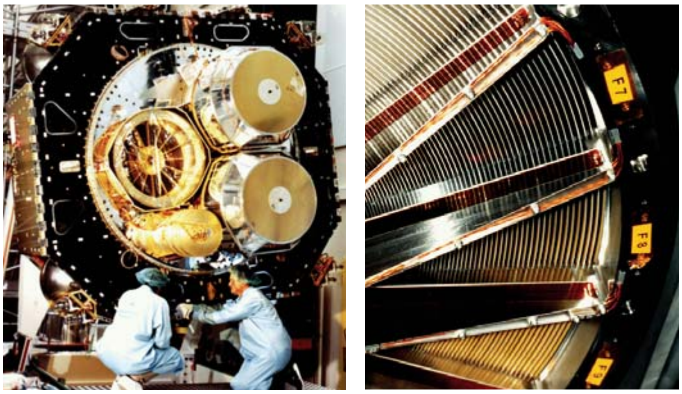


▲ **WOLTER DESIGN** X-rays traveling through a Wolter mirror design are twice reflected at grazing-incidence angles, once off a parabolic mirror and then off a hyperbolic mirror, before coming to a focus. Multiple mirror pairs nested inside each other help capture more photons.

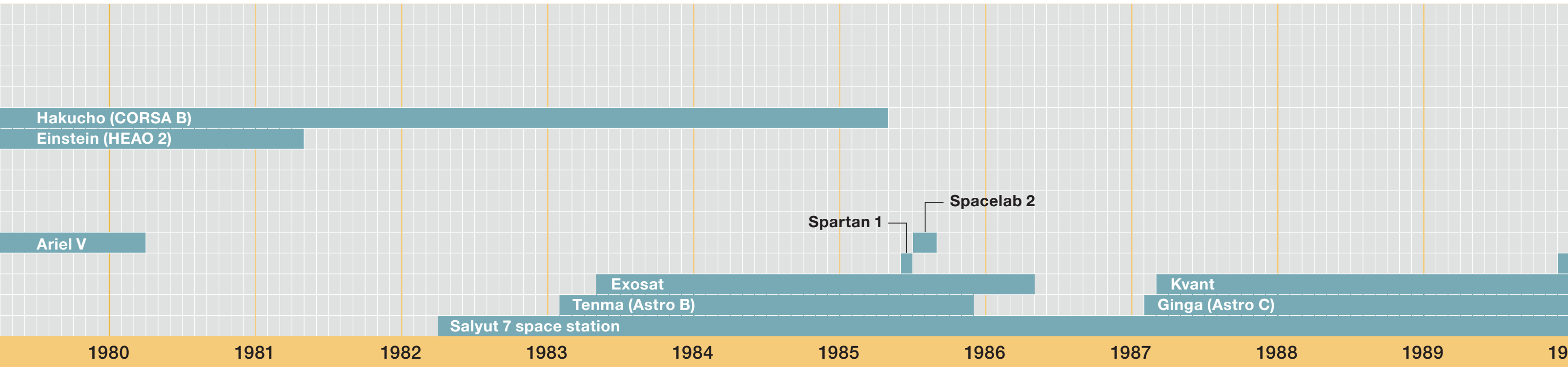
But two months after a successful demonstration of mirror performance — and 16 years after the mission was first proposed — NASA's Astrophysics Division Director Charlie Pellerin called the science team together. "At the meeting he tells us there's not enough money to build [Chandra], and we need to work with him to figure out how to downscope it," Tananbaum recalls. "We were . . . incredulous, is the kindest word; ballistically angry is more accurate."

Nevertheless, the team didn't have much choice. So, instead of nesting six mirror pairs, the scientists decided four pairs would suffice. The heaviest, most expensive instru-

▼ **RUSSIAN DOLLS** Each of XMM-Newton's three X-ray telescopes contains 58 gold-coated mirror pairs nested inside each other.



ARIEL V LAUNCH: JOHN IVES & JOHN RAYMONT; WOLTER MIRRORS: ESA / AOES MEDIALAB; PEOPLE WORKING ON XMM-NEWTON: DORNIER SATELLITENSYSTEME GMBH; XMM-NEWTON MIRRORS: D. DE CHAMBURE / XMM-NEWTON PROJECT / ESA / ESTEC



ment, a calorimeter designed to measure X-ray spectra at extremely high resolution, was moved to another mission. And the team gave up servicing: Chandra had been intended for occasional upgrades, as the Hubble Space Telescope was, but NASA officials chose a new, high-Earth orbit, out of range of astronauts, to ensure that servicing would remain off the table. That change came with a side benefit, though: This orbit, unlike Hubble's, allowed more time for observing, with less time spent in our planet's potentially damaging radiation belts. The high orbit also avoided the thermal, mechanical, and power stresses that spacecraft in lower orbits feel when they shift from daylight to darkness every 90 to 100 minutes.

Meanwhile, another X-ray telescope was in development on the other side of the ocean. In 1985 the European Space Agency decided to build the X-ray Multi-Mirror Mission, later known as XMM-Newton. Designed to cover the same energy range as Chandra, the two telescopes are complementary: Chandra's focus is sharp X-ray vision, while XMM-Newton's aim is to gather as many photons as possible.

"To say it bluntly, it's a huge light bucket," says Axel Schwope (Leibniz Institute for Astrophysics Potsdam, Germany). XMM-Newton's design called for three X-ray telescopes, each with 58 mirror pairs nested like so many Russian dolls. Although coarser than Chandra's mirrors, the sheer number of them invites photons in at an unprecedented rate. As a result, XMM-Newton's images aren't as sharp but contain a wealth of energy information.

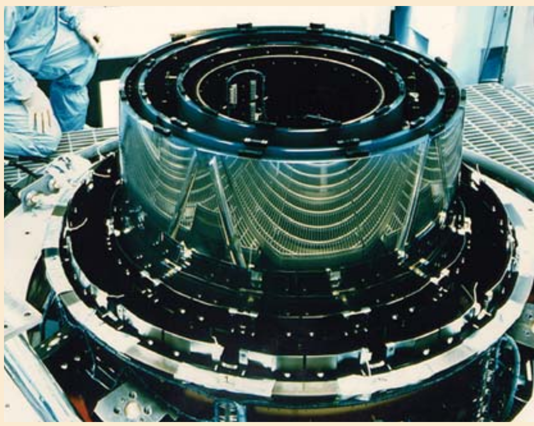
Finally, on July 23, 1999, NASA Commander Eileen Collins and her crew deployed the Chandra X-ray Observatory. Less than half a year later, on December 10, XMM-Newton climbed into space aboard the Ariane 504 rocket.

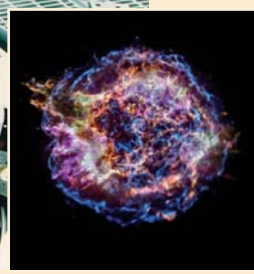
▲ **TO ORBIT** Eileen Collins, the first female Space Shuttle commander, led the team that placed Chandra in high-Earth orbit. The astronauts pose with a model of the spacecraft. From the left: Eileen Collins, Steven Hawley, Jerry Ashby, Michel Tognini, and Cady Coleman.

From First Light to Legacy

The first observation through any new telescope may provoke anxiety. But Chandra's first light proved especially nerve-racking — and then enlightening. One of the first sources Chandra sighted was PKS 0637-752, a quasar that the astronomers expected to appear as a point of light if Chandra's mirrors were bringing the X-rays to a proper focus. "Immediately we see this big elongation on the side and it's like, 'Oh my god! The mirror's broken!'" Elvis says. The smeared image was reminiscent of the initial ones taken by Hubble, which had launched almost a decade before with flawed mirrors.

"So we're looking to see, is there a problem with the aspect, are we jittering, is there really something wrong that's causing this?" Tananbaum says. It was Tom Aldcroft, then

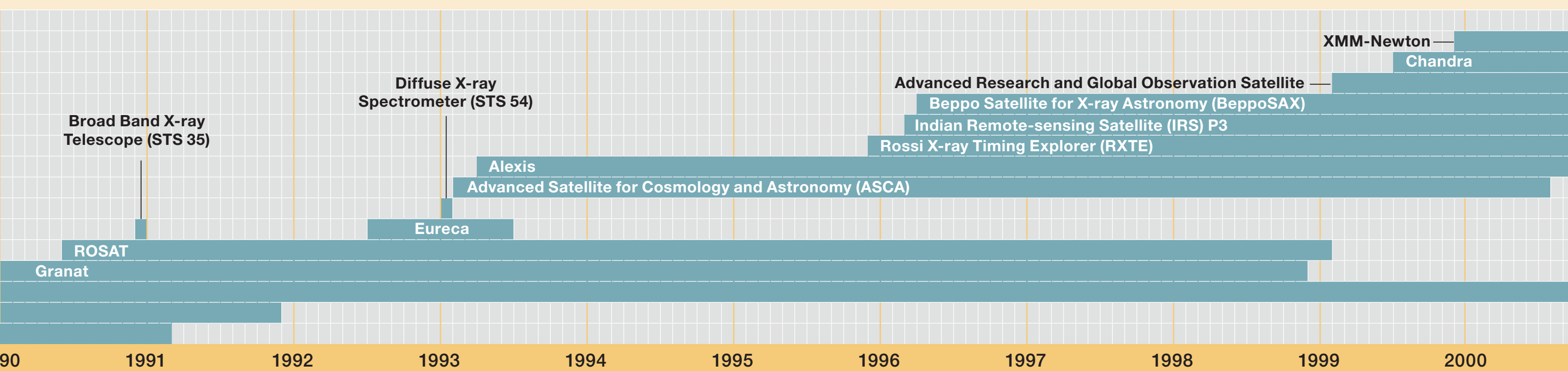




▶ **CHANDRA** Chandra has four nested mirror pairs, compared to XMM-Newton's 58 mirror pairs, so it collects fewer photons for any given celestial target. But those mirrors are so incredibly smooth, they provide unprecedented spatial resolution, providing image detail equivalent to that of optical telescopes.

▶▶ **STARDEATH** Chandra's image of Cassiopeia A, the bloom of gas left over after a massive star went supernova some 340 years ago, reveals a star turned inside out. While iron (purple) was fused in the stellar core just before it collapsed into a neutron star, the shockwave blasted clumps of the element far from the remnant's center.

COLLINS AND CREW: NASA; CHANDRA MIRRORS: EASTMAN-KODAK; SUPERNOVA REMNANT: NASA / CXC / SAO



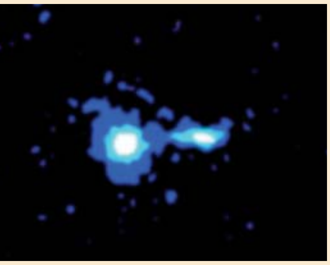
the aspect operations scientist, who looked up the source and discovered that a radio image showed an extension in the same direction. Chandra was simply imaging the powerful jet emanating from near the black hole.

"We went to point at another source . . . and it also had a jet!" Tananbaum says, laughing. The widespread existence of X-ray-emitting jets highlights Chandra's capabilities, Elvis notes: "Einstein showed that everything is an X-ray source; Chandra showed that pretty much everything is extended."

Meanwhile, the three X-ray telescopes onboard XMM-Newton have collected an abundance of photons from hundreds of thousands of sources, providing energy information that's crucial to interpreting the science. Together, Chandra and XMM-Newton have revolutionized the field once more.

Curse of the Calorimeter

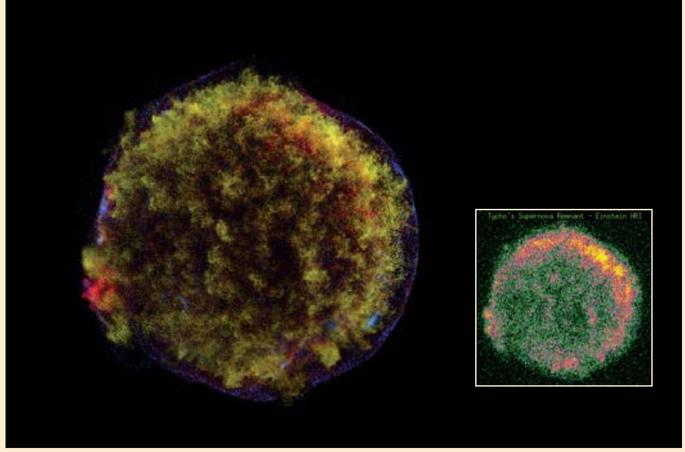
One instrument that could explore the X-ray spectrum — but hasn't yet — is a *microcalorimeter*. By recording the minute changes in heat due to incoming X-ray photons, this instrument would act as an extremely sensitive and high-resolution spectrometer unlike any flown so far.



▲ **UNEXPECTED JET** Chandra revealed a jet extending several hundred thousand light-years from the distant quasar PKS 0637–752.

A microcalorimeter could help astronomers understand what sustains galaxy clusters against collapse or dissolution, and it could measure the elements and energy supernovae distribute throughout the universe. It could also help solve a key cosmological mystery: the case of the missing matter. Dark matter aside, astronomers can't even account for all normal matter in their observations of stars, dust, and gas. Tentative findings from Chandra and XMM-Newton suggest that this missing mass might lurk as hot, tenuous gas between galaxies. But the needed measurements are exceedingly difficult to make with current instruments.

A microcalorimeter originally intended to accompany Chandra into space was bumped to another mission, which was later cancelled. In 2000 a more advanced version of that instrument flew on the Japanese Astro E mission, but the



▲ **TYCHO** Einstein could resolve turbulent structures, such as in the remains of a Type Ia supernova that appeared in Cassiopeia in 1572 (*inset*). Chandra later captured far finer detail within the Tycho remnant.

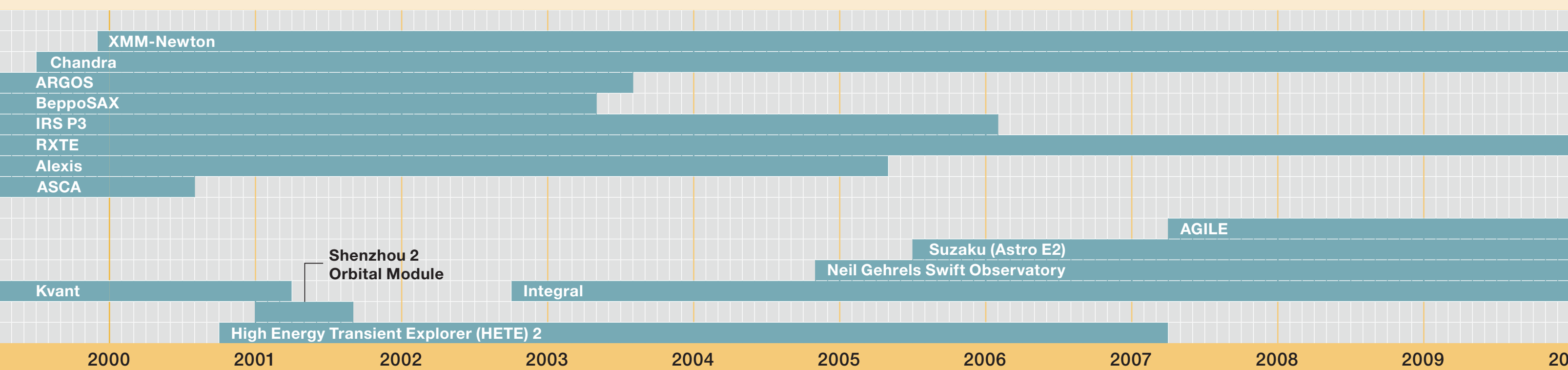
rocket carrying it exploded shortly after launch. A replacement was flown on Astro E2, later christened Suzaku, but that too failed: A mistake in communication led to a design flaw that boiled away the cryogen required to keep the instrument cool, rendering it useless before the instrument could take a single observation.

The next project, called Hitomi (Japanese for "pupil of the eye"), integrated a lot of changes, including advances to the instrument itself and improvements in communications. "They decided to be paranoid," says Ann Hornschemeier (NASA Goddard Space Flight Center). Before all the instruments were deployed or even the (transparent) shutter opened, the Hitomi team took promising observations of hot gas drifting in the Perseus galaxy cluster. "But I don't think anybody would have guessed that that would be the end of the mission," Hornschemeier adds.

On March 26, 2016, a series of minor errors

▶ **PULSAR IN ANDROMEDA** XMM-Newton spotted the first known pulsar spinning in our sister galaxy.

JET: NASA / CXC / SAO; TYCHO BY CHANDRA: X-RAY: NASA / CXC / GSFC / B. WILLIAMS ET AL., OPTICAL: DSS; TYCHO BY EINSTEIN: NASA; PULSAR: ANDROMEDA: ESA / HERSCHEL / PACS / SPIRE / J. FRITZ, U. GENT / XMM-NEWTON / EPIC / W. PIETSCH, MPE



caused the spacecraft to spin out of control and, within hours, break apart (*S&T:* July 2016, p. 11). Now, NASA and the Japanese Aerospace Exploration Agency are working together on yet another replacement mission: The X-ray Imaging and Spectroscopy Mission (XRISM) is designed specifically to recover the science lost with the Hitomi incident. Due to launch in early 2022, the spacecraft will house an X-ray imager in addition to a calorimeter. Time will tell if this fourth try is the charm.

Future of the Field

X-rays' inability to penetrate Earth's atmosphere means the future of X-ray astronomy depends very much on which instruments fly into space. Without a full slate of projects being proposed, designed, built, and launched, the field is in constant danger of going blind at these energies.

Fortunately, there's no shortage of smaller missions, often targeted at answering specific questions. But the open questions outnumber the upcoming missions. For now, 20-year-old Chandra and XMM-Newton — both still going strong — are holding down the fort. "We should be grateful to the engineers who built them," Kretschmar says. "If they had just been built to spec, they would have been dead already."

Ultimately, though, the field needs another flagship mission. "I think we are now on the verge — 'verge,' if you have a patient timeline that allows for another decade or so — of going to the next step," he adds.

The next big thing is the Advanced Telescope for High Energy Astrophysics (Athena), a European mission with NASA involvement that's due to launch in 2031. Hornschemeier calls its Wide Field Imager a "point source discovery machine" thanks in part to its unprecedented 40-by-40-arcminute field of view. The mission will also carry a calorimeter that will be a vast improvement on the one flying on XRISM.

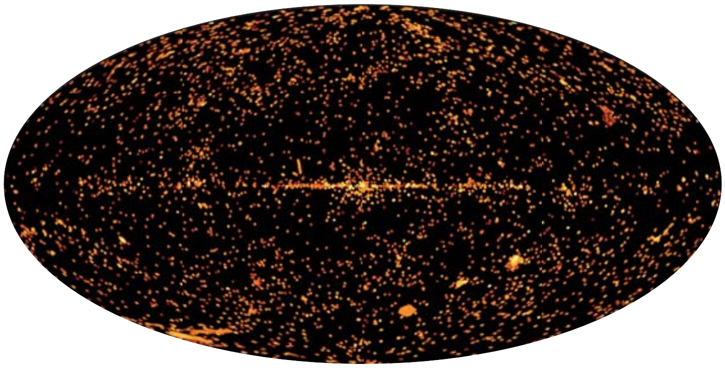
But for other astronomers, Athena's capabilities are too limited for it to be the sole flagship, mainly because it sacrifices detail and depth for its incredible breadth. Its imager will have five-arcsecond resolution compared to Chandra's sub-arcsecond focus, and it won't be able to find sources as faint as Chandra can.

These astronomers are proposing a new X-ray mission: Lynx. It's vying for priority as the astronomy community meets to decide NASA's science priorities for the next 10 years. Lynx promises a focus comparable to Chandra's on-axis, while maintaining sharp imaging (better than 1 arcsecond resolution) over a 20-fold expanded field of view. Coupling this high resolution with increased photon-collecting power, Lynx would reveal sources as much as 100 times fainter than what Chandra can detect. Lynx could see the very first black holes, investigate the hot gas that envelopes galaxies, and provide details on the energetic feedback coming from supermassive black holes and stars forming within galaxies. But it faces tough competition, running against three other projects focusing on visible, ultraviolet, and infrared wavelengths. Next year the National Academies will identify which of these large missions should receive priority for continued development.

As it has for decades, the field of X-ray astronomy continues to brim with uncertainty, discovery, and promise.

■ *S&T* News Editor **MONICA YOUNG** was an X-ray astronomer in her first life. Now she's an editor with X-ray vision.

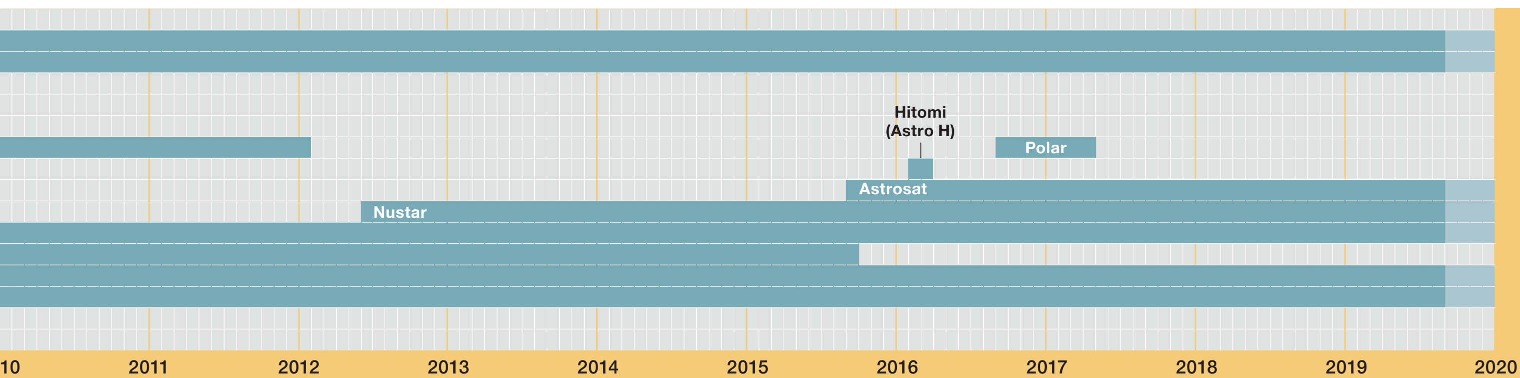
FURTHER READING: Relive two decades on the frontier of discovery with Chandra and XMM-Newton: **https://is.gd/20xrays**



SERENDIPITOUS SOURCES

XMM-Newton's field of view is equivalent to the full Moon, so any given X-ray image holds an extra 50 to 100 sources that weren't the target of the observations. After two decades, all of these extra sources add up — XMM-Newton's Survey Science Center has now amassed 531,454 unique X-ray sources over 1,000 square degrees on the sky. The figure above shows the density of observed objects in the 8th data release of the XMM-Newton Serendipitous Source Catalogue, mapped in galactic coordinates.

ESA / XMM-NEWTON / EPIC / M. WATSON (UNIVERSITY OF LEICESTER, UK)



During his investigations of the structure of the atom in the early 20th century, the brilliant physicist and Nobel Prize winner Ernest Rutherford worked in a ramshackle lab with a limited budget. Although competing against far better-funded researchers, Rutherford remained undeterred and resourceful, and inspired his colleagues with a simple declaration: "We haven't got the money, so we'll have to think."

A practical man, Rutherford embraced the constraints of his situation and turned them to his advantage. In amateur astronomy, deep-sky visual observers with small telescopes face their own constraints, especially light-gathering capability. When you have a big 18-inch Newtonian, for example, the universe is yours. You can choose from thousands of objects which to observe, hundreds of which will appear big, bright, and spectacular. When you plan an observing session, you can have your pick from an embarrassment of celestial riches. In a smaller telescope, all these sights will look dimmer and most will appear less impressive — if they're visible at all. Dedicated deep-sky observers with small telescopes might echo Rutherford's challenge and say, "We haven't got the aperture, so we'll have to think."

Aside from being lightweight and easy to handle, a small telescope has one big advantage over a larger instrument: It has a much wider field of view. For example, a small telescope, say a refractor or Newtonian reflector with a focal ratio of f/6 or f/7 and a focal length of 480 mm to 700 mm, along with a 1.25-inch 24-mm eyepiece with an apparent field of view of 68°, provides a generously wide true field of 2.3° to 3.4°. Move up to a 35-mm eyepiece of the same design with a 2-inch barrel and you get a true field of view of 3.4° to 5°. With this sort of field, dark skies, and with a little planning, it's just a matter of finding beautiful deep-sky objects — and especially groupings of objects — that not only look magnificent in such a small scope, but actually look better than in a larger instrument. There are many such groupings to find in the night sky, enough to keep you engaged for a long time, especially in the relatively rich skies of northern summer.

Small-Scope Summer

Embrace the constraints of a small instrument for deep-sky observing this season.


BRIAN VENTRUDO

Clusters and Supergiants in Scorpius

Turn a small scope towards the widest part of the summer Milky Way in Sagittarius and Scorpius, for example, and it's hard not to see something good.

Start with the region around the red supergiant star **Alpha (α) Scorpii** (Antares) at the heart of the constellation Scorpius. Center your field of view between Antares and the star Sigma (σ) Scorpii and you'll see within a 2° field the colorful supergiant as well as two globular clusters, all set against a rich tapestry of stars along the Milky Way. The brighter cluster, 6th-magnitude **Messier 4**, is a little more than 1° west of Antares. At a distance of 7,200 light-years, this relatively loose cluster, noted for its central bar that runs north-south, is one of the nearest such objects to Earth. Look about ½° northwest of Antares to glimpse the 10th-magnitude globular cluster **NGC 6144**, a somewhat challenging object to see because of the glare of Antares and its distance of around 30,000 light-years. To the north, in the same field, the stars eerily drop off to near darkness as a result of an inky foreground dark nebulosity. You can't take all this in at a glance with a big reflector.

If you can manage a 4° field of view, you can capture the splendid, widely spaced triple star **Rho (ρ) Ophiuchi**, north of the dark nebula Barnard 44, in the same field as Antares and M4. In dark sky, the reflection nebula **IC 4604** appears as a ghostly wisp surrounding Rho. About 2° west-northwest of Rho lies the globular cluster **M80**.

Move eastward and southward in Scorpius and you arrive at the dazzling open clusters **M6** and **M7**. These objects are a little too far apart to fit in a single field of view in most small telescopes, but each is large enough to frame nicely in a 2° field that's bejeweled with stars. M6, the Butterfly Cluster, is the smaller of the two clusters. The larger and more impressive M7, sometimes called Ptolemy's Cluster, is nearly 1½° across. Observe each of these galactic clusters with an 80-mm extra-low dispersion (ED) refractor on a night when the sky over the southern horizon is particularly clear, and you'll recall why you became a stargazer in the first place.

Farther south in Scorpius lies another lovely grouping of faint stars that appears to emanate northward from the star **Zeta (ζ) Scorpii**. The striking gauzy appearance of this nearly 2°-long assembly to the unaided eye has led many stargazers to call it the **False Comet**. Were it not so far south, it would surely have made Messier's list; it's hard to find a more comet-like apparition in the entire sky.

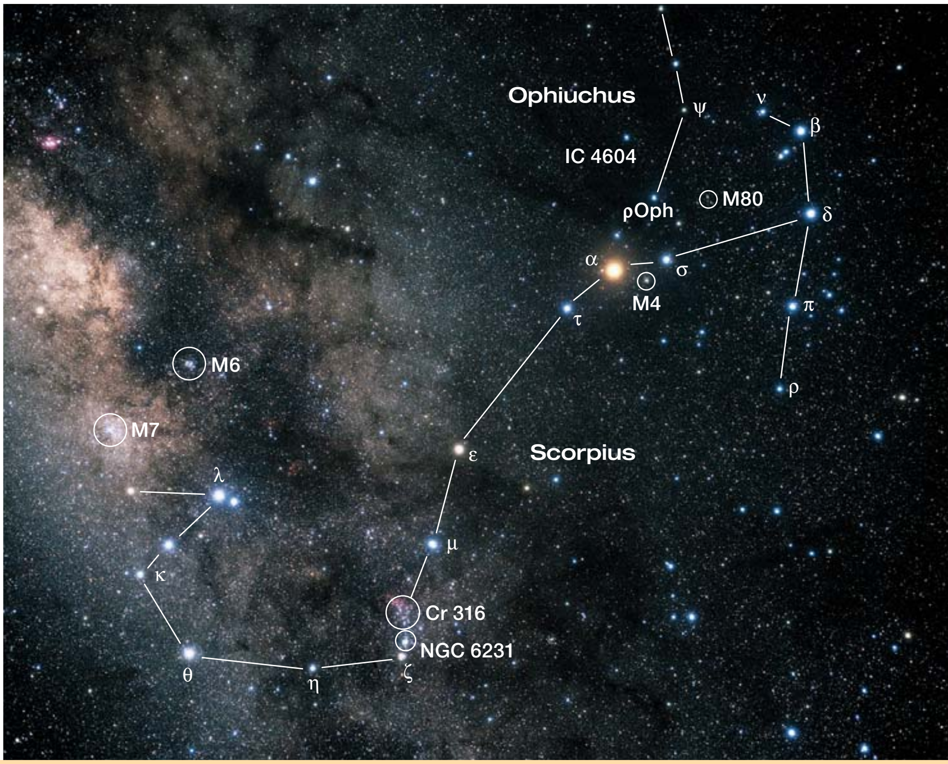
Turn a small telescope toward the False Comet and the region explodes into a profusion of relatively young, blue-white supergiant stars. At the southern end, Zeta Sco is a wide

Turn a small telescope toward the False Comet and the region explodes into a profusion of relatively young, blue-white supergiant stars.

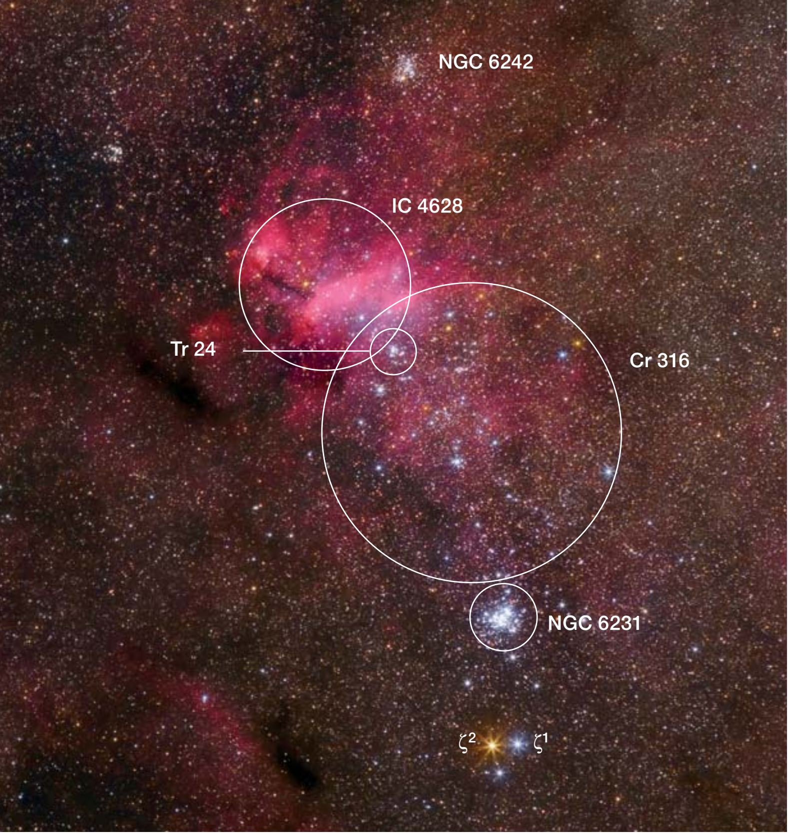
optical double, easy to split in binoculars. The fainter of the two components, 5th-magnitude Zeta^1 Sco, is one of the intrinsically brightest stars in the galaxy with a luminosity of nearly one million Suns. Just north of Zeta^1 lies **NGC 6231**, a tiny open cluster that makes up the head of the False Comet. Sometimes called the Northern Jewel Box, NGC 6231 lies at a distance of about 5,200 light-years and is packed with big, blue supergiant stars. If NGC 6231 lay at the same distance as the Pleiades from Earth, it would appear roughly the same size as that cluster, but its stars would be some 50 times brighter, with some as bright as Sirius!

Move north-northeast of NGC 6231 and in the same 2° field of view you see the looser open clusters **Trumpler 24** and **Collinder 316**, which make up the "tail" of the False Comet. Together, these objects form one of the finest fields in the sky, but one that's difficult to see from the middle latitudes of the Northern Hemisphere because of its declination of about –42°.

▼ **A RICH FIELD** The region of Scorpius is rich with deep-sky sights. That it crawls so close to the southern horizon for observers at mid-northern latitudes can be frustrating. Any clear summer night is a good night to observe, but still, transparent skies will offer the best looks. Try to time your session for when the target stands at its highest.

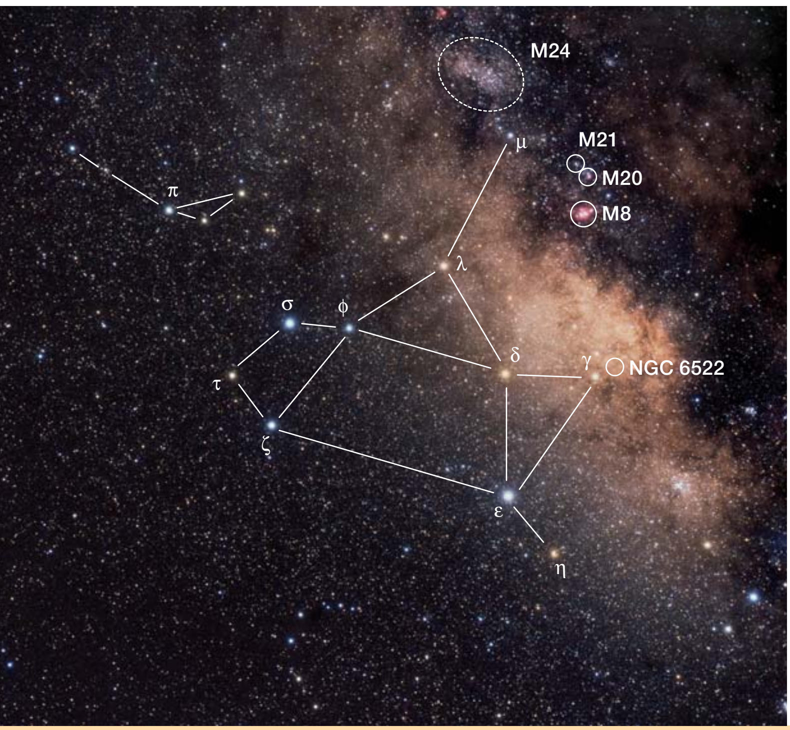


AKIRA FUJII



▲ **FALSE COMET** The curl of the Scorpion's tail cradles a stunning collection of deep-sky objects. NGC 6231, Trumpler 24, Collinder 316, and IC 4628 combine to mimic the appearance of a comet passing through the southern sky.

▼ **LOOK INSIDE** The spout of the Teapot asterism of Sagittarius points to a portal to the universe — or at least, a portal to our galaxy. Baade's Window, a piece of sky unobscured by dust or gas, allows astronomers to look some 25,000 light-years back toward the galactic center. The opening surrounds the globular cluster NGC 6522, which glimmers next to Gamma Scorpii.



Surfing the Star Fields of Sagittarius

While Scorpius is a delight, Sagittarius is even better. Look about ½° northwest of Gamma (γ) Sagittarii, the star that marks the tip of the spout of the Teapot asterism of Sagittarius. Center your gaze on the faint smudge of the 10th-magnitude globular cluster NGC 6522. Within a region about 1½° across that surrounds the cluster, you can look through **Baade's Window**, a break in the dark, sooty clouds of the Milky Way that offers a clear view for some 25,000 light-years just south of the galactic center. These are some of the most distant stars you can see in our galaxy. While this area is arguably more appealing in a larger instrument, seeing a slice of the central core of the Milky Way with a 3- or 4-inch instrument makes for an inspiring stop on this tour.

Now move 6.5° north of Gamma to center your field on **M8** and **M20**, two naked-eye emission nebulae better known as the Lagoon Nebula and the Trifid Nebula, respectively. Here, within a single 3° field of view, are assembled a half dozen lovely deep-sky sights. The most obvious is the Lagoon Nebula. Within the brighter and larger western half of its luminous cloud shines the 6th-magnitude star 9 Sgr. Across the gulf created by the dark nebulae Barnard 88 and Barnard 296 lies the fainter half of the Lagoon, which partly shrouds the newly minted star cluster NGC 6530, the hot, young stars of which set the nebula aglow.

The Trifid Nebula lies just 1.5° north of the Lagoon complex. It's smaller and less distinct than the Lagoon but spectacular nonetheless. The Trifid gets its name from the dark cloud Barnard 85, which appears to split the nebula into three sections (*S&T:* June 2016, p. 57). This trifurcation is visible in small scopes, although it takes a little effort and patience to see. A nebula filter, one with a relatively broad bandwidth around the O III and H-beta bands, can improve the contrast of the emission nebulosity without dimming the stars too much. The Lagoon Nebula is about 4,100 light-years away, but the Trifid may be almost twice as far, with current estimates reaching as high as 9,000 light-years. Both lie in a rich star-forming region of the Milky Way.

Without repositioning your field of view, look northeast of the Trifid to find the relatively loose open star cluster **M21**. This cluster is often passed over in favor of M8 and M20, but it's a fine object in a glittering field. Look also for the group of 6th- and 7th-magnitude stars connecting M20 with M21. This asterism is sometimes called Webb's Cross after Reverend T. W. Webb, the 19th-century amateur astronomer who first noted it. The cross has its base in the Trifid Nebula and its head in M21. The somewhat crooked arms stick out in a southeast-northwest direction.

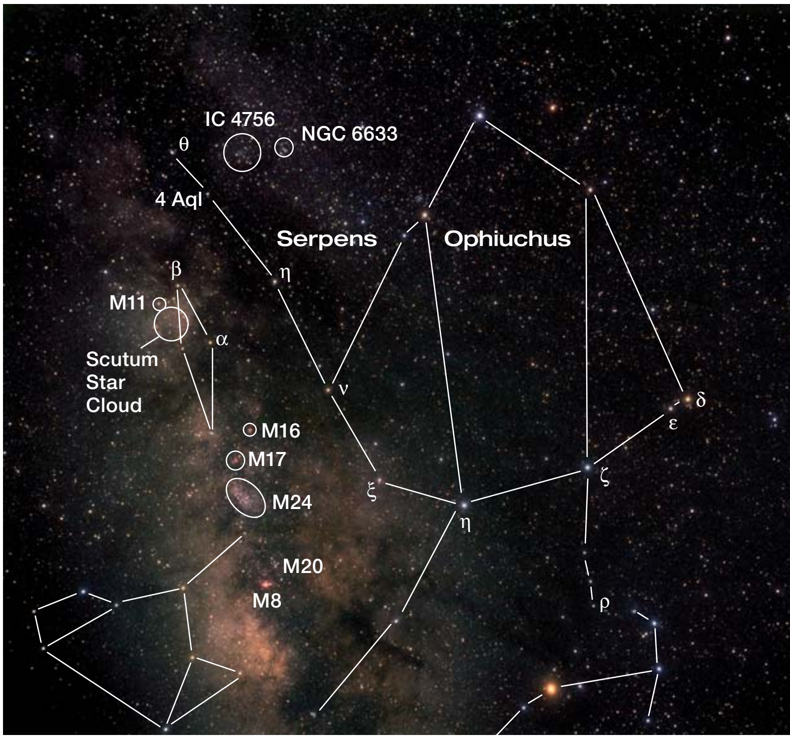
While it's not a star cluster, nebula, or galaxy, **M24**, the Small Sagittarius Star Cloud, must surely rank high on any list of the best sights for a small telescope. M24 appears as a bright patch of Milky Way about 2° north of Mu (μ) Sagittarii at the top of the Teapot, and it spans an oval region

FALSE COMET: LORAND FENYES / STOCKTREK IMAGES / GETTY IMAGES; SAGITTARIUS: AKIRA FUJII roughly 1° × 2° in size, ideal for any small telescope and a low-power, wide-field eyepiece.

Like Baade's Window, the shimmering M24 complex appears as a result of a gap in the dark galactic dust clouds, affording us a clear view more than 9,000 light-years into the Sagittarius Arm of the Milky Way. If there were no dust or cold gas, the entire Milky Way from Cygnus to Scutum and into Sagittarius (and beyond into Centaurus and Crux in the Southern Hemisphere) would appear as bright and luminescent as M24, more than bright enough to cast shadows on a dark night. The individual stars in M24 range from magnitude 6 down to invisible in a small telescope. The cloud takes on a three-dimensional quality in a good scope and steady seeing, and some observers see the aggregate color as blue or even green. If you have a very dark sky, look for the small oval dark nebulae Barnard 92 and Barnard 93 on the north edge of the cloud. You could spend an entire night examining M24, and it would not be a wasted night.

The Northern Summer Milky Way

Moving northward from M24, pause to take in **M17** (the Swan Nebula) and **M16** (the Eagle Nebula). The pair is separated by about 2.3° of sky, so you need a good 3° field of view to frame them well. Initially, they may not seem as impressive as the Lagoon and Trifid, but patient observers with pristine sky are rewarded with a glimpse of the shape and structure of these distant star factories.



▲ **MOVING NORTH** Follow the spangled course of the Milky Way from the Teapot in Sagittarius through Scutum to the tail of Serpens Cauda. Gently nudge your field of view northwest of Theta Serpentis to find the broad open cluster IC 4756.

AKIRA FUJII

Observations and Discoveries with Small Scopes

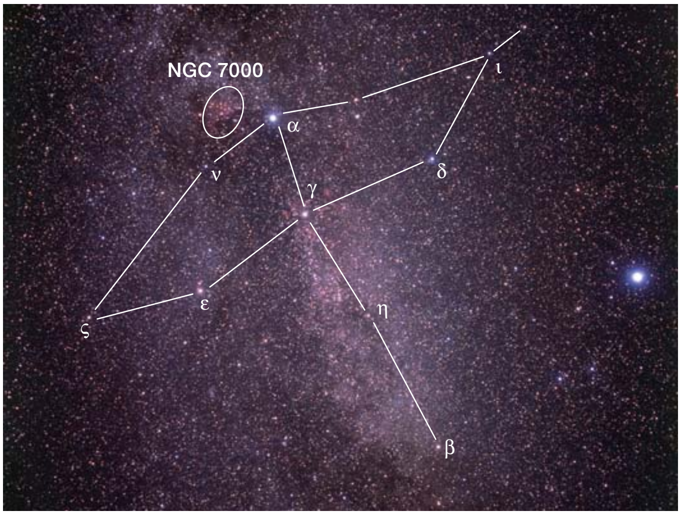
Until the late 18th century, most astronomical discoveries were made with small telescopes, usually long-focal-length refractors with apertures of less than three or four inches. The biggest moons of Jupiter were discovered by Galileo and Simon Marius in 1610 with 1-inch refractors. Christiaan Huygens discovered the rings of Saturn and the planet's largest moon, Titan, with a 63-mm refractor, which he often stopped down to 35 mm. William Herschel discovered the planet Uranus with a 6-inch reflector, but he might as well have used a smaller telescope because Uranus is relatively bright.

And, of course, there were the comet hunters and pioneering deep-sky observers. Charles Messier and Pierre Méchain discovered 21 comets between them, along with dozens of objects that now comprise the famous Messier List. They used 4-inch (or smaller) refractors. Even after Herschel made an exhaustive catalog of the deep sky, subsequent observers continued to discover a few deep-sky stragglers. The 6th-magnitude reflection nebula NGC 1333 in Perseus, for example, was overlooked by Herschel, but discovered in 1855 by the German astronomer Eduard Schönfeld with a 3-inch refractor.

In the 20th century, the pace of discovery with small telescopes slowed but didn't stop. Patrick Moore's first research paper, about craterlets on the Moon observed with a 3-inch refractor, was published when he was still a teenager.

Many comet hunters through the 20th century favored small, wide-field telescopes. Famed comet hunter Minoru Honda honed his craft with a 3-inch refractor he built from a discarded lens. His first observations were made from a battlefield near Singapore during World War II while his fellow soldiers slept. His work inspired a generation of Japanese comet hunters armed with small instruments. A little luck aided some discoveries: In 1983, George Alcock discovered Comet IRAS–Araki–Alcock (C/1983 H1) with a pair of 15×80 binoculars while kneeling on the floor of his home and looking through a double-paned window.

Serious observation and discoveries with small scopes continue to the present day. In 2004, amateur astronomer Jay McNeil discovered a variable nebula with a 3-inch refractor and CCD. The nebula waxes and wanes due to outbursts from an active protostar. In 2016, Giuseppe Donatiello discovered a dwarf spheroidal galaxy some 10 million light-years away with a 5-inch refractor and CCD. Amateur Donald Bruns used a 4-inch refractor to detect the deflection of starlight predicted by Einstein's general theory of relativity, improving on the 1919 measurement by Sir Arthur Eddington (*S&T:* Aug. 2018, p. 22).



◀ **CONTINENTAL CLOUD** The emission nebula NGC 7000, familiarly called the North America Nebula, is about 120 arcminutes across. This makes it too big to fit into the field of view of all but the widest of wide-view telescopes, but it's a great binocular object.

Continue north-northeast to find yet another gap in the dark interstellar soot. Look for the tight knot of the open cluster M11, the Wild Duck Cluster, about 2° from Beta (β) Scuti. This attractive cluster marks the northern edge of the **Scutum Star Cloud**, a dazzling, hammer-shaped agglomeration of stars that appears as an offshoot of the immense dark nebulosity of the Great Rift that bisects the Milky Way. Visible to the naked eye, the cloud is about 1.5° across and is surrounded by large and small patches of dark nebulae.

About 5° north of the celestial equator and 4½° degrees northwest of Theta (θ) Serpentis, look for **IC 4756**, one half

LIGHTED LACE The Veil Nebula is usually considered a target for large telescopes. While it's true that it takes aperture and magnification to reveal the nebula's structure, a small scope equipped with a nebula filter can capture the brighter parts of the cloudy complex.

CYGNUS: AKIRA FUJII; VEIL NEBULA: NASA / ESA / HUBBLE HERITAGE (STSCI / AURA) / DSS2 / J. HESTER (ASU) / DAVIDE DE MARTIN (ESA) of a pair of splendid open clusters. Its partner in light, **NGC 6633**, shines about 3° beyond it. To frame both clusters in the same field requires at least a 4° field of view, but if you can manage it, you'll be rewarded with an impressive sight in a busy but beautiful part of the sky. IC 4756 is by far the larger of the two clusters, spanning at least 1° in an already rich field. This may explain why many early deep-sky cartographers with narrow-field instruments passed it by. Messier missed it, and even the venerable *Norton's Star Atlas* didn't include this sprawling cluster.

Just 3° northwest of IC 4756, NGC 6633 is tighter and easier to distinguish from the background field. It's arguably more beautiful as well, with a thick bar that runs northeast to southwest. Both NGC 6633 and IC 4756 are at least 600 million years old, old enough to have evolved a few colorful stars. NGC 6633 lies about 1,000 light-years away. IC 4756 is more distant at 1,300 light-years, which means their difference in size is real.

▲ **A MISNOMER** Although this wispy section of the Veil Nebula is named after Edward Charles Pickering, director of the Harvard College Observatory from 1877 to 1919, it was actually discovered photographically in 1904 by Harvard computer Williamina Fleming.

As was the case with Sagittarius, when you aim a wide-field scope toward the constellation Cygnus, it's hard not to see something pleasing to the eye, especially in the **Cygnus Star Cloud** between **Beta Cygni** (Albireo) and Gamma Cygni (Sadr). Albireo itself, a colorful and easily split double, is set against a glittering background of stars. Just east of Alpha Cygni (Deneb), at the tail of the celestial swan, lies **NGC 7000**, the North America Nebula, which is just a little too wide to frame in all but the widest-field telescopes.

And then there's the **Veil Nebula**, as intricate and sublime a sight to be found anywhere in the northern sky. A sprawling remnant of a star that detonated as a supernova some 8,000 years ago, the Veil is a rewarding target with any good telescope, large or small. The entire complex, known as the Cygnus Loop, consists of three main sections. The eastern Veil is a long braided arc composed of two bright segments, **NGC 6992** and **NGC 6995**. **NGC 6960**, which comprises the western Veil (sometimes called the Witch's Broom), is more linear and clearly bisected by the 4th-magnitude foreground star 52 Cygni. Eastern and western elements fit in a 4° field and are visible in a small telescope in pristine, dark sky. A nebula filter with a generous passband helps. Between these two extremities, at the north end of the Loop, lies **Pickering's Triangle**, a much more challenging sight. A small scope reveals little of the famous braided texture in each segment of the Veil Nebula; that's a job for a larger instrument. But only a small, wide-field scope can give you an expansive view of the entire complex.

There are plenty more deep-sky arrangements and groupings for a small telescope in the summer months, and dozens more on the autumn and winter side of the sky and in the Southern Hemisphere. And while this tour may not cure you of aperture fever, it might help you embrace the constraints of small optics and think more expansively about what to look for in the deep sky. Hopefully I've given you some ideas and inspiration to seek out celestial sights and vistas that are not only passably observable in a small telescope, but are actually more beautiful and accessible than in a larger instrument. It's a big universe, and even with a little telescope, there's a lot to see.

■ **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. Brian writes about astronomy and stargazing at his website **CosmicPursuits.com**.

Wide-field Observing Tips

To get the best possible view with a small scope, you need to maximize the amount of light coming through the eyepiece while minimizing light from other sources. Avoid light pollution and follow these suggestions.

1. Make sure your optics are clean, especially your eyepieces. Remove the oil and dust and other deposits, especially on the eye lens and filters. A little dust on your objective lens won't hurt, however.
2. Ensure your observing eye is completely dark-adapted and make sure it stays that way during your observing session.
3. Use averted vision to expose the most sensitive part of your retina.
4. If you use a filter, make sure it has a relatively broad bandwidth (20–30 nm) around the H-beta and O III lines around 500 nm.
5. Wait until objects are near the meridian, their highest point in the sky, so their faint light passes through less of Earth's atmosphere. It also helps to observe on nights of low humidity and high atmospheric clarity to minimize the scatter caused by dust and water vapor in the atmosphere.

Mysterious in origin and ethereal in nature, Wolf-Rayet nebulae will intrigue both observer and reader alike.

In 1867, French astronomers Charles Wolf and Georges Rayet made a puzzling discovery. Using a visual spectrometer, they scanned the Cygnus Milky Way with the Paris Observatory's 40-cm (16-inch) reflector and spotted three 8th-magnitude stars with remarkable spectra. Instead of the narrow, dark absorption lines usually seen in stellar spectra, these stars displayed broad and strong emission lines. Adding to the mystery, most of the prominent lines appeared to belong to an unknown element, which was later discovered to be helium.

These and similar stars are now known as Wolf-Rayet, or WR, stars, and they form a rare and exotic class. The brightest and nearest is 2nd-magnitude Gamma^2 (γ^2) Velorum, a spectroscopic binary consisting of an extraordinary WR star and O-type companion. In 1883 English-born astronomer Ralph Copeland described its beautiful spectrum from the high altitude of Peru's side of Lake Titicaca:

> *Its intensely bright line in the blue, and the gorgeous group of three bright lines in the yellow and orange, render its spectrum incomparably the most brilliant and striking in the whole heavens.*

In the mid-1970s, astronomers determined WR stars are highly luminous descendants of massive O-type stars. Since then, multiwavelength studies from radio to X-ray have investigated their copious mass loss and developed the evolutionary model outlined below.

In a brief but stable main-sequence phase, a fast stellar wind sweeps up ambient interstellar material and compresses it into a thin shell. Behemoth O-type stars with some 60 solar masses or more soon evolve off the main sequence, becoming luminous blue variables. Less massive ones transition into red supergiants. In either case, the star continues to eject a hydrogen-rich envelope, and a slower stellar wind forms a dusty circumstellar nebula inside the existing interstellar bubble.

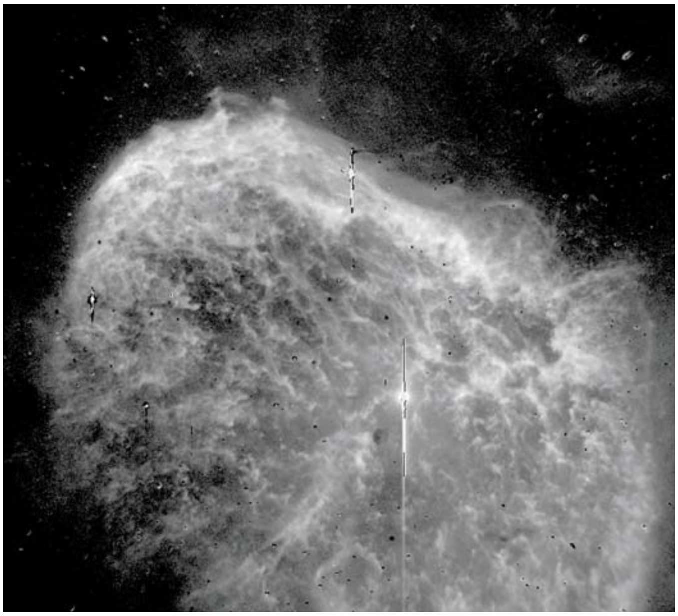
The short-lived WR stage begins as the helium-rich core is exposed. The star then blasts a powerful wind up to 3,000 km/s (in some cases, higher speeds have been recorded), shedding between 10^{-5} and 10^{-4} solar masses per year. This amount may seem insignificant, but it's a billion times the Sun's annual mass loss. The wind sweeps up the nearby circumstellar material into a glowing, ionized gas bubble.

Astronomers classify WR stars into two main types, *WN* and *WC*, based on the optical spectra. *WN* stars display strong emission lines of helium and nitrogen, while *WC* stars are carbon- and helium-dominant. These types are further divided into subclasses (*WN*2 to *WN*9 and *WC*4 to *WC*9) based on the relative strengths of their emission lines. There's a third, rare class, the *WO* stars, which are similar to *WC* stars but with more prevalent oxygen lines.

Visible nebulae surround at least 60 of the 661 known galactic WR stars. They display a variety of features, including complete shells, arcs (partial shells), clumps, filaments, and diffuse emissions. Most nebulae surround *WN*-type stars, and three spectacular wind-blown bubbles headline this class: NGC 6888 in Cygnus, NGC 2359 in Canis Major, and NGC 3199 in Carina. Follow along and we'll chase down the top wind-blown bubbles across the entire sky, with the help of O III and narrowband filters.

NGC 6888, the Crescent Nebula, lies 2.7° southwest of 2nd-magnitude Gamma Cygni (Sadr), along the spine of the Milky Way. At a magnification of 25×, my 80-mm finder (equipped with an O III filter) shows an elongated arc of nebulosity passing through the 7.2-magnitude star HD 192182, along with an 8th-magnitude star 7′ to its southeast. My 8-inch reflector captures two-thirds of the entire oval shell. The brightest piece extends both east and southwest from HD 192182. A broader portion of the bubble with lower surface brightness is on the southwest end. Although numerous Milky Way stars sparkle within the nebula, only the WR star HD 192163 (also called WR 136) is actually *inside* the nebula, slightly north of center.

Catch a



NGC 6888: BRIAN D. MOORE / JEFF HESTER / PAUL SCOWEN / REGINALD DUFOUR / NASA / ESA; SH 2-308: DON GOLDMAN

▶ **THE CRESCENT NEBULA** This ground-based image of NGC 6888 and its central star, WR 136, highlights the cataclysms that giant stars undergo in their death throes (the vertical lines are blooming spikes). During the red supergiant phase, the star gently puffs some of its insides into the surrounding space. As it transitions to the WR phase, a fast and furious stellar wind switches on, lighting up the medium around the star.

ETHEREAL BUBBLE More than 5,000 light-years away in Canis Major, Sh 2-308 spans some 50 to 60 light-years. Powering this bubble is WR 6, the bright blue star at the center.

Wind-Blown Bubble

ARCS AND FILAMENTS Lying in the Cygnus OB 3 association, WR 134 is responsible for this delicate arc captured by the Mayall 4-meter telescope at Kitt Peak National Observatory. During the WR phase, the fast stellar wind plows into the ambient medium, which may include matter previously shrugged off by the supergiant. When the high-speed winds collide with the nebula around the star, they generate shocks that we see as arcs in the visible.

T. A. RECTOR / UNIVERSITY OF ALASKA ANCHORAGE / H. SCHWEIKER / WIYN / NOAO / AURA / NSF

The nitrogen-rich star's powerful stellar wind, blowing at a blistering speed of 2,000 km/s, plowed into the surrounding ISM and visibly fractured the northwest side of the bubble.

Through my 18-inch reflector, an exquisite 18′ × 11′ ellipse tilts northeast to southwest and appears suspended in a rich Milky Way field. An irregular convex section tightly curls between HD 192182 and the 8th-magnitude star to its southeast. The brightest strip, though, extends 7′ further southwest, and a filamentary triangular wedge forms a diffuse bridge to the central WR star. Several 11th- to 13th-magnitude stars pepper the southwestern fringe where hazy nebulosity leaks inwards, condensing in a 30″ clump. The southeast-facing side dissolves away, but I do detect a dim yet nearly complete ring.

As the prototype wind-blown bubble, NGC 6888 is one of the most researched Wolf-Rayet nebulae. A 2012 spectroscopic study found several nested shells formed by ejections and collisions as its nitrogen-rich central star evolved. While the progenitor star was still on the main sequence, its winds swept up gas in the interstellar medium (ISM) and formed an external "skin." At the WR stage, with a wind gusting up to 1,600 km/s, an inner elliptical bubble formed and expanded inside a larger spherical nebula. Based on the bubble's expansion rate of 75 km/s, NGC 6888's *dynamical age* (the length of time the bubble has been expanding) is 30,000 years.

Slide your scope just 2° to the south of NGC 6888 to find 8th-magnitude HD 191765 (WR 134) and HD 192103 (WR 135), two of Wolf and Rayet's three original stars. In 1971 Canadian astronomer David Crampton identified the nearby crescent-shaped **WR 134 Nebula**. A follow-up investigation in 2008 found that WR 135 is the source of a larger H I bubble. Both stars lie within the Cygnus OB 3 association at a distance of 6,000 light-years.

The Milky Way is patchy in this area, making it tough to identify the nebula. But when I added an O III filter, the background sky darkened and the view improved dramatically. At 73×, I found a broad nebulous crescent, perhaps 15′ × 4′, curling across the field from north to south and opening to the east. The arc appeared thicker in the middle and gradually tapered to the south. WR 134 is the brightest star in a 3′ chain and sits 10′ east of the crescent.

Sh 2-308, perhaps the quintessential celestial bubble, is a snap to find. Just point your scope at 3.9-magnitude Omicron^1 (o^1) Canis Majoris — the nebula is centered only 15′ north. The bubble is windblown material from the WR star EZ Canis Majoris (HD 50896), which varies between magnitude 6.7 and 6.9 every 3.8 days. The nitrogen-rich star's powerful stellar wind, blowing at a blistering speed of 2,000 km/s, plowed into the surrounding ISM and visibly fractured the northwest side of the bubble. At a distance of more than 5,000 light-years, this shell spans 50 to 60 light-years in diameter.

My 8-inch reflector displays a ghostly arc, while my 18-inch at 73× reveals most of a delicate 35′ bubble. The western flank is the most obvious feature — a long, wispy arc curving gradually from north to south. A careful view teased out subtle filigreed structure with weak filamentary strands. The arc passes through a triangle of 8th- to 9th-magnitude stars at the south end and disappears near Omicron^1. The southeast section was very difficult to follow, but I picked it up again along the eastern boundary. A brighter 10′ misty patch containing several 10th- to 12th-magnitude stars is at the north end. The rim dims again for a short stretch on the northwest corner before completing a circuit. Nearly transparent nebulosity suffuses the interior of the shell.

NGC 2359, popularly called Thor's Helmet, is located 4⅓° northeast of Gamma Canis Majoris (Muliphein). The 11.6-magnitude power source is HD 56925 (WR 7), which carved out a complex nebula from its strong and episodic mass loss. Its stellar wind snowplowed and ionized the surrounding gas, resulting in its blue-green emission. At a distance of 12,000 light-years, the central "helmet" is expanding at a velocity of 10 to 30 km/s and spreads some 16 light-years wide. The ruddy-colored outer wings are part of an ionized H II nebula and contain a large quantity of hydrogen expelled during the precursor stages.

▲ **THOR'S HELMET** This view of NGC 2359, created from images forming part of the Digitized Sky Survey 2, shows a good example of the "nested shells" manifestation of episodic mass loss from the successive phases of the death throes of massive stars. The exact mechanisms governing mass loss from Wolf-Rayet stars are still largely unknown. Thor's Helmet lies some 12,000 light-years away in Canis Major, and the main bubble is around 16 light-years in diameter.

ESO / DIGITIZED SKY SURVEY 2 / DAVIDE DE MARTIN

SOUTHERN CRESCENT If you're a Northern Hemisphere observer, you'll have to travel south to see NGC 3199, which lies in Carina. This object has been much observed, including by the European Southern Observatory's 2.6-meter Very Large Survey Telescope, which captured this image.

My 80-mm finder shows a 5′ roundish glow at 13×, and higher power adds a portion of the wings. Through my 18-inch at 108×, the wispy central bubble has a brighter rim along the west side, forming a thick semicircular C. Near the north edge, three 12th-magnitude stars are aligned, and an 11th-magnitude star is attached at the south end. WR 7 is offset northwest of center, near the bubble's inner edge.

The helmet's southern wing angles west-southwest as a bright 4′ bar, then narrows and stretches west an additional 5′. The northern wing sprouts to the northwest and is slightly broader and more uniform in surface brightness. A third, dimmer filament shoots 10′ east from the north side of the bubble. My 24-inch f/3.7 reflector reveals a filamentary, multishell structure with knots and lacy arcs of nebulosity.

NGC 3199, dubbed the Southern Crescent, is one of several showpieces in the constellation Carina. This nebula lies too far south for most U.S. observers, but place it on your bucket list for a trip near or south of the equator. From the Cape of Good Hope, John Herschel described it as,

> *the great falcated* [sickle-shaped] *nebula,*
>
> and remarked it was
>
> *brighter to the south following* [east] *part, and dies off to the north preceding* [west], *having a curved form and forked tail.*

In deep optical images, NGC 3199 is the brightest part of a complete wreath spanning 22′ in diameter. As we've seen with other nebulae, the 11th-magnitude WR star HD 89358 is displaced 4.5′ west of the geometric center, and it's nestled within a small triangle of fainter stars. Distance estimates range from 7,500 to 12,000 light-years, implying a physical diameter of at least 50 light-years.

At a Costa Rica star party (latitude 10° north), NGC 3199 was faintly visible in my 9×50 finder as a nebulous bar. In a 13.1-inch reflector, I saw an impressive kidney-shaped nebula, extending 12′ × 7′ north to south and opening to the east. The southern half was brighter than the northern, and the inner (eastern) edge was more sharply defined. Several 11th- and 12th-magnitude stars glittered on the southeast end. Despite a careful look, I found no sign of the bubble's eastern half.

Wind-Blown Bubbles

Object	WR No.	HD	Spectral Type	Mag(v)	Size	RA	Dec.
NGC 6888	136	192163	WN6	7.5	17′	$20^h\ 12.1^m$	+38° 21′
WR 134 Nebula	134	191765	WN6	8.1	20′	$20^h\ 10.2^m$	+36° 11′
Sh 2-308	6	50896	WN4	6.7–6.9	40′	$06^h\ 54.2^m$	–23° 56′
NGC 2359	7	56925	WN4	11.6	27′	$07^h\ 18.5^m$	–13° 13′
NGC 3199	18	89358	WN4	10.8	22′	$10^h\ 17.0^m$	–57° 55′
WR 23 Nebula	23	92809	WC6	9.0	30′	$10^h\ 41.6^m$	–58° 46′
NGC 2020	—	269748	WN4	13.2	3′	$05^h\ 33.2^m$	–67° 43′

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

ESO

A few years later I used an 18-inch reflector in rural Australia and found NGC 3199 rich in intricate detail. With a narrowband filter, the mottled nebula contained subtle patches, knots, and dark veins. A thin 5′ ribbon straddled the outer western edge, running north and south, and much fainter nebulosity appeared to leak out and flow east from the south end. Through a 25-inch scope, I was able to trace the full perimeter of the bubble.

The next stop is the astonishing Carina Nebula, which surrounds the famous luminous blue variable, Eta (η) Carinae. This region, the Carina OB1 association, has produced many of our galaxy's most massive stars, including at least five Wolf-Rayet stars. In 1980, French astronomer Marie-Claire Lortet and collaborators discovered a partial ring centered 10′ west of the 9th-magnitude carbon-rich star WR 23 (HD 92809).

It's easy to pass right over the **WR 23 Nebula** as it blends into the dense nebulosity at the north end of the Carina Nebula. But using a narrowband filter I traced a large 20′ semicircular arc opening to the east. The central portion is a bit brighter and contains a wide pair of 10th- and 11th-magnitude stars. The arc hooks sharply east at the north end and dissipates into the star field, while the southern end leads to a thick east-west bar of nebulosity. The ring is incomplete along the east side due to heavy dust obscuration. Experiment with different filters — I found a hydrogen-beta filter also enhanced its visibility.

For our final target, we'll leave the Milky Way and head to the neighboring Large Magellanic Cloud, which has a major collection of more than 150 WR stars. And despite a distance of 165,000 light-years, the emission nebula **NGC 2020** is faintly visible through an 8-inch scope. In images, the nebula sports a distinctive blue ring with a double rim, suggesting a tilted short cylinder, and a circular, diffuse H II region surrounds the ring.

I had a memorable view of NGC 2020 in April of this year in Australia through a 25-inch reflector. At 264×, the roundish 3′ nebula formed a classic smoke ring, with a dark center spanning 45″ × 30″. The 13th-magnitude WR star HD 269748 shines just north of center, and a 12th-magnitude star is pinned against the south edge.

▲ **YOUNG AND OLD** Two rather dissimilar nebulae sit side by side in the Large Magellanic Cloud. The pinkish nebula at right (NGC 2014) is an emission nebula, powered by a cluster of hot, young stars. The bluish nebula at left is a WR nebula (NGC 2020), powered by a single, massive dying star. The color differences are due in part to the different chemical compositions of the surrounding medium: The hot winds from the young stars plow into a nebula composed mostly of hydrogen, whereas the WR winds collide with heavier elements previously expelled by the red supergiant star, primarily oxygen in this case.

What's the ultimate fate of a WR star? In a relatively short time span, the core will become iron-rich and no longer able to support nuclear fusion. At that point gravity will win the final battle with radiation, initiating a cataclysmic collapse. Because of their extreme mass, WR stars are strong candidates to end their lives in a spectacular core-collapse supernova (Type Ib or Ic). Long-duration gamma-ray bursts may be produced — the signature of a phenomenally high energetic event. The blast will leave a lasting legacy by seeding our galaxy with vast amounts of heavy elements for future generations of stars and planets.

■ A deep-sky fanatic for 40 years, Contributing Editor **STEVE GOTTLIEB** keeps an eye on the sky for us from northern California. He welcomes your questions and comments at **steve_gottlieb@comcast.net**.

NGC 2020: ESO; X-RAY: ESA / XMM-NEWTON / J. TOALÁ / D. GOLDMAN

WR Nebulae Also Shine in X-rays

Astronomers have detected X-ray emission from four Wolf-Rayet nebulae to date: NGC 6888, Sh 2-308, NGC 2359, and NGC 3199 (all featured in this article). During the WR phase, the star's strong and fast wind rams into the slower wind shed during the red supergiant or luminous blue variable phase. Shock waves ripple through the surrounding medium, heating it to tens of millions of degrees, hot enough to emit X-rays. In the image at left of NGC 3199, obtained with the European Space Agency's XMM-Newton satellite, the hot X-ray-emitting gas is colored blue, while the yellow-green and red (oxygen and sulfur, respectively) trace out the visible arc — compare this with the image opposite. – **DIANA HANNIKAINEN**

 by Igor Palubski and Aomawa Shields

Red Dwarf Habitab

Life on worlds around the smallest, most common stars would have to cope with environments vastly different from our own.

It's hard to imagine life existing in an environment fundamentally different from Earth, a planet rich in vegetation and oceans orbiting a bright, yellow star. Indeed, for decades astronomers focused on Sun-like stars when hunting for habitable worlds, a decision that made logical sense for a number of reasons. Such stars have lifetimes of roughly 10 billion years, providing ample time for life to emerge if it follows the pattern it did on Earth. And Sun-like stars don't pose the hazardous threats that other stars might when it comes to flares and magnetic activity, instead living relatively quiet lives. Above all of the reasons to pursue life around stars like the Sun, though, is one single fact that cannot be overvalued: The only known example of a habitable planet orbits one of these stars.

Over the last two decades, however, astronomers' interest has shifted from Sun-like or "*G*-dwarf" stars to an entirely different class of stars: *M*-dwarf or "red dwarf" stars. The latter are much smaller and less massive than Sun-like stars, making planets around them easier to find. They're also far more common. As such, astronomers are discovering large numbers of planetary systems around these stars. As additional space- and ground-based telescopes come online in the coming decades, they will find many more such systems.

Some of these planets — including those orbiting the red dwarfs Proxima Centauri, Trappist-1, and LHS 1140 — have garnered widespread attention, largely because they're relatively nearby. The fact that their stars hang out in our stellar backyard means that we might soon be able to measure the planets' atmospheric compositions and search for biologically generated fingerprints, called *biosignatures*. The first habitable exoplanet discovered beyond our solar system might end up orbiting a star very different from our own.

Would life on such a world even exist? Astronomers have traditionally defined a star's *habitable zone* as the range of dis-

LEAH TISCIONE / S&T

▶ **HOW TO BREW A HABITABLE PLANET** Although astronomers have traditionally defined a star's habitability based on the zone where temperatures permit liquid water, true habitability involves a cocktail of factors — and some might surprise you.

ility Recipe

tances from a star where conditions on an Earth-like planet would permit liquid water to flow on its surface. But true habitability involves a glorious cocktail of factors, from the host star's luminosity and magnetic activity to the planet's rotation rate and the composition of its atmosphere and surface. When it comes to red dwarfs, the prospects are not all sunshine and rainbows, but life — perhaps an unfamiliar form of it — could still thrive.

Habitability Gamble

There are many reasons why red dwarf stars might be the best places to look for habitable planets. First among them is sheer numerical superiority. These puny stars comprise about 70% of all stars in the Milky Way. This means that when astronomers swivel their telescopes toward a random patch of the sky, most of the planets they'll find will orbit red dwarfs.

Furthermore, the two most widely used techniques for detecting exoplanets — the transit and radial velocity methods — work better with small stars. An Earth-size planet orbiting a small star will eclipse a higher percentage of the star's visible surface (and thus its starlight) than the same planet orbiting a large star. Similarly, an Earth-size planet orbiting a less massive star will cause that star to wobble more than if it orbited a heftier star. Thus, astronomers discover more planets around small stars using these methods.

Furthermore, the gas clouds that collapse to make red dwarf systems appear to form small planets more easily than they do big ones. NASA's Kepler spacecraft found that although red dwarfs host far fewer gas giant planets than Sun-like stars do, they have 3.5 times more small planets in the Earth-size regime. In fact, 1 in 4 red dwarf star systems is estimated to have an Earth-size planet in the habitable zone.

For all these reasons, detecting habitable planets is not only easier but also more likely around red dwarfs than around other types of stars.

Unfortunately, because these stars are much cooler than most other stars, their habitable zones are significantly closer to them, much like a person must stand closer to a small campfire than to a large one to feel the same amount of heat. This close distance presents a number of complications to the habitability of orbiting planets.

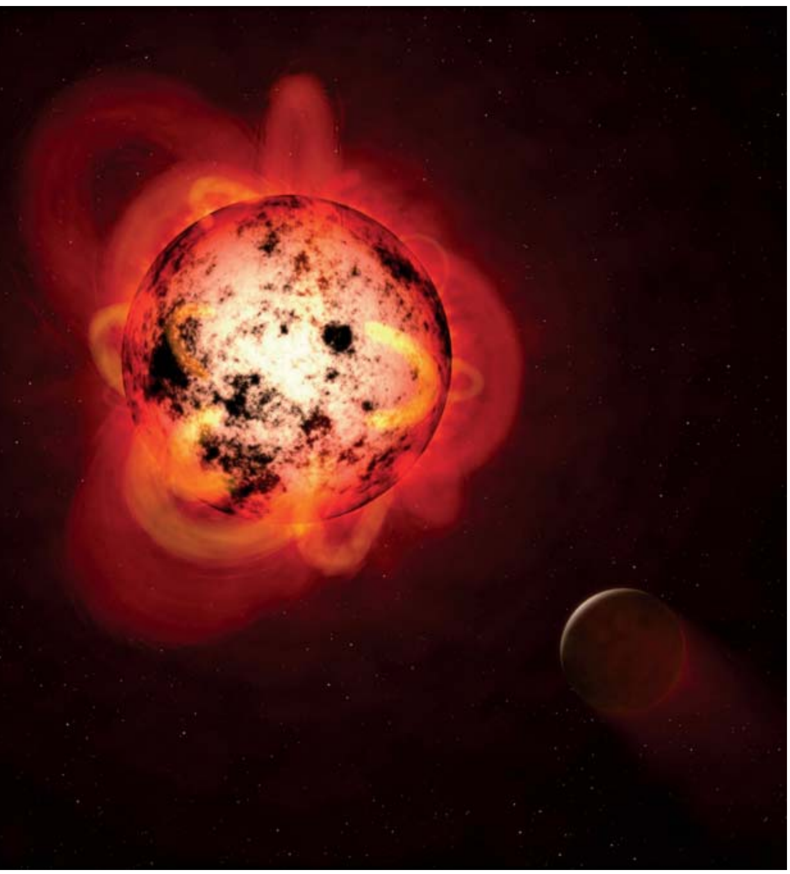
For starters, such proximity creates strong tidal forces, which can slow down the planet's rotation rate and affect its atmospheric circulation. This effect, known as *tidal locking*, can play out in a number of ways. It can slow down the planet only a little, or it can slow down the planet a lot, to a point called *synchronous rotation*, in which the same side of the planet always faces the star — meaning it's always daytime on that side of the planet and nighttime on the other. Who would want to live on a planet where it's always day or night? Could life even survive on such a world?

Indeed, the prevailing concern has long been that the nightside of a synchronously rotating planet could become so cold that the entire atmosphere would freeze out, condensing onto the surface to create an icy, airless world. Not the greatest prospect for a fun nightlife.

But all is not lost. Recent research using sophisticated global climate models has shown that a thick atmosphere could transport enough heat to the nightside of a synchronously rotating planet to prevent atmospheric freeze-out. Additionally, synchronous rotation might even create an advantage for habitability: If a tidally locked planet has an ocean, then the stronger convection in its atmosphere — a consequence of longer daytime illumination — could gener-

Because these stars are much cooler than most other stars, their habitable zones are significantly closer to them, much like a person must stand closer to a small campfire than to a large one to feel the same amount of heat.

▼ **NEVER-ENDING STORMS** Red dwarf stars are tumultuous. On a typical day, they display gigantic arcing prominences and a wealth of dark sunspots, but they also erupt with intense flares that, over time, could strip a nearby planet's atmosphere. One look at this artist's conception and it's easy to see why astronomers initially thought that any planets around stars like this one would be sterile.

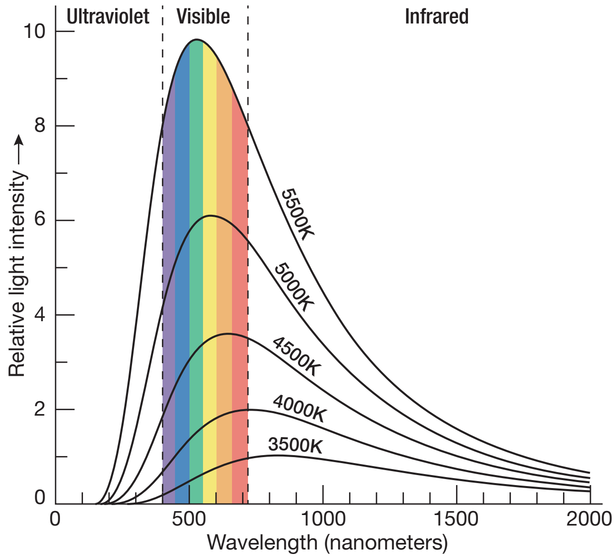


NASA / ESA / STScI / G. BACON

ate a thick blanket of clouds on its dayside. Those clouds would reflect the star's light back to space, lowering surface temperatures. This process might allow these planets to orbit their stars at much closer distances than they otherwise would, essentially buffering them against so-called *runaway greenhouse* states.

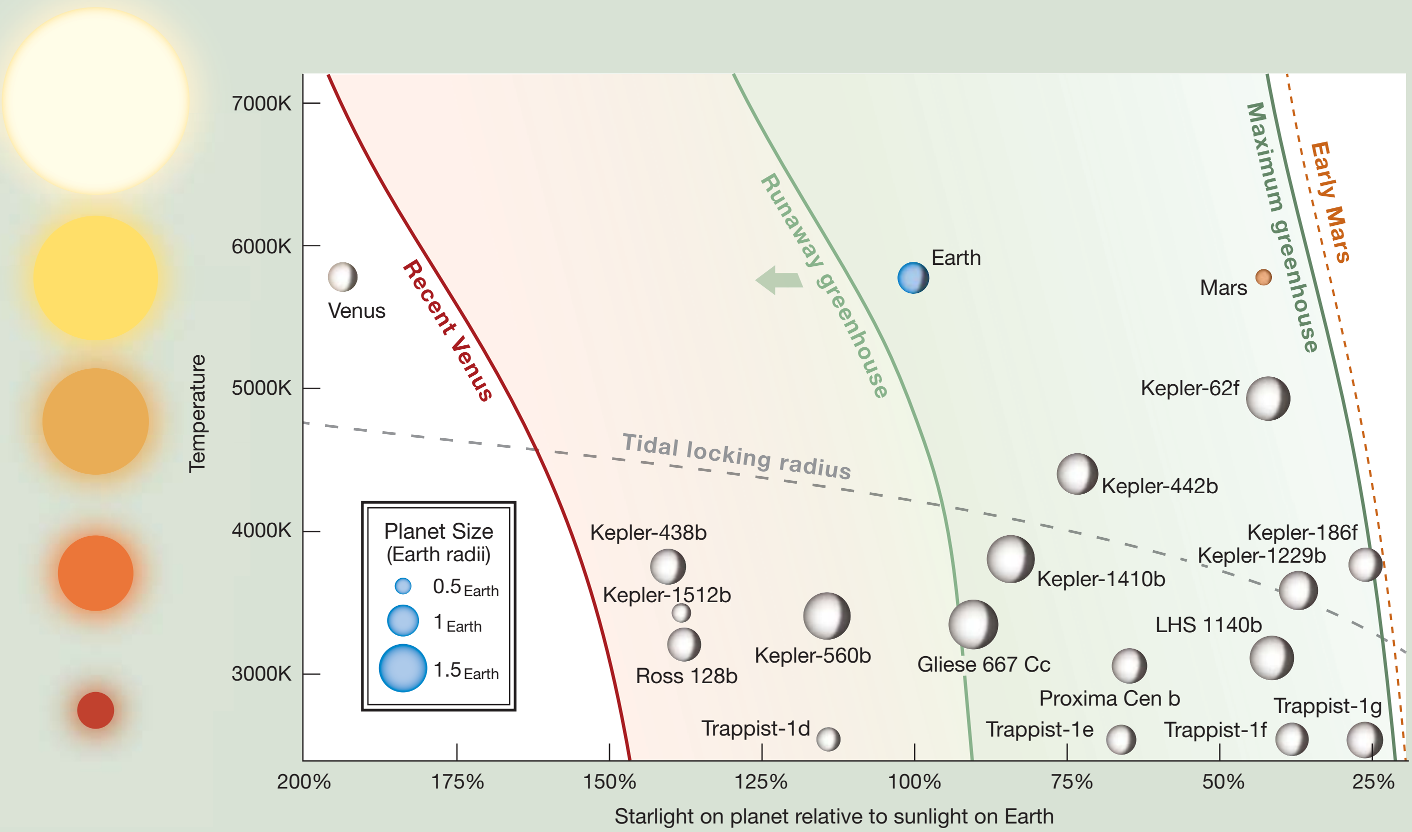
Besides the tidal interactions between a planet and its parent star, there may also be interactions between planets, as worlds around *M*-dwarfs often form closely packed together. In such cases, the gravitational pull of a planet's neighbors will change its rotation rate and might even transform the shape of the planet's orbit, making it more (or less) elongated. Since the orbit's shape, or *eccentricity*, determines how much starlight reaches the planet throughout its year, each interaction will change the total amount of light the planet receives. If the planet's spin axis is also tilted, then the interaction will also change how that starlight is distributed across different parts of the globe. There could be bizarre planets where climate conditions change significantly throughout the year.

Eccentric orbits aren't all bad, though. As a planet in an eccentric orbit swings through its closest approach to its

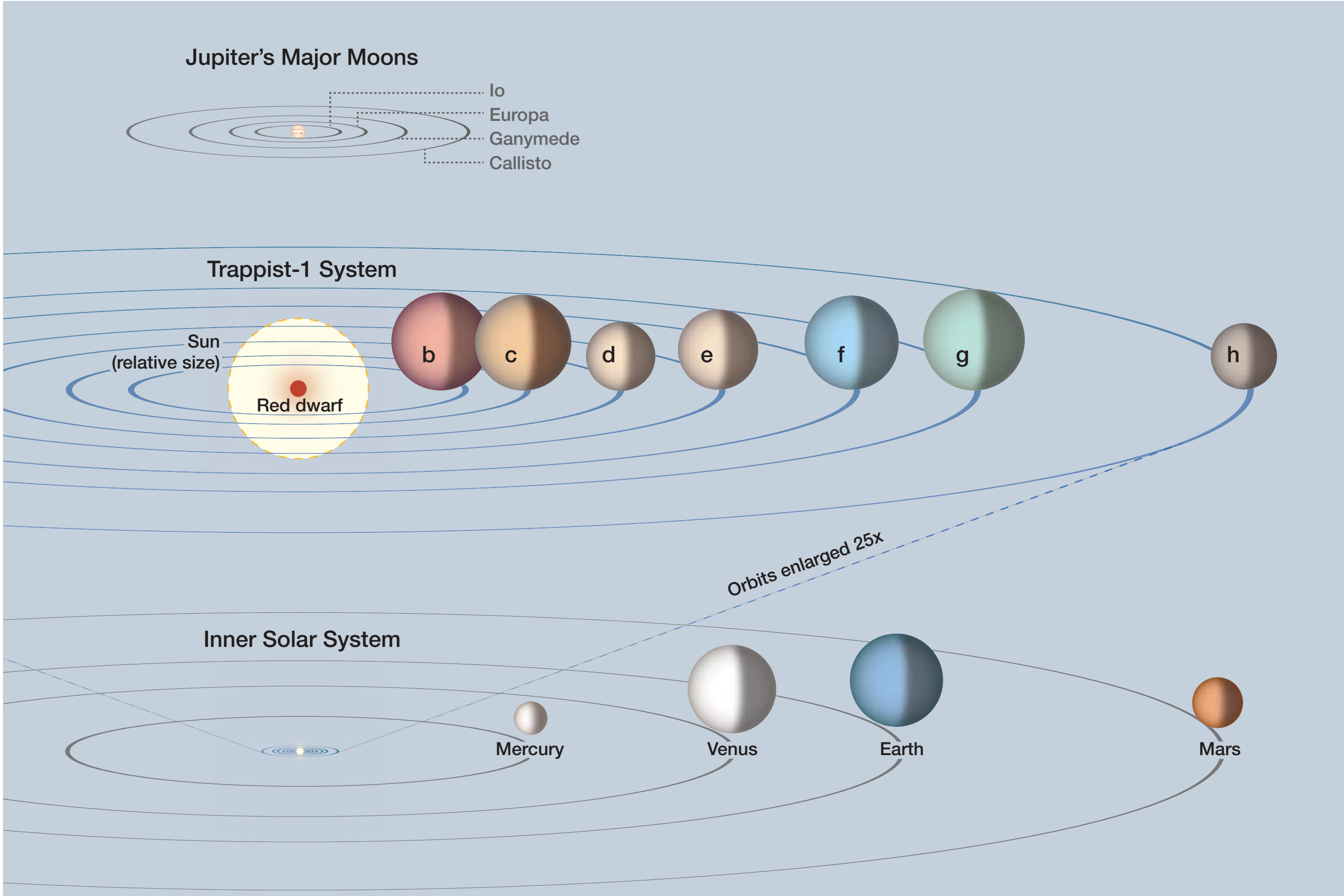


▲ **PEAK WAVELENGTHS** Cooler stars emit most of their radiation at longer wavelengths. While the Sun emits mostly visible and ultraviolet light, red dwarfs emit more infrared — a difference that could affect nascent life on an orbiting planet. (Color intervals are approximate.)

▼ **SHIFTING ZONES** Shown here are confirmed, potentially rocky exoplanets that fall in their stars' habitable zones, as compiled by Chester Harman (NASA Goddard Institute for Space Studies). The tidal locking radius was calculated by Jun Yang (Peking University) and colleagues.



WAVELENGTHS: WIKIPEDIA; ZONES: GREGG DINDERMAN / *S&T*, SOURCE: JUN YANG ET AL. / *ASTROPHYSICAL JOURNAL LETTERS* 2014 AND CHESTER HARMAN, JR.



▲ **SEVEN WILD ABODES** The Trappist-1 system, which contains the largest number of known planets in the habitable zone around a single red dwarf, might be habitable — despite harsh conditions. A recent study suggests that at least one of the seven worlds might still possess liquid water.

GREGG DINDERMAN / S&T, SOURCE: NASA / JPL-CALTECH

star, the induced tidal stretching and squeezing can heat the planet's interior and drive plate tectonics, which scientists think enhances habitability by recycling carbon and other materials (*S&T:* July 2013, p. 18).

Forever Young and Tempestuous

Another complication that awaits planets around red dwarfs relates to the inordinately long lives of the parent stars. Because of their low masses, red dwarfs burn through their nuclear fuel *very* slowly. They are the tortoises of the stellar family. As a result, they have lifetimes that are significantly longer than those of Sun-like stars. We're talking trillions of years for the lowest-mass red dwarfs — compared with 10 billion years for our Sun. Because those lifetimes are longer than the current age of the universe (13.8 billion years), no red dwarf star has ever died.

Now, this could be a good thing or a very bad thing from a habitability standpoint. On the one hand, red dwarf stars' long lifetimes provide ample time for life to emerge, develop, and evolve way past any kind of life on Earth, including humans. And that's an exciting prospect. Perhaps life on a red dwarf planet will have evolved to be so technologically advanced that we won't have to worry about figuring out how to find it. It will find us.

On the other hand, the lengthy lifetimes of red dwarf stars also mean that they take a long time to settle down. Stars are much more active when they are young, spewing out flares and significant amounts of extreme ultraviolet (EUV) light towards an orbiting planet. For red dwarfs, this tumultuous period can last as long as a billion years. That's one *long* phase of the terrible twos. Over the course of that time, strong EUV emission could pelt the surface of the planet, evaporating its oceans and sending water vapor high into the atmosphere, where radiation can break it up into its separate components of hydrogen and oxygen. The lighter hydrogen escapes more easily to space, while the heavier oxygen would remain behind, creating an O_2-rich world. Any future observational measurements of such a world from space might erroneously assume that the detection of oxygen indicates the world is teeming with life, when the reality is that the planet has long been desiccated.

However, if a planet begins with enough water that it can retain some over its star's tumultuous time, a planet could remain habitable. This scenario might be the case for the Trappist-1 system. Trappist-1 hosts the largest number of known planets in the habitable zone orbiting a single red dwarf star. A recent study has shown that, even if the system's seven detected worlds are subject to high amounts of EUV emission and flares from their host star, at least one of the seven planets may still possess enough liquid water to preserve habitable surface conditions. And the Trappist-1 worlds aren't alone: Data on the thousands of planets detected by the Kepler space telescope suggest that the universe might be rich in water worlds.

Unfortunately, those red dwarf planets that manage to preserve their oceans might still become uninhabitable due to the side effects of orbiting a cool, small star. Strong stellar winds — another consequence of the red dwarf environment — might render the Trappist-1 planets uninhabitable by stripping away their atmospheres. Additionally, intense ultraviolet light, typical of red dwarf flare events, may remove most of a planet's atmospheric ozone, a crucial element in shielding Earth's surface from harmful ultraviolet rays. Yet, the amount of atmospheric depletion can vary greatly depending on each star's behavior, and surface conditions might mitigate its dangers. If the world has large oceans, for example, life could still develop underwater even in the absence of a thick ozone layer.

Even a planet's magnetic field could suffer because the planet is too close to the star. This field is powered by the churning motion of liquid metal deep within the planet and sustained by both the planet's rotation and the flow of heat from the core to the outer layers. A magnetic field has long been considered a characteristic of a habitable planet, because it can protect the atmosphere from the harmful effects of stellar flare activity, charged particles, and cosmic rays. But unfortunately, planets orbiting red dwarfs might host fairly weak fields. Some scientists suggest that, because the planets are tidally locked and tidally heated, their interiors might not sustain the churning motion needed to power a global field. The topic remains an active area of research.

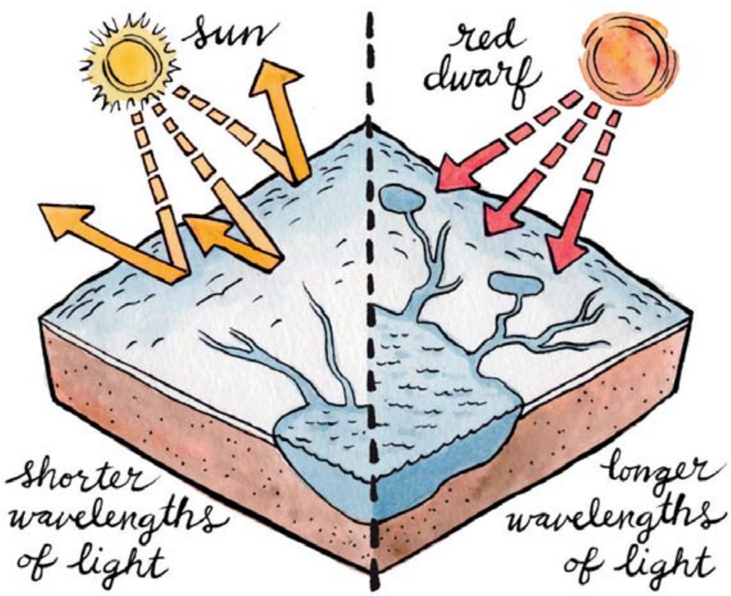
Life-giving Glow?

Another key difference between red dwarfs and other stars is that the type of light they produce — and that planets receive — is quite different. Whereas visible and ultraviolet light make up a large fraction of what Earth receives from the Sun, red dwarfs emit primarily at longer wavelengths (particularly in the infrared waveband). This difference is key to their planets' habitability, as recent research shows that infrared radiation interacts differently with planetary atmospheres and surfaces than does visible or ultraviolet light.

Stars are much more active when they are young, spewing out flares and significant amounts of extreme ultraviolet light. For red dwarfs, this tumultuous period can last as long as a billion years.

Molecules prevalent in planetary atmospheres, such as water, carbon dioxide, and methane, strongly absorb infrared radiation. And the more that an atmosphere absorbs, the warmer it (and its planet) will be. Thus, despite red dwarfs' cool, dim nature, their planets might more easily maintain balmy surface temperatures than worlds around hotter, brighter stars. In addition, red dwarf planets wouldn't need as much CO_2 or other greenhouse gases in their atmospheres in order to stay warm.

Additionally, it isn't just atmospheric molecules that can absorb this longer-wavelength emission. Water ice and snow also strongly absorb infrared wavelengths. The interaction between the red dwarf spectrum and icy or snowy surfaces may have an important effect on planetary climate — one very different than the one we experience here. On Earth, water ice reflects the shorter wavelengths of sunlight, sending them back to space and cooling the globe, which leads to the formation of more ice (which reflects more sunlight, further lowering temperatures, etc.). At its best, this process regulates our planet's climate; at its worst, it leads to ice ages.

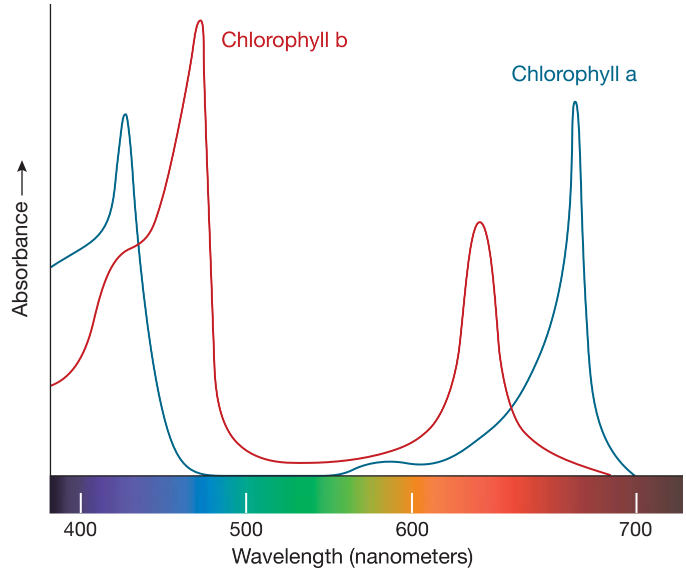


▶ **FIRE AND ICE** On Earth, water ice reflects the relatively shorter wavelengths of sunlight, sending them back to space and cooling the globe. Then more ice forms, which reflects more sunlight, further lowering temperatures in a feedback loop. But on a planet orbiting a red dwarf, water ice absorbs the star's longer wavelengths, creating a warming effect instead.

LEAH TISCIONE / S&T

But on a planet orbiting a red dwarf, ice and snow will instead absorb much of the incoming light from its star. This warming effect, combined with the warming from the atmosphere, means that water-dominated planets might be more resistant to freezing over than similar planets orbiting brighter stars. If planets around a red dwarf do freeze, they might thaw out more easily over time as their host stars — like all other stars — naturally brighten. The fact that these planets are fairly resistant to climate extremes and exit those extremes easily on the rare occasion they do happen, means that they're more climatically stable and will therefore provide a greater chance for life.

Scientists are just beginning to consider the climatic impacts of different types of surface environments on red dwarf planets. The news isn't all balmy. New research finds that if temperatures within a red dwarf planet's oceans plummet below -23°C, salt could crystallize in bare sea ice, forming what is known as a *hydrohalite crust*. At infrared wavelengths, hydrohalite is brighter than snow, which means that it doesn't absorb starlight but reflects it — so much so that its presence could cool the surface more than researchers had thought possible. We still have much to learn about how different surfaces — from distinct kinds of soil and vegetation to ocean and ice — might interact with the light from red dwarfs.



▲ **ABSORBING LIGHT** On Earth, plants primarily use the pigments chlorophyll a and b, which absorb sunlight strongly in the visible range of the spectrum. Plants on red dwarf planets might be able to absorb light at these wavelengths as well, but they would have to rely on stellar flares, which emit light across the entire electromagnetic spectrum. The growth of vegetation would then depend not on seasons but on the red dwarf's cycles of flare activity.

Life's Spark

It is far too soon for us to comprehensively answer the question of what kind of life might be possible on a red dwarf planet. But we can ask a more specific question: Is photosynthesis possible?

On Earth, plants use the pigment chlorophyll, which absorbs stellar light strongly in the visible range of the spectrum (400–700 nanometers), to transform sunlight and carbon dioxide into food. In the process, they produce oxygen, vital to respiration and in the production of the protective ozone layer around Earth. Given the small amount of visible light that red dwarfs emit, photosynthesis as we know it might not be possible on planets around such stars. However, life on these planets would presumably evolve to harvest the wavelengths most available. Vegetation on planets around red dwarfs might absorb radiation across a wider range of the spectrum or specifically use infrared wavelengths.

The star's flares might also provide what its calmer glow does not. Stellar flares emit radiation across the entire electromagnetic spectrum, including visible light. So it might be the case that the strong flare activity, usually thought of as damaging to life, could supply vegetation with enough visible light to conduct the kind of photosynthesis that plants do on Earth. In this scenario, the cycle governing the loss and growth of vegetation could become inextricably tied to the cycles of flare activity for a red dwarf, an unusual symbiotic prospect.

This relationship could be even more profound at ultraviolet wavelengths — and that's crucial. Researchers think that ultraviolet radiation is a necessary ingredient in the chemical processes leading up to the formation of basic life. If that's true, then the paucity of ultraviolet light coming from *M*-dwarfs would pose an obstacle to the development of life. But flares might solve the problem: The blasts of ultraviolet photons that bombard the planet with every stellar outburst might compensate for this intrinsic deficit — providing enough light to help life emerge.

We are only at the beginning of understanding what worlds around these stars might be like. But over the next decade, we'll see space- and ground-based projects with instruments sensitive enough to observe an abundance of small terrestrial planets. NASA's Transiting Exoplanet Survey Satellite (TESS; *S&T:* Mar. 2018, p. 22) spacecraft, for example, spends 27 days staring at each patch of sky, a length of time comparable to the orbital period of planets in the habitable zones around red dwarfs. These cool, dim stars are thus the favored targets for the TESS mission. In fact, 75% of the planets TESS is expected to detect should orbit red dwarfs. The most promising planets will be close enough that follow-up studies might identify biosignatures in their atmospheres, telling astronomers that life is likely present.

If there exists a habitable planet orbiting a red dwarf, we now have a real chance of finding it.

■ **IGOR PALUBSKI** is a graduate student at the University of California, Irvine. **AOMAWA SHIELDS** is the Clare Boothe Luce Assistant Professor of Physics and Astronomy at the University of California, Irvine, and Director of the Shields Center for Exoplanet Climate and Interdisciplinary Education.

4–5 DUSK: The thin waxing lunar crescent is in Virgo the next two evenings. Find it on the 4th when it's some 3° right of Gamma (γ) Virginis (Porrima). The following evening, the Moon is less than 7° upper right of Alpha (α) Virginis (Spica).

7 DUSK: The first-quarter Moon is in Libra, equidistant from Alpha and Beta (β) Librae — you may know Alpha as the double star Zubenelgenubi.

9 DAWN: Mercury arrives at its greatest western elongation from the Sun. Look for the little world before sunrise low on the east-northeastern horizon, where it should be visible until the 26th. Binoculars will improve the view.

9 EVENING: The waxing gibbous Moon and Jupiter are around 2° apart, with Antares not far to the pair's lower right. The trio sets in the southwest after midnight local time, with the red supergiant leading the way.

11 EVENING: Enjoy the view of the Moon and Saturn, a little more than 3° apart, as they shine in the Teapot of Sagittarius.

12–13 LATE NIGHT TO DAWN: The predicted peak of the Perseids — in the early morning hours of the 13th — coincides with the nearly full Moon, which will hamper observations. However, the shower is active from July 17th to August 24th, so it's worth casting a glance skyward in search of meteors in the weeks preceding and following the peak.

24–25 DAWN: The waning crescent Moon is in Taurus, a mere 2° from the red giant Aldebaran on the morning of the 24th. The next morning, the Moon is less than ½° from Zeta (ζ) Tauri, and the star will be occulted for much of western North America.

27 DAWN: The thin lunar crescent is some 6–7° from Pollux, in Gemini. It's above the eastern horizon about two hours before twilight begins.

28 DAWN: The sliver of the Moon, in Cancer, is in or near M44, the Beehive Cluster (depending on your viewing location).

— DIANA HANNIKAINEN

This image, taken with the European Southern Observatory's 2.2-meter telescope at La Silla in Chile, shows the open cluster Messier 11, also known as the Wild Duck Cluster. The cluster lies some 6,200 light-years away in Scutum, the Shield. The young, hot, blue cluster stars are surrounded by redder, older background stars. ESO

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
August 1
03:12 UT

FIRST QUARTER
August 7
17:31 UT

FULL MOON
August 15
12:29 UT

LAST QUARTER
August 23
14:56 UT

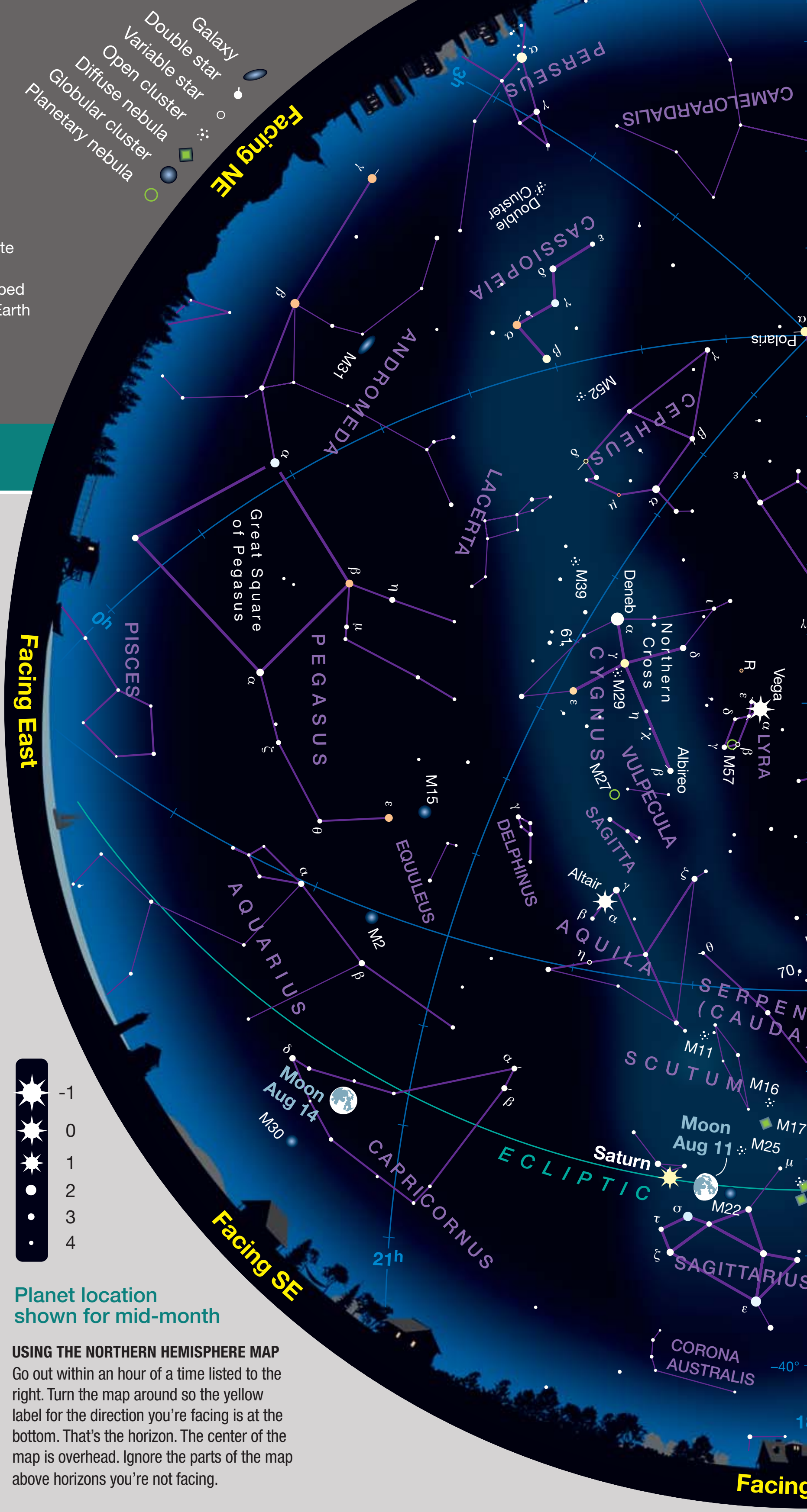
NEW MOON
August 30
10:37 UT

DISTANCES

Perigee 359,398 km	August 2, 07^h UT Diameter 33′ 15″
Apogee 406,244 km	August 17, 11^h UT Diameter 29′ 25″
Perigee 357,176 km	August 30, 16^h UT Diameter 33′ 28″

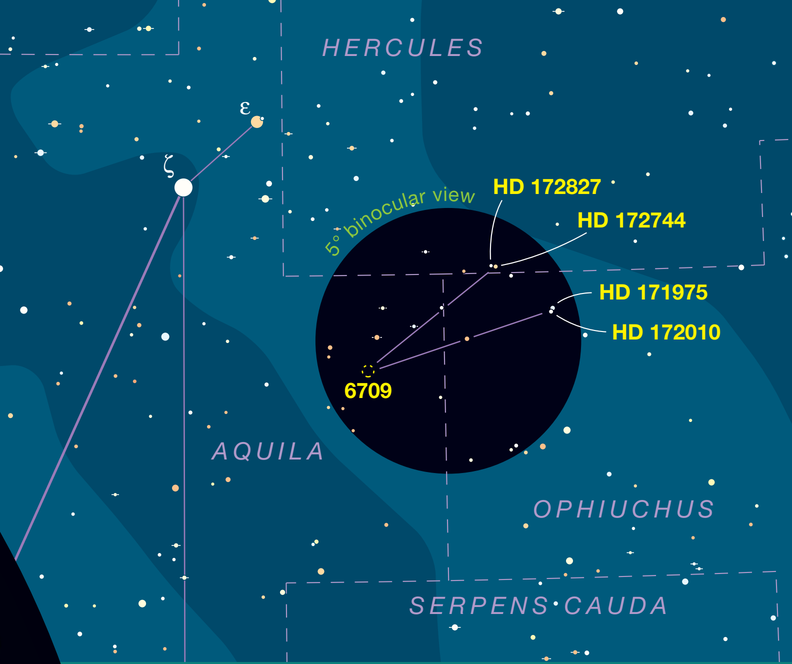
FAVORABLE LIBRATIONS

• Mare Humboldtianum	August 15
• Hermite Crater	August 17
• Pascal Crater	August 18
• Lavoisier Crater	August 23



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.



Binocular Highlight by Mathew Wedel

Something for Everyone

One of my favorite objects in the summer Milky Way is the open cluster **NGC 6709**. It lies close to the western border of Aquila, the Eagle, almost exactly 5° southwest of Zeta (ζ) Aquilae. From our vantage point, the cluster is perched just on the edge of the Cygnus Rift, the great lane of dark dust clouds that stretches from the celestial Swan to the galactic center in Sagittarius, the Archer. For once, this isn't a coincidental alignment; at 3,500 light-years from us, NGC 6709 is at approximately the same distance as the vast dust clouds that make up the rift. With a diameter of a little less than 15 light-years, the cluster therefore serves as a visual yardstick, allowing us to appreciate just how breathtakingly colossal are the large-scale structures of our galaxy.

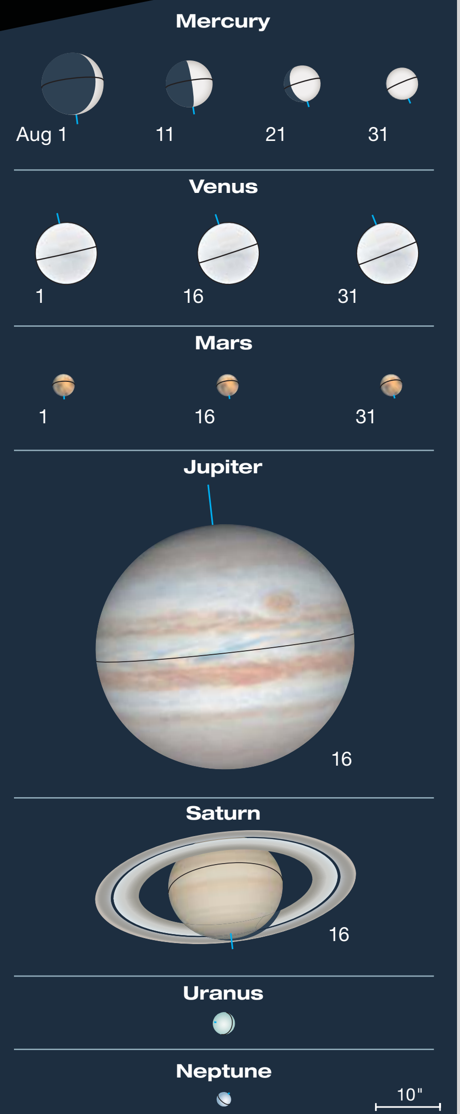
I also like NGC 6709 for another reason: It's pretty. Suspended as it is between the brighter lights of Cygnus and Sagittarius, I think NGC 6709 is sometimes overlooked. But it's well worth a visit. Not only is the cluster a charming object in its own right, it's the focal point of a neat binocular asterism. Fanning about 3° west-northwest from NGC 6709 is a thin wedge, densely packed with stars, that looks a bit like the tail of a comet streaming away from the cluster. This comet tail is bookended at its corners by a pair of nice binocular doubles: **HD 172827** and **HD 172744** on the northeast, and **HD 171975** and **HD 172010** on the southwest. The cluster itself holds some fine, if challenging, stars, including a pair of red giants on its southeast margin. NGC 6709 has a little something for everyone — go see what it has for you.

■ Binocular observing gives **MATT WEDEL** many opportunities to learn the difference between looking and seeing.

WHEN TO USE THE MAP

Late June	1 a.m.*
Early July	Midnight*
Late July	11 p.m.*
Early Aug	10 p.m.*
Late Aug	Dusk

*Daylight-saving time



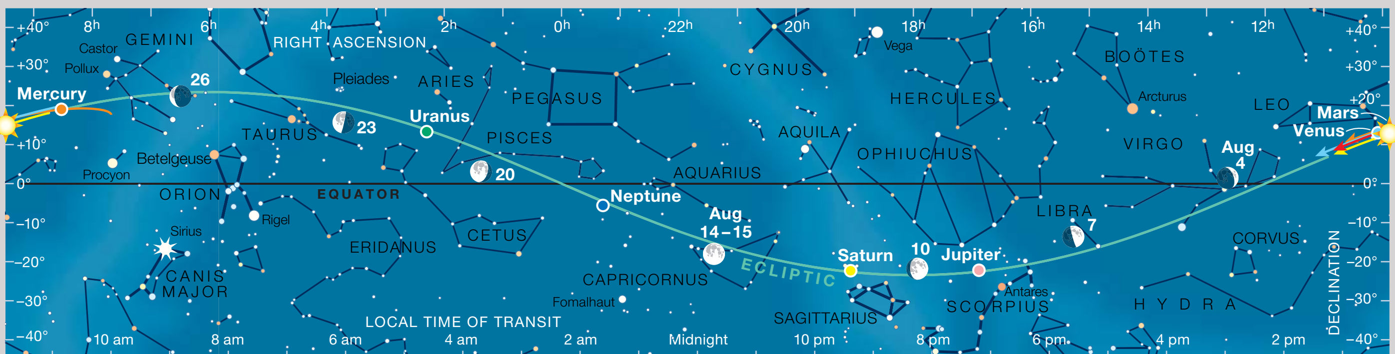
PLANET DISKS have south up, to match the view in many telescopes. Blue ticks indicate the pole currently tilted toward Earth.

PLANET VISIBILITY **Mercury:** visible at dawn from the 3rd to the 26th • **Venus:** hidden in the Sun's glow all month • **Mars:** hidden in the Sun's glow all month • **Jupiter:** visible at dusk, sets near midnight • **Saturn:** visible at dusk, sets after midnight

August Sun & Planets

	Date	Right Ascension	Declination	Elongation	Magnitude	Diameter	Illumination	Distance
Sun	1	$8^h\ 42.6^m$	+18° 12′	—	–26.8	31′ 31″	—	1.015
	31	$10^h\ 35.1^m$	+8° 55′	—	–26.8	31′ 41″	—	1.010
Mercury	1	$7^h\ 39.5^m$	+17° 40′	15° Mo	+2.0	9.7″	13%	0.695
	11	$8^h\ 02.9^m$	+19° 17′	19° Mo	–0.2	7.3″	44%	0.919
	21	$9^h\ 05.6^m$	+17° 43′	14° Mo	–1.1	5.7″	81%	1.173
	31	$10^h\ 22.6^m$	+12° 02′	4° Mo	–1.7	5.0″	99%	1.337
Venus	1	$8^h\ 28.6^m$	+20° 03′	4° Mo	–3.9	9.7″	100%	1.728
	11	$9^h\ 18.9^m$	+16° 55′	2° Mo	—	9.6″	100%	1.731
	21	$10^h\ 07.5^m$	+13° 00′	2° Ev	–4.0	9.6″	100%	1.729
	31	$10^h\ 54.5^m$	+8° 30′	5° Ev	–3.9	9.7″	100%	1.721
Mars	1	$9^h\ 26.4^m$	+16° 17′	11° Ev	+1.8	3.5″	100%	2.650
	16	$10^h\ 03.5^m$	+13° 07′	6° Ev	+1.8	3.5″	100%	2.670
	31	$10^h\ 39.8^m$	+9° 38′	1° Ev	+1.7	3.5″	100%	2.675
Jupiter	1	$16^h\ 52.5^m$	–22° 05′	126° Ev	–2.4	42.7″	99%	4.619
	31	$16^h\ 54.2^m$	–22° 14′	98° Ev	–2.2	39.1″	99%	5.039
Saturn	1	$19^h\ 06.6^m$	–22° 16′	157° Ev	+0.2	18.3″	100%	9.105
	31	$19^h\ 00.3^m$	–22° 29′	127° Ev	+0.3	17.7″	100%	9.407
Uranus	16	$2^h\ 16.7^m$	+13° 09′	106° Mo	+5.8	3.6″	100%	19.528
Neptune	16	$23^h\ 16.4^m$	–5° 50′	155° Mo	+7.8	2.4″	100%	29.015

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. is 149,597,871 kilometers, or 92,955,807 international miles.) For other dates, see skyandtelescope.com/almanac.



The Sun and planets are positioned for mid-August; 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). "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.

Celestial Palette

We continue with our exploration of colors in the heavens.

A circumhorizontal arc shimmers over rooftops and treetops.

In last month's column, we began a survey of colors visible in the summer night skies. That column focused on star colors. We continue now with the hues of summer's various nebulae and star clusters — with a bonus at the end.

Extra colors in the brightest planetaries. An arc of bright planetary nebulae is visible from Lyra to Aquarius on late-summer and early-autumn evenings. These glowing grave wreaths of stars are the Ring Nebula (M57) in Lyra, the Dumbbell Nebula (M27) in Vulpecula, the Saturn Nebula (NGC 7009) in Aquarius, and the Helix Nebula (NGC 7293) also in Aquarius.

The Saturn Nebula displays the most intense characteristic color of these nebulae: blue (or greenish-blue if the lenses of your eyes have become too yellowed by decades of exposure to the Sun's ultraviolet radiation). The Helix Nebula has great total brightness yet is spread out so much that it has low surface brightness, which makes it hard to see its color.

But what about the Ring Nebula and Dumbbell Nebula? In small- and medium-size telescopes the Ring may not show color, appearing just like a mystical phosphorescent smoke ring floating in space. But long ago I was delighted to glimpse red, yellow, and blue in the Ring for the first time — with one of the first commercial 13-inch Dobsonians. Soon after, I did so with a 10-inch telescope. (By the way, you may need a night of good seeing, i.e., excellent observing conditions with little to no atmospheric disturbance, to detect these colors in M57.)

You may have to work to draw color out of the gauzy white haze of M27, too. If you start with the nebula's apple-core shape in small scopes and then move up to larger scopes, you begin filling in (un-eating!) the apple. At what apple-ture — I mean aperture! — do you start detecting colors?

Our Sun will puff out into a planetary nebula as it dies. But more massive stars produce supernova remnants (SNRs). The most famous SNR of summer is the Veil Nebula in Cygnus, whose strands are visually red, white, and blue — in large amateur telescopes. How much aperture (maybe 16 inches?) do *you* need to detect its colors?

Diffuse nebulae and both kinds of star cluster. Photographs show the red of emission nebulae and blue of reflection nebulae in parts of some bright summer nebulae like the Trifid Nebula (M20) and the Lagoon Nebula (M8). Can you start detecting these colors in fairly small telescopes (see page 22)?

And what about open star clusters? The Double Cluster in Perseus is still pretty low at the time of our all-sky map on pages 42–43, but one member of this dynamic duo of clusters is famous for housing a smattering of warm-hued stars. My favorite open cluster of all is the Wild Duck Cluster (M11) near the meridian in the south on our map. I see the basic fan shape of this cluster as an avalanche of stars tumbling from the 8th-magnitude brightest sun, which shines near the apex of the fan. This star's color has been called "saffron" by the skilled and poetic observer Steve O'Meara.

O'Meara also looks for color in globular clusters, noting that M2 in Aquarius has "a yellow outer core that has a diffuse, pale-blue halo." I certainly see this. Do you agree with O'Meara that the Great Globular Cluster in Hercules (M13) has a yellow core with a slightly greenish halo?

The palette of atmospheric optics. For a change of pace from the wonderful subtle colors of objects in night skies, switch to day and the intense colors found in many phenomena of atmospheric optics. The yellow (between red and blue) in some *parhelia* (better known as "sun dogs" or "mock suns") can be especially vivid. Look in cirrus clouds for the rainbowlike circumzenithal arc way above the Sun when the Sun is 32° or less above the horizon, and the circumhorizontal arc way below the Sun when the Sun is 58° or more above the horizon. When thin clouds partially veil the Sun, look for a blue-green and red "cloud corona" around the Sun's reflection in a car's windshield or a humble puddle of rainwater. For more on these and numerous other phenomena, check out Les Cowley's superb website **atoptics.co.uk**.

■ FRED SCHAAF welcomes your letters and comments at **fschaaf@aol.com**.

To find out what's visible in the sky from your location, go to skypub.com/almanac.

Two Large, One Small

The two gas giants continue to enthrall us during the earlier part of the night, while plucky Mercury delights us in the morning.

This is the summer of the terrestrial planets Venus and Mars huddling out of sight near the Sun while the gas giant planets Jupiter and Saturn promenade in glorious view for much of the night.

The last of the five classic bright planets, Mercury, spends the summer dodging in and out of the solar glare. And though it's most often in that glare and not easily visible, August is an exception: Mercury spends much of the month giving us a fine apparition before sunrise.

DAYTIME

Venus and **Mars** are both lost in the glare of the Sun throughout August. On August 26th, Mars reaches aphelion, its farthest from the Sun in space, when it's at a distance of 1.67 a.u. from our star. Then, amazingly, just 7 days later, Mars comes to conjunction with the Sun and is at almost its very farthest possible from Earth, 2.67 a.u.

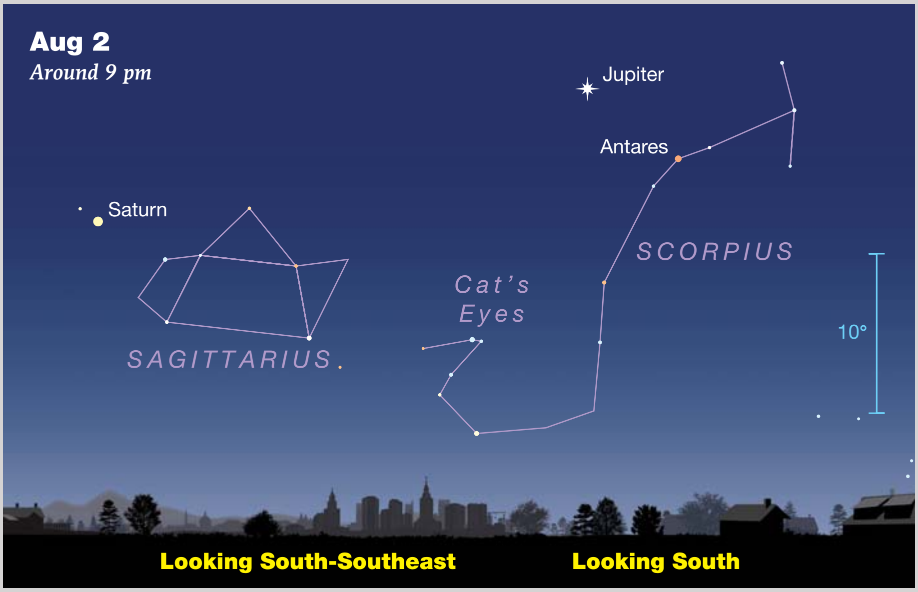
Mars doesn't emerge into visibility until the middle of October when it does so at dawn, but Venus starts coming into view at dusk in mid-September.

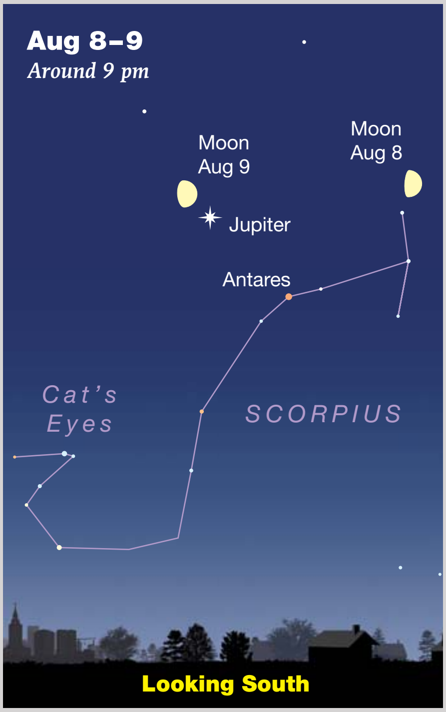
DUSK TO NIGHT

Jupiter lingers near Antares all month. It retrogrades to a minimum of 6¾° from the star on August 11th before beginning to ever so slowly move eastward and away from Antares. The giant planet fades a bit — from magnitude –2.4 to –2.2 — and shrinks from about 43″ to 39″. But the key observational fact about Jupiter this month is that it's highest around nightfall — which is therefore the prime time to look for detailed views of the planet's cloud features in the telescope. As soon as evening twilight ends, astrophotographers at dark sites can go for majestic views of Jupiter's brilliant beacon surrounded by the bright and dark Milky Way clouds of southern Ophiuchus (see *S&T:* July 2019, p. 57). The setting time of Jupiter backs up from about 2 a.m. to midnight daylight-saving time during the course of August.

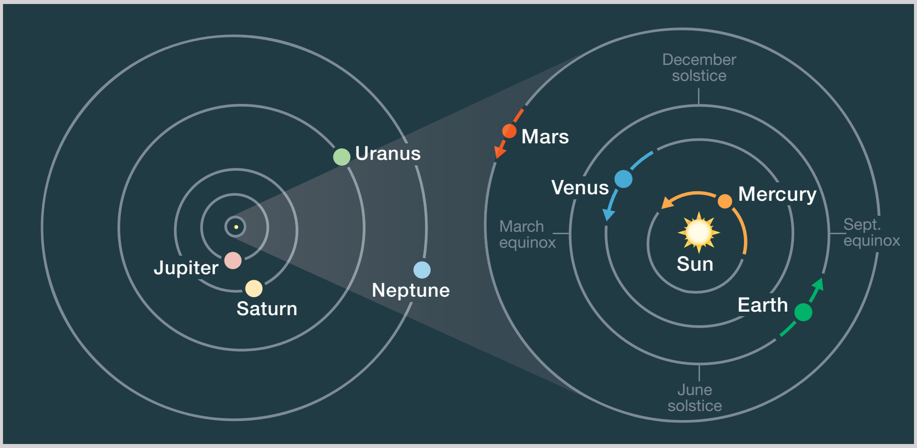
Saturn was at opposition on July 9th but only loses a little bit of apparent

▼▶ 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.





brightness and size in August. The golden world's magnitude diminishes from +0.2 to +0.3 and its equatorial diameter from 18.3″ to 17.6″ this month. The rings remain tilted to 24.7°, just a few degrees from their maximum angle. As with Jupiter this year, Saturn's southerly position calls for observing it in the telescope when it's at its highest, crossing the meridian. It transits around 11:30 p.m. daylight-saving time at the start of August and before 9:30 p.m. at month's end. Saturn shines between the little, dim Teaspoon of Sagittarius and the bright handle of the Teapot of Sagittarius. It continues to retrograde and closes the gap from 5° to 4° between itself and magnitude-2.1 Nunki, or Sigma (σ) Sagittarii. Saturn sinks below the horizon around 4 a.m. in early August and around 2 a.m. at the end of the month.



ORBITS OF THE PLANETS

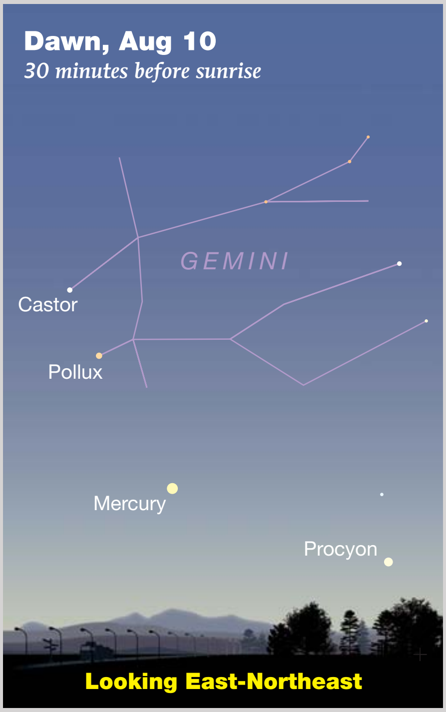
The curved arrows show each planet's movement during August. The outer planets don't change position enough in a month to notice at this scale.

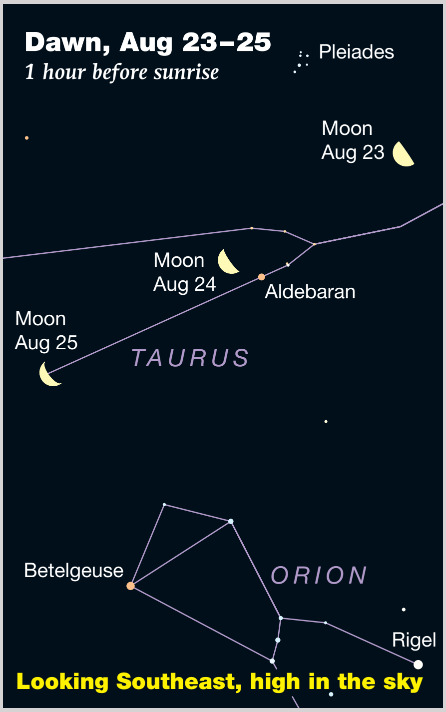
NIGHT TO DAWN

Neptune reaches opposition on September 10th but in August transits the meridian well after midnight daylight-saving time. **Uranus**, two magnitudes brighter than its fellow ice giant Neptune, doesn't rise until after evening twilight begins and for much of the month is at its highest after the start of morning twilight. See **https://is.gd/urnep** for a finder chart to help you locate Neptune in Aquarius and Uranus in Aries.

DAWN

Mercury has its best morning apparitions for observers at mid-northern latitudes within a month or two of the autumn equinox. On August 3rd it rises more than an hour before the Sun but has brightened only to magnitude 1.4 so is just marginally visible (use binoculars). On August 9th, however, Mercury reaches a greatest western elongation of 19° from the Sun, shines at zero magnitude, and rises about 90 minutes before the Sun for viewers around latitude 40°N. The little world is only about 38% illuminated that morning. It stands more than 10° above the east-northeast horizon by 30 minutes before sunrise that day. Mercury continues to brighten throughout August but drops deep enough into the Sun's glow to be lost from view by about August 26th on its way to superior conjunction on September 3rd.





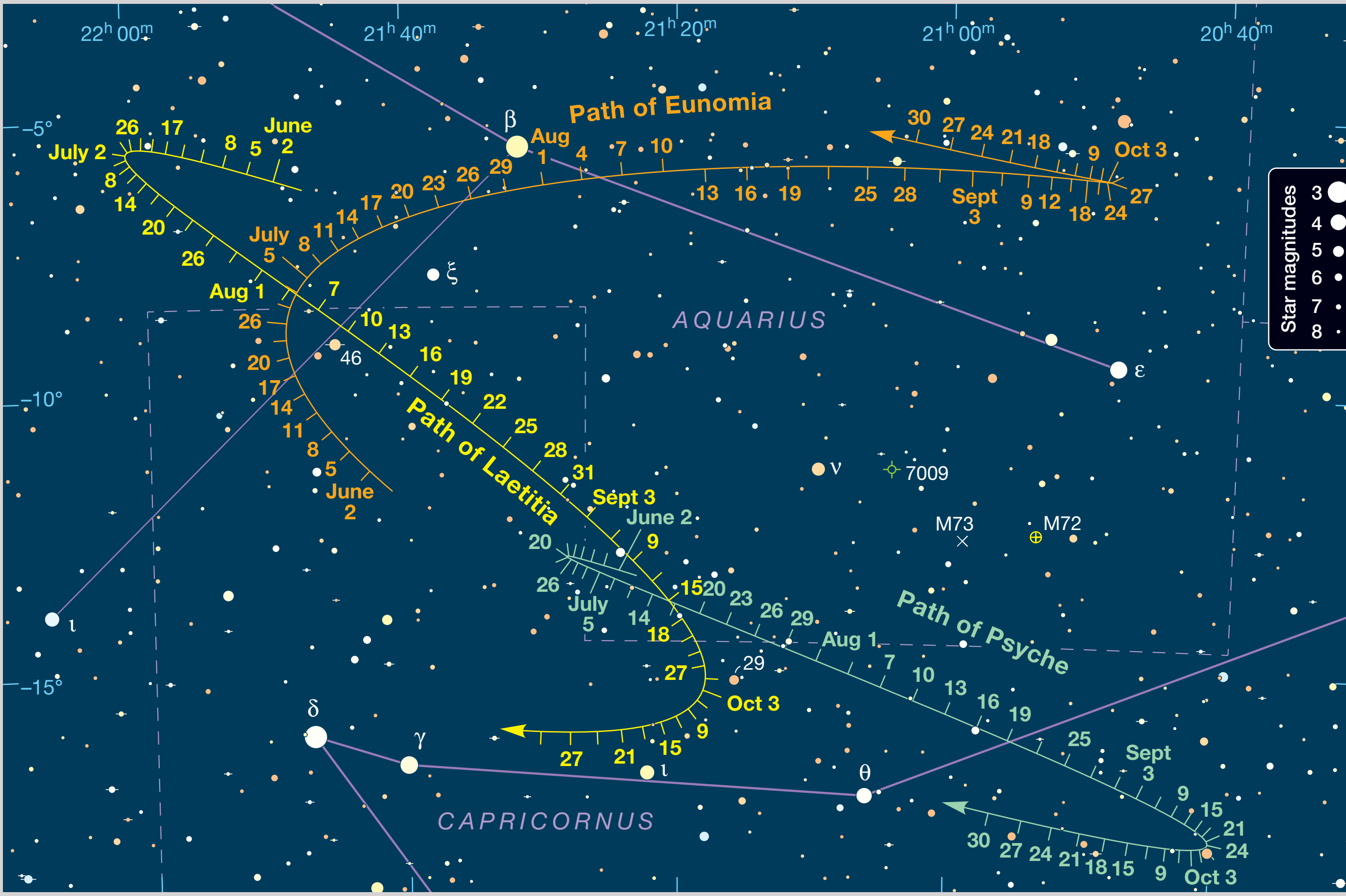
MOON PASSAGES

The Moon is waxing gibbous, close to Beta (β) Scorpii at nightfall on August 8th. The next evening, the Moon beams some 2° upper left of Jupiter at nightfall, with Antares not too far, around 6°, lower right of the planet. On the 11th, the still-swelling Moon is not far to the right of Saturn. The Moon is a waning crescent around 2° above or upper left of Aldebaran on the morning of the 24th, and less than ½° from Zeta (ζ) Tau on the morning of the 25th. Find an even thinner lunar crescent lower right of Pollux at dawn on the 28th.

■ **FRED SCHAAF** is the author of *The Starry Room: Naked Eye Astronomy in the Intimate Universe*, a collection of essays published by Dover Publications.

Three for One

Three asteroids, traveling conveniently close to one another in the southern sky, come to opposition this month.



Look for asteroids 16 Psyche, 15 Eunomia, and 39 Laetitia in Capricornus and Aquarius this month. The chart above shows the asteroids' paths, with tick marks indicating their positions every three days at 0h UT, which corresponds to evening of the previous date for those in North America.

Asteroids 16 Psyche, 15 Eunomia, and 39 Laetitia wander through western Aquarius and northern Capricornus this season, offering an excellent opportunity for observers to spot all three in a single observing session. Shining between 8th and 9th magnitude, any of the trio should be visible in a small telescope or 10×50 binoculars.

Asteroid **16 Psyche**, traveling across Capricornus, sets the stage for the month, reaching opposition on the night of August 6–7. The 9.3-magnitude asteroid rises at sunset and sets at sunrise on that date, and will be about 20° high by the time full darkness sets in. The waxing crescent Moon hangs around another hour or so after the end of twilight, but will be well out of the way by the time Psyche culminates at 1 a.m. daylight-saving time. Psyche stands around 35° high for observers at mid-northern latitudes as it transits the meridian. The most convenient star-hops begin at Theta (θ) and 29 Capricorni.

The Moon in the days immediately following opposition will be more of a nuisance — the full Moon on August 15th will certainly interfere — but as the Moon wanes, Psyche remains well placed for observation, culminating earlier with each passing night. By the end of the month, Psyche transits about an hour before midnight and stands only 2° lower than it did on the night of opposition. Taking a second look at the asteroid will help you verify your first observation, as Psyche will have traveled to a new position.

Psyche's a fascinating object. It's small, about 210 km (130 miles) across on average, and metallic, composed mostly of iron-nickel. Psyche's pure metal composition has led planetary scientists to conclude that the asteroid could be the remnant core of a planet that's been stripped of its outer layers through repeated collisions. If this turns out to be the case, Psyche would be the only metallic planet core discovered to date and would offer a chance to find out more about our Earth's and other planetary cores, buried as they are beneath the mantle and crust. Arizona State University and NASA's Jet Propulsion Laboratory are planning a mission to Psyche, scheduled to launch in 2020 (**https://psyche.asu.edu**). This will be the first mission to study a metal asteroid.

After you've sketched the location of Psyche in your observing logbook, move northeast to search for asteroid **15 Eunomia**. Eunomia reaches opposition on August 12th, when it rises in an evening sky already held by a waxing gibbous Moon. This means that the asteroid will be easier to observe earlier or later in the month, weather permitting. Shining at magnitude 8.2 at opposition, and 8.3 on the night of August 6–7 (Psyche's opposition), Eunomia is noticeably brighter than Psyche. It's also higher in the sky, crossing the meridian about halfway between horizon and zenith all month. Beta

NASA / JPL-CALTECH / ARIZONA STATE UNIVERSITY / SPACE SYSTEMS LORAL / PETER RUBIN

▲ This artist's concept shows the 5-panel solar arrays of the spacecraft proposed for the Psyche mission. The spacecraft will "cruise" for 3½ years on solar-electric power to reach the asteroid, then spend 21 months in orbit around the metal world.

(β) Aquarii is the closest bright star to Eunomia's path in early August.

Italian astronomer Annibale de Gasparis, observing from Naples, discovered Eunomia in 1851. Composed of silicates and nickel-iron, Eunomia holds about 1% of the asteroid belt's total mass. Like Psyche, Eunomia has a history full of impacts and collisions, but some 75% of its original material is thought to remain intact. The other 25% belongs to the Eunomian family, a group of roughly 6,000 stony bodies that orbit in the intermediate asteroid belt.

Asteroid **39 Laetitia** offers a chance for an observing trifecta: three moving targets in a single night. Laetitia reaches opposition on the night of August 16–17 — hello, Moon! — so grabbing it earlier in the month is a good idea. The 5th-magnitude star 46 Capricorni is a good starting point for an early August star-hop.

Laetitia follows a path that runs northeast to southwest across Aquarius and Capricornus this summer. The asteroid moves from Aquarius into Capricornus the first week of July, then returns to Aquarius in early September. Laetitia is at its brightest for the year, magnitude 9.1, near opposition. However, it's just a little dimmer, magnitude 9.4, on the night of August 6–7, when it culminates at an altitude of 41° or so. By the end of September, Laetitia's brightness drops to magnitude 10.1, out of binocular range unless you break out the 15×70s.

Discovered in 1856 by the French astronomer Jean Chacornac, Laetitia is, like Eunomia, a stony main-belt asteroid. The most recent measurements obtained by Wide-field Infrared Survey Explorer (WISE)/Near-Earth Object WISE suggest that Laetitia has an irregular ellipsoidal shape with an average diameter of 180 km (112 miles). It's possible that Laetitia is a binary system, with two similarly sized components orbiting a common barycenter.

Just getting started with asteroids? Check out the Asteroid Observing Program sponsored by the Astronomical League (AL). The program is designed to help AL members learn how to observe and identify asteroids. A 4-inch scope is recommended to get started on your list. To observe dimmer asteroids, the AL recommends a 6-inch scope. You'll also need to be ready to sketch at the eyepiece. Visit the program website at **https://is.gd/astrcobs** for more information.

Moon Blocks Star

THE WANING MOON HIDES a 3rd-magnitude star in Taurus on the morning of August 25th. Zeta (ζ) Tauri, a spectroscopic binary system that marks the tip of the Bull's southern horn, will disappear behind the bright, leading edge of the lunar crescent and reappear at the dark limb as much as an hour later. The predicted path of visibility covers a large swath of North and Central America, but for most observers in those locations, this will be a daylight event.

Observers in the Far West are better situated — the occultation occurs in the dark, early morning hours with the Moon climbing higher as the event progresses. San Diego, Los Angeles, San Francisco, and Salt Lake City see the entire occultation in darkness. For Denver, Phoenix, Las Vegas, and Mexico City, the reappearance of Zeta occurs in a twilight sky. Observers in northern Canada and Alaska will miss this one entirely.

San Francisco, Sacramento, and other places along the northern limit of the event path should watch for a grazing event, when Zeta seems to skim by the Moon's northern limb. The star will blink off and on, as if controlled by a light switch, as it's alternately covered and revealed by lunar mountains and valleys.

Complete occultation timetables for hundreds of cities and towns in the predicted path of visibility are available from the International Occultation Timing Association (IOTA). Visit **https://is.gd/IOTApredict** and click on the link for the appropriate star and date. The event page includes three tables: for the star's disappearance, its reappearance, and the locations of the cities and towns in the event path. The *Moon Alt* column provides the altitude of the Moon in degrees above the horizon. The *CA°* column shows the cusp angle where the star disappears and reappears. Use it to determine how many degrees from the Moon's northern or southern cusp you'll need to look to see the event.

Here are a few timings: **San Francisco,** *disappearance* 3:59 a.m., *graze* 4:20 a.m., *reappearance* 4:31 a.m. PDT; **Sacramento,** *d.* 4:02 a.m., *gr.* 4:21 a.m., *r.* 4:32 a.m. PDT; **Los Angeles,** *d.* 3:46 a.m., *r.* 4:38 a.m. PDT; **San Diego,** *d.* 3:43 a.m., *r.* 4:39 a.m. PDT; **Las Vegas,** *d.* 3:52 a.m., *r.* 4:44 a.m. PDT; **Phoenix,** *d.* 3:45 a.m., *r.* 4:47 a.m. MST; **Salt Lake City,** *d.* 5:05 a.m., *r.* 5:49 a.m. MDT; **Denver,** *d.* 5:04 a.m., *r.* 6:03 a.m. MDT; **Guadalajara, Mexico,** *d.* 5:34, *r.* 6:42 a.m. CDT; **Mexico City,** *d.* 5:41 a.m., *r.* 6:43 a.m. CDT.

A So-So Shower

Every August, we're treated to the meteor shower par excellence — provided conditions are favorable, of course. Offspring of Comet 109P/Swift-Tuttle, the Perseids put on a reliably good show every year. However, the shower is expected to peak on the evening of August 12th this year, just in time to share the night sky with a 95%-lit waxing gibbous Moon. So it's unlikely any of us will see the predicted 100+ meteors an hour near peak in 2019. Thankfully, this prolific shower is also long-lived, so you'll certainly see shower meteors if you're out under dark skies earlier in the month. In fact, you can start looking in late July, as soon as the full Moon gets out of the way. Watch the shower rise toward maximum after the first-quarter Moon on August 7th.

Action at Jupiter

JUPITER, ALREADY AT ITS HIGHEST by the time true darkness falls, brightens in Ophiuchus. The gas giant shines at magnitude –2.4 at the opening of August and improves to a luminous –2.2 by the end of the month. At the same time, the planet slims at the equator, contracting from 43″ across on August 1st to 39″ by August 31st. Jupiter's at the end of its retrograde journey, reaching its western stationary point on the 11th. After this apparent pause, it resumes direct (eastward) motion, edging ever closer to Sagittarius.

Any telescope shows the four big Galilean moons, and binoculars usually show at least two or three. In binoculars, the moons are all but indistinguishable from one another. Use the diagram on the facing page to identify them by their relative positions on any given time and date.

All of the August interactions between Jupiter and its satellites and their shadows are tabulated on the facing page. Find events timed for when Jupiter is at its highest in a dark sky, just after nightfall.

Here are the times, in Universal Time, when the Great Red Spot should cross Jupiter's central meridian. The dates, also in UT, are in bold. (Eastern Daylight Time is UT minus 4 hours.)

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

August 1: 8:32, 18:28; **2:** 4:24, 14:19; **3:** 0:15, 10:11, 20:06; **4:** 6:02, 15:58; **5:** 1:54, 11:49, 21:45; **6:** 7:41, 17:36; **7:** 3:32, 13:28, 23:24; **8:** 9:19, 19:15; **9:** 5:11, 15:06; **10:** 1:02, 10:58, 20:54; **11:** 6:49, 16:45; **12:** 2:41, 12:36, 22:32; **13:** 8:28, 18:24; **14:** 4:19, 14:15; **15:** 0:11, 10:07, 20:02; **16:** 5:58, 15:54; **17:** 1:50, 11:45, 21:41; **18:** 7:37, 17:32; **19:** 3:28, 13:24, 23:20; **20:** 9:15, 19:11; **21:** 5:07, 15:03; **22:** 0:58, 10:54, 20:50; **23:** 6:46, 16:41; **24:** 2:37, 12:33, 22:29; **25:** 8:24, 18:20; **26:** 4:16, 14:12; **27:** 0:08, 10:03, 19:59; **28:** 5:55, 15:51; **29:** 1:46, 11:42, 21:38; **30:** 7:34, 17:29; **31:** 3:25, 13:21, 23:17.

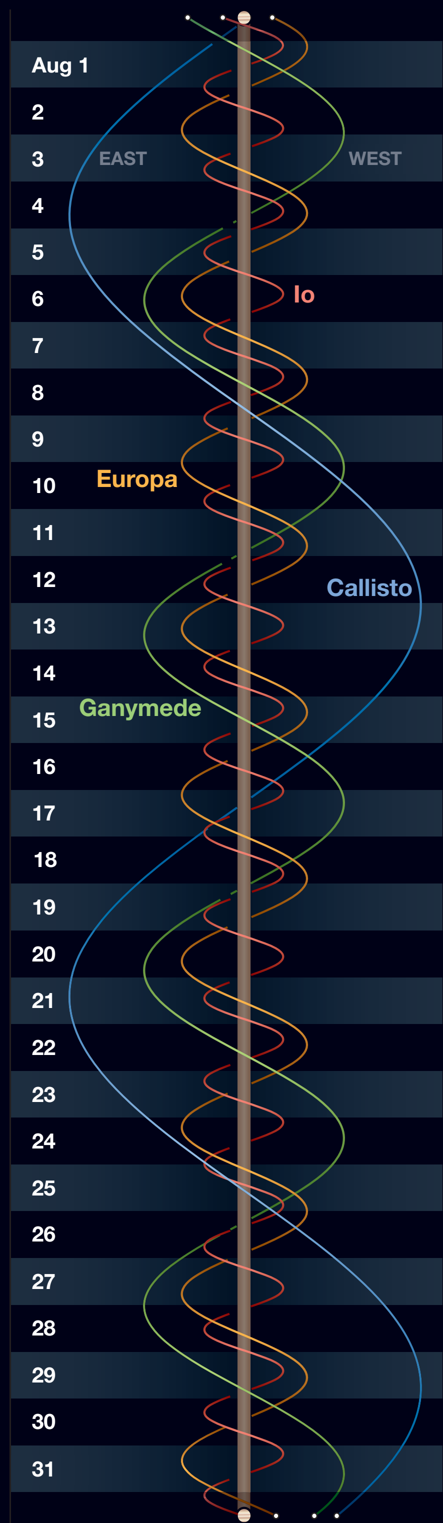
These times assume that the spot will be centered at System II longitude 310°. If the Red Spot has moved elsewhere, it will transit 1⅔ minutes earlier for each degree less than 310° and 1⅔ minutes later for each degree more than 310°.

Phenomena of Jupiter's Moons, August 2019

Aug. 1	3:13	III.Tr.I
	5:33	III.Tr.E
	7:25	III.Sh.I
	9:53	III.Sh.E
	11:51	I.Oc.D
	15:07	I.Ec.R
	23:24	II.Oc.D
Aug. 2	4:01	II.Ec.R
	9:12	I.Tr.I
	10:15	I.Sh.I
	11:23	I.Tr.E
	12:27	I.Sh.E
Aug. 3	6:18	I.Oc.D
	9:36	I.Ec.R
	17:30	II.Tr.I
	19:39	II.Sh.I
	19:57	II.Tr.E
	22:09	II.Sh.E
Aug. 4	3:39	I.Tr.I
	4:44	I.Sh.I
	5:50	I.Tr.E
	6:55	I.Sh.E
	17:08	III.Oc.D
	19:31	III.Oc.R
	21:31	III.Ec.D
Aug. 5	0:02	III.Ec.R
	0:45	I.Oc.D
	4:04	I.Ec.R
	12:37	II.Oc.D
	17:19	II.Ec.R
	22:07	I.Tr.I
	23:12	I.Sh.I
Aug. 6	0:18	I.Tr.E
	1:24	I.Sh.E
	19:13	I.Oc.D
	22:33	I.Ec.R
Aug. 7	6:43	II.Tr.I
	8:58	II.Sh.I
	9:10	II.Tr.E
	11:28	II.Sh.E
	16:34	I.Tr.I
	17:41	I.Sh.I
	18:45	I.Tr.E
	19:53	I.Sh.E
Aug. 8	6:51	III.Tr.I
	9:13	III.Tr.E
	11:24	III.Sh.I
	13:41	I.Oc.D
	13:53	III.Sh.E
	17:02	I.Ec.R
Aug. 9	1:50	II.Oc.D
	6:37	II.Ec.R
	11:02	I.Tr.I
	12:10	I.Sh.I
	13:13	I.Tr.E
	14:21	I.Sh.E
Aug. 10	8:08	I.Oc.D
	11:31	I.Ec.R
	19:57	II.Tr.I
	22:16	II.Sh.I
	22:24	II.Tr.E
Aug. 11	0:46	II.Sh.E
	5:30	I.Tr.I
	6:39	I.Sh.I
	7:41	I.Tr.E
	8:50	I.Sh.E
	20:49	III.Oc.D
	23:14	III.Oc.R
Aug. 12	1:31	III.Ec.D
	2:36	I.Oc.D
	4:03	III.Ec.R
	6:00	I.Ec.R
	15:04	II.Oc.D
	19:55	II.Ec.R
	23:57	I.Tr.I
Aug. 13	1:07	I.Sh.I
	2:09	I.Tr.E
	3:19	I.Sh.E
	21:04	I.Oc.D
Aug. 14	0:28	I.Ec.R
	9:12	II.Tr.I
	11:35	II.Sh.I
	11:39	II.Tr.E
	14:05	II.Sh.E
	18:25	I.Tr.I
	19:36	I.Sh.I
	20:36	I.Tr.E
	21:48	I.Sh.E
Aug. 15	10:33	III.Tr.I
	12:57	III.Tr.E
	15:23	III.Sh.I
	15:32	I.Oc.D
	17:53	III.Sh.E
	18:57	I.Ec.R
Aug. 16	4:18	II.Oc.D
	9:13	II.Ec.R
	12:53	I.Tr.I
	14:05	I.Sh.I
	15:04	I.Tr.E
	16:16	I.Sh.E
Aug. 17	10:00	I.Oc.D
	13:26	I.Ec.R
	22:26	II.Tr.I
Aug. 18	0:53	II.Sh.I
	0:54	II.Tr.E
	3:23	II.Sh.E
	7:21	I.Tr.I
	8:34	I.Sh.I
	9:32	I.Tr.E
	10:45	I.Sh.E
Aug. 19	0:34	III.Oc.D
	3:00	III.Oc.R
	4:28	I.Oc.D
	5:31	III.Ec.D
	7:55	I.Ec.R
	8:04	III.Ec.R
	17:33	II.Oc.D
	22:31	II.Ec.R
Aug. 20	1:49	I.Tr.I
	3:02	I.Sh.I
	4:00	I.Tr.E
	5:14	I.Sh.E
	22:56	I.Oc.D
Aug. 21	2:24	I.Ec.R
	11:42	II.Tr.I
	14:10	II.Tr.E
	14:12	II.Sh.I
	16:42	II.Sh.E
	20:17	I.Tr.I
	21:31	I.Sh.I
	22:28	I.Tr.E
	23:42	I.Sh.E
Aug. 22	14:21	III.Tr.I
	16:46	III.Tr.E
	17:24	I.Oc.D
	19:23	III.Sh.I
	20:53	I.Ec.R
	21:54	III.Sh.E
Aug. 23	6:48	II.Oc.D
	9:17	II.Oc.R
	9:17	II.Ec.D
	11:49	II.Ec.R
	14:46	I.Tr.I
	16:00	I.Sh.I
	16:57	I.Tr.E
	18:11	I.Sh.E
Aug. 24	11:52	I.Oc.D
	15:21	I.Ec.R
Aug. 25	0:58	II.Tr.I
	3:26	II.Tr.E
	3:30	II.Sh.I
	6:01	II.Sh.E
	9:14	I.Tr.I
	10:28	I.Sh.I
	11:25	I.Tr.E
	12:40	I.Sh.E
Aug. 26	4:23	III.Oc.D
	6:21	I.Oc.D
	6:51	III.Oc.R
	9:30	III.Ec.D
	9:50	I.Ec.R
	12:04	III.Ec.R
	20:04	II.Oc.D
	22:33	II.Oc.R
	22:35	II.Ec.D
Aug. 27	1:07	II.Ec.R
	3:42	I.Tr.I
	4:57	I.Sh.I
	5:53	I.Tr.E
	7:09	I.Sh.E
Aug. 28	0:49	I.Oc.D
	4:19	I.Ec.R
	14:15	II.Tr.I
	16:43	II.Tr.E
	16:49	II.Sh.I
	19:20	II.Sh.E
	22:10	I.Tr.I
	23:26	I.Sh.I
Aug. 29	0:22	I.Tr.E
	1:37	I.Sh.E
	18:13	III.Tr.I
	19:17	I.Oc.D
	20:39	III.Tr.E
	22:48	I.Ec.R
	23:22	III.Sh.I
Aug. 30	1:54	III.Sh.E
	9:20	II.Oc.D
	11:50	II.Oc.R
	11:53	II.Ec.D
	14:25	II.Ec.R
	16:39	I.Tr.I
	17:55	I.Sh.I
	18:50	I.Tr.E
	20:06	I.Sh.E
Aug. 31	13:46	I.Oc.D
	17:17	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.

Unruly Crater Rays

These long, bright streaks crisscross the lunar surface yet defy easy explanation.

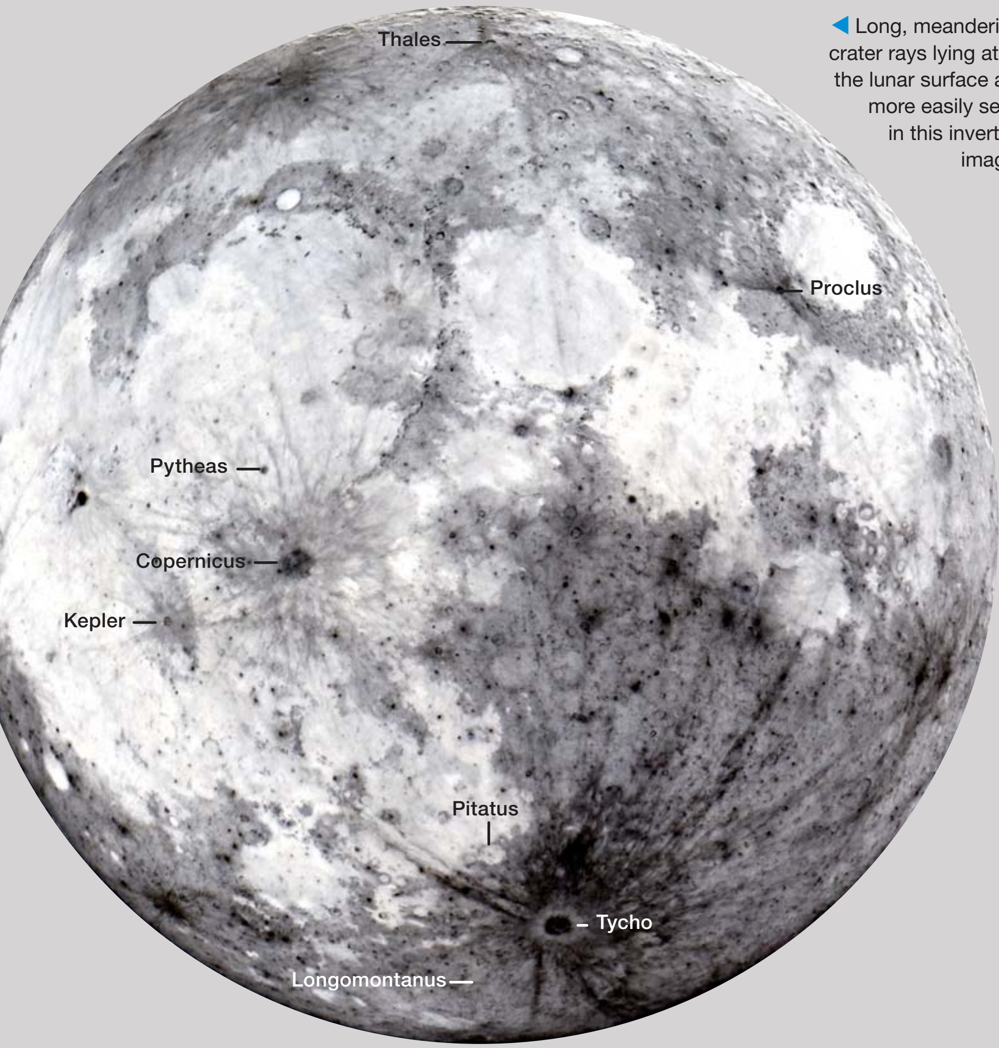
Crater rays are among the most prominent, yet least studied, lunar surface features. That's due to their unruliness. Ray lengths, widths, shapes, distributions, and brightnesses vary even for a single crater. The best-known ray system radiates from **Tycho**, an 83-km-wide crater violently excavated into the lunar highlands about 85 million years ago. Like splashes of bright flour, rays drape over highlands, maria, mountains, and craters — so they must have fallen out of the sky and must be relatively young. Their great lengths, averaging about six times the diameter of the source crater, imply that significant energy was required to emplace them over such great distances.

As part of his investigation of the physics of impact crater formation, the pioneering lunar geologist Eugene Shoemaker observed that rays themselves often contain numerous *small* craters, often elongated in the same direction as the ray. Shoemaker deduced that rays are debris ejected during a crater's violent formation. The ejecta followed ballistic trajectories at low angles and relatively low velocity. Large chunks account for the weak secondary craters within the rays. You can easily see secondary craters in the ray from **Copernicus** that extends north from the Carpathian Mountains (**Montes Carpatus**) to east of **Pytheas**.

Rays are bright because of two factors. Rocks on the lunar surface darken over time due to space weathering from cosmic rays, the solar wind, and other microscopic erosional processes; an impact kicks up deeper, undarkened material. Secondly, impacts in the lunar highlands, like the one that formed Tycho, eject anorthositic rocks rich in light-hued aluminum compounds but deficient in darker iron and magnesium. So highland ejecta tend to make brighter rays.

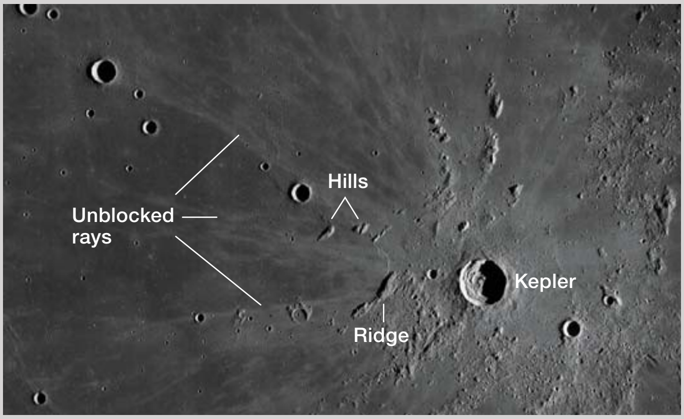
Over hundreds of millions of years, rays slowly fade due to space weathering. Rays made of mare lavas disappear in about 750 million years, whereas those that contain bright anorthosites remain visible for about a billion years. So rays are transitory features visible for a finite period. Since every lunar crater formed with bright rays, and in the Moon's first half-billion years cratering was much more intense than in later epochs, bright rays must have crisscrossed the Moon like psychedelic zebra stripes.

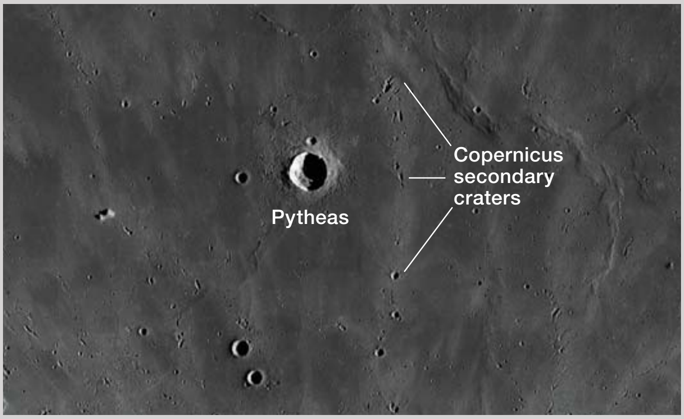
Rays are not single lines of brightness but consist of a series of bright,



◀ Long, meandering crater rays lying atop the lunar surface are more easily seen in this inverted image.

SEAN WALKER / S&T





▲ *Left:* The rays produced by ejecta from the impact that created Kepler were impeded by hills and a long ridge to the crater's west. *Right:* The crater ray east of Pytheas contains many secondary craters originating from Copernicus.

usually linear segments. This gives rays their characteristic feathery and discontinuous look, as visible in those seen near Pytheas and the more splotchy ones from Tycho visible on the floor of **Pitatus**. Each bright segment includes a patch of secondary craters as well as rock flour.

Looking straight down on Tycho, a striking non-uniformity is seen: the near-absence of rays to the west. This "zone of avoidance" indicates that the projectile that impacted the lunar surface to form Tycho came from the west at a low angle, perhaps only 20° to 25° above the lunar surface. The momentum of the projectile carried bright ejecta downrange for hundreds of kilometers. If you look closely, you can see that the young craters **Proclus** and **Thales** have bright rays as well as distinct zones of avoidance.

One aspect of rays still not understood is their pattern near their originating crater versus those seen farther out. For example, Copernicus is surrounded by a circle of ray brightness extending about one crater diameter on all sides. Emerging from that are around 15 to 20 rays, some short, others more extensive. The ray to the east of Pytheas is nowhere near radial to Copernicus, and, in fact, if extended back toward Copernicus, it completely misses the crater's east rim. Similarly, Tycho's bright ray that tracks southwest over **Longomontanus** is tangent to Tycho's rim. How does this occur, particularly without an appreciable lunar atmosphere?

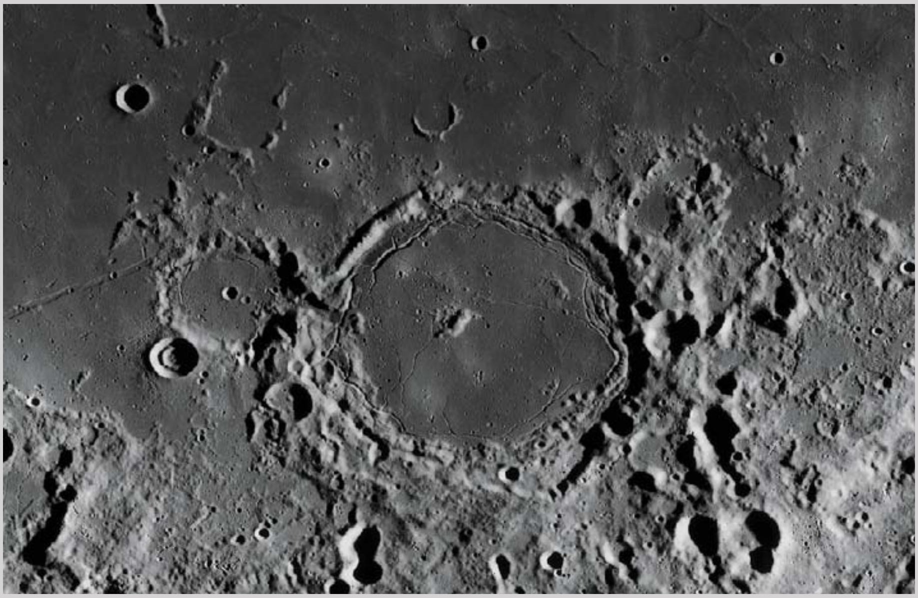
Like Copernicus, the 29-km-wide crater **Kepler** is surrounded by a large halo of bright material, with rays extending some 200 to 300 km. Notice that those rays radiating west of Kepler have two narrow zones of avoidance. One bright ray extends to the northwest and another goes southwest. If you observe when the Sun is about 25° above Kepler so that both the rays and the surface topography are visible, you'll see that between Kepler and the dark mare areas with few rays lies a short linear ridge, and to its northwest, two more hills. The 500-meter-high ridge and hills seem to have blocked Kepler's rays, indicating that the material must have had been ejected nearly horizontally.

Also, notice the wispy ray in the middle of the dark zone (seen in the image at top left) that got through the gap between the ridge and the hills.

Two reasons that rays are still not fully understood is that there are very few measurements of their lengths, something that can now be easily accomplished using LROC's *Quickmap* software (**quickmap.lroc.asu.edu**). The other reason is there currently isn't a standardized classification system. So that begs the question: What are you waiting for?

■ Contributing Editor **CHUCK WOOD** frequently explores the LROC *Quickmap* to further his understanding of the Moon.

▼ Patchy ray material originating from Tycho is visible on the floor of Pitatus.



NASA / LUNAR RECONNAISSANCE ORBITER (3)

To celebrate 20 years of Sue French's stellar contributions to *Sky & Telescope*, we will be sharing the best of her columns in the coming months. We have updated values to current measurements when appropriate.

The Glorious Eagle

Many lesser-known clusters and nebulae swarm around the mighty Eagle Nebula.

Glorious bird! thy dream has left thee,
Thou hast reached thy heaven —
Lingering slumber hath not reft thee
Of the glory given —
With a bold and fearless pinion,
On thy starry road,
None, to fame's supreme dominion,
Mightier ever trode.
—James Gates Percival, *Genius Waking*

The Eagle Nebula is one of the most celebrated deep-sky wonders, thanks to the stunning and popular 1995 Hubble Space Telescope image showcasing the glorious Pillars of Creation, shown below. These dense columns of gas and dust nestled in the heart of the Eagle Nebula nurture infant stars forming within. Yet these magnificent structures may be mere ghosts of a time long past.

The Pillars of Creation reach through the heart of the Eagle Nebula.

NASA / ESA / HUBBLE HERITAGE TEAM

Infrared images from Spitzer Space Telescope show a hot gas cloud that some astronomers interpret to be a supernova shock wave advancing toward the Pillars. If true, the shock wave may have destroyed the Pillars 6,000 years ago. But because the Eagle Nebula is about 7,000 light-years away, it would be another thousand years or so before the devastation is seen through telescopes on Earth. The supernova itself might have graced our sky as a bright star one or two millennia ago.

How strange and rare that we're caught in the astronomically brief moment when we can gaze at a relatively nearby celestial treasure that may no longer exist! And the sight is not reserved for those imaging the sky or armed with immense telescopes. The Eagle can be viewed through small telescopes, and you can even glimpse a bit of the Pillars under dark, transparent skies.

On one particularly fine night, I devoted some time to sketching **Messier 16** (the Eagle Nebula and its embedded star cluster) as seen through my 130-mm refractor at 63×. I find sketching to be a wonderful way to garner detail from complex deep-sky objects. As I study an object, I seem to slowly develop an enhanced image — almost as photographic film does over time. My sketch on the facing page shows a throne-like structure emblazoned on the Eagle's breast. In the three Pillars of Creation, it corresponds to the central shaft and the bar connecting it to the longest pillar. This dark throne is approximately 4 light-years tall.

The Eagle dwells in a realm of the sky rife with nebulae and star clusters. Its unsung neighbor **Trumpler 32** resides just 38′ northwest and shares the field with M16 through my 6-inch reflector at 38×. This nice little cluster is a hazy cobweb with a corona of faint, dewdrop stars glimmering on the sable walls of night. At 154× about 20 stars overspread 11′ of sky. A prominent knot of several stars dominates the southern part of the cluster. At high magnification, my 10-inch reflector reveals a wealth of suns, many so faint that they blink in and out of view.

On the opposite side of the Eagle, we find the emission nebula **Sharpless 2-48**. Look 1° southeast of M16 for a 7th-magnitude star, the brightest in the area. Centered 12′ south-southeast of that star is a 6′ trapezoid of stars 9th magnitude and fainter. Through my 6-inch reflector at 95×, the brightest region of this patchy nebula surrounds the western side of the trapezoid and spreads 4′ westward. Dimmer nebulosity extends to the trapezoid's eastern side and becomes more attenuated as it reaches southeast.

The large, faint nebula **Sharpless 2-54** lies 1¾° north of the Eagle. Under a dark sky, binoculars will give you a nice view if you place the Eagle in the southern part of the field. I perused this emission nebula through my 15×45 image-stabilized binoculars while in the northern Adirondack Mountains, one of the darkest areas in my home state of New York. They revealed a 1° × 2° star-rich haze that's wide in the west and tapers toward the east-northeast. Much of the haze I see may well be the light of unresolved stars. This section of the Milky Way stands out as a somewhat isolated star cloud bounded on the west by the dusky clouds of the Great Rift and lined with smaller dark nebulae on the east. Nonetheless, it's a pretty sight.

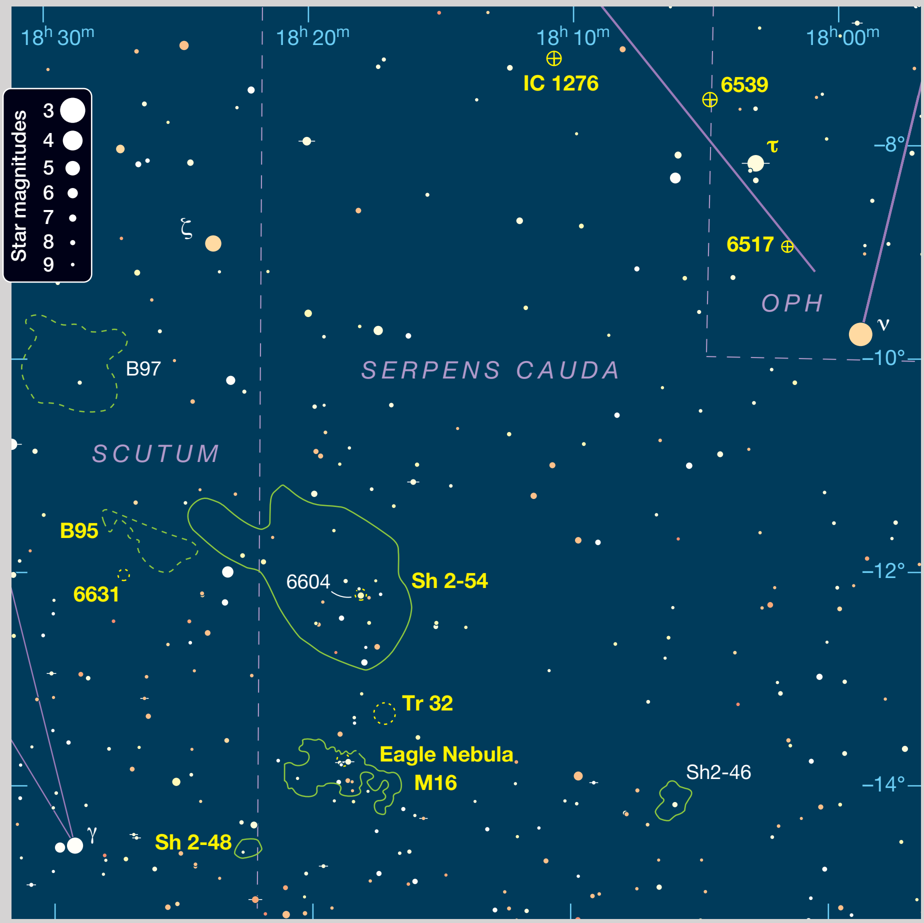
Barnard 95 is the most obvious dark nebula on the eastern end of Sh 2-54. Through my 6-inch scope at 38×, it seems to grow blacker toward the center. Barnard 95's inkiest area spans about 10′, while the entire nebula is perhaps twice that size and quite irregular.

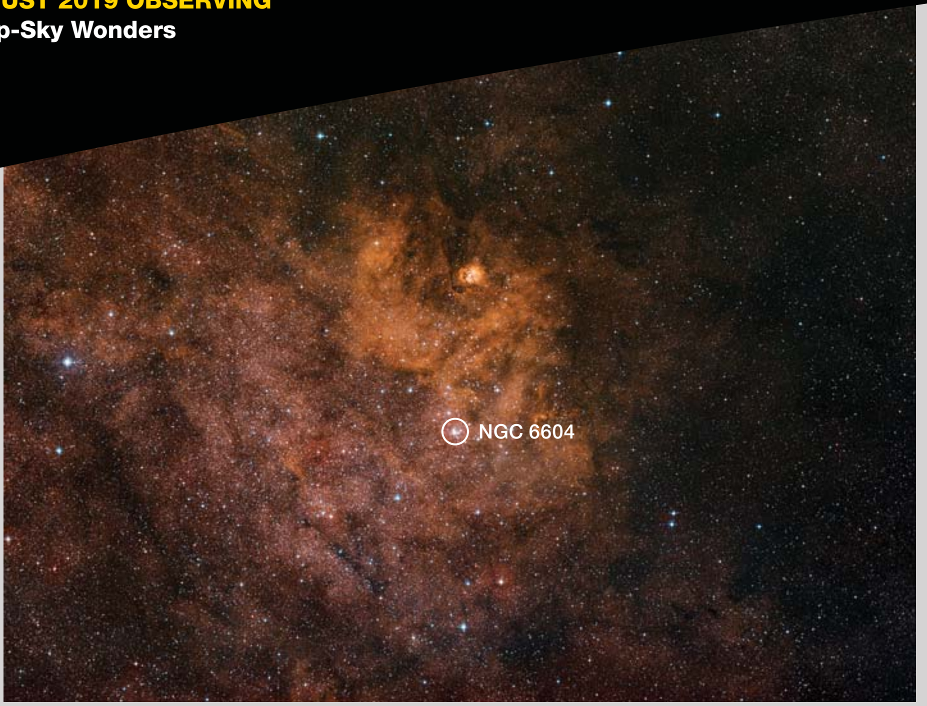
NGC 6631 is a little misty patch off its southeastern side. The open cluster is elongated southeast-northwest with an 11th-magnitude star at the northwestern end. At 95× NGC 6631 shows 20 faint to very faint stars in a 5′ glow; at 154× it's crowded with minute stars.

Next we'll trek northwest to a trio of globular clusters. The first of the group

▲ *Left:* The author's sketch of the Eagle Nebula demonstrates that many of the features in the image at right are visible through a 5-inch telescope. *Right:* Like most Hubble Space Telescope images, this photograph of the Eagle Nebula (taken through a small professional ground-based telescope) uses a false-color palette. Emissions from hydrogen are shown as green, oxygen as red, and sulfur as blue. The Pillars of Creation are in the center.

SKETCH: SUE FRENCH; EAGLE NEBULA: T. A. RECTOR (NRAO / AUI / NSF AND NOAO / AURA / NSF) / B. A. WOLPA (NOAO / AURA / NSF)





▲The emission nebula Sharpless 2-54 spans more than 2° of sky. When scanning the nebula with her binoculars, the author overlooked NGC 6604, the tiny knot of stars in the southwest sector of the nebula. Can you see this open cluster in your telescope?

is **NGC 6517**, located 1.1° northeast of Nu (ν) Ophiuchi and 5′ north-northeast of a 10th-magnitude star. The cluster is easy to overlook at low power but emerges nicely through my 105-mm refractor at 122×. It covers a scant 1½′ and grows brighter toward the center. A 9′-long zigzag of six field stars passes west of the cluster. With my 10-inch reflector at 115×, NGC 6517 is 2½′ across and clasps a tiny bright nucleus. The outer regions appear granular, while the interior is coarsely mottled. NGC 6517 is elongated northeast-southwest at 213×, and a faint star guards its south-southwestern edge.

Moving 50′ north-northeast of NGC 6517 brings us to the lovely double star **Tau (τ) Ophiuchi**. Tau is a visual binary with a period of 257 years. Currently the 5.9-magnitude companion is 1.5″ west-northwest of its 5.3-magnitude primary and coming 0.1″ closer every seven years. The pair is comfortably split through my 4.1-inch refractor at 174×. To my eye, the brighter star glows yellow-white, and its companion shines yellow. As we'd expect for a double that exhibits a visible shift in position over a relatively short period of time, Tau is a nearby pair only 170 light-years away.

At low power, Tau shares the field of view with the globular cluster **NGC 6539**, which straddles the Ophiuchus-Serpens border 44′ northeast of Tau. Through my 105-mm scope at 87×, this softly glowing ball of light is 5′ across and patchy in brightness. Some faint foreground stars dot the western side of the cluster.

Nudging the telescope 1.5° east-northeast takes me to the subtle lights of **IC 1276**, nestled in the northern corner of a 13′ triangle of 11th- and 12th-magnitude stars. This dim globular cluster presents a 2′ halo and a tiny mottled center barely ½′ across. At 122× I see a very faint star punctuating the cluster's western side and an occasional glint in the core. With my 10-inch scope at 213×, several threshold stars form an east-west band across the cluster's face.

NGC 6539 has the same intrinsic brightness as NGC 6517, but it's closer to us and looks correspondingly brighter. These clusters lie at distances of 25,400 and 35,200 light-years, respectively. IC 1276 is comparatively nearby at 17,600 light-years, but it gives off a fifth as much light. This makes it the faintest of the three globulars by a small margin. The natural glory of these clusters is diminished not only by distance, but also by interstellar dust between us and them. The dust grains absorb and scatter the light emitted by the globulars, dimming each by about three magnitudes.

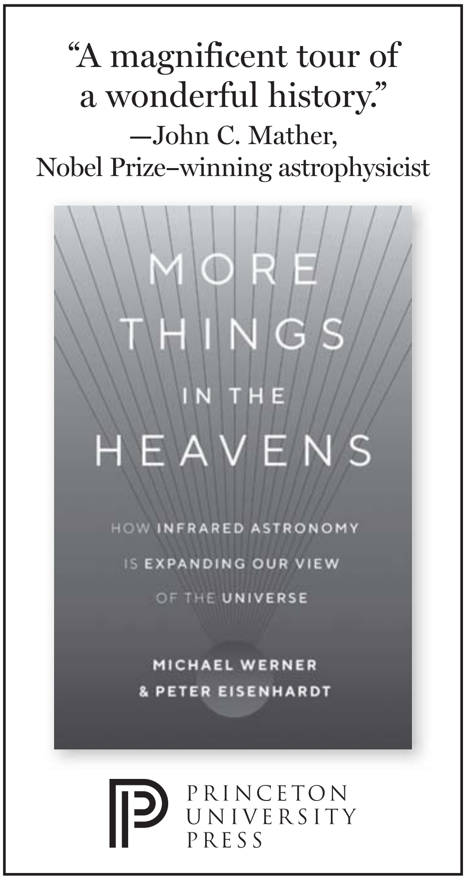
■ Contributing Editor **SUE FRENCH** penned this column for the August 2009 issue of *Sky & Telescope*.

The Eagle and Its Nestlings

Object	Type	Mag(v)	Size/Sep	RA	Dec.
Messier 16	Cluster / nebula	6.0	34′ × 27′	18^h 18.8^m	–13° 50′
Trumpler 32	Open cluster	12.2	12′	18^h 17.2^m	–13° 21′
Sh 2-48	Emission nebula	—	10′	18^h 22.4^m	–14° 36′
Sh 2-54	Emission nebula	—	144′ × 78′	18^h 19.7^m	–12° 04′
B95	Dark nebula	—	30′	18^h 25.6^m	–11° 45′
NGC 6631	Open cluster	11.7	7.0′	18^h 27.2^m	–12° 02′
NGC 6517	Globular cluster	10.2	4.0′	18^h 01.8^m	–8° 58′
Tau Ophiuchi	Double star	5.3, 5.9	1.5″	18^h 03.1^m	–8° 11′
NGC 6539	Globular cluster	9.3	7.9′	18^h 04.8^m	–7° 35′
IC 1276	Globular cluster	10.3	8.0′	18^h 10.7m	–7° 12′

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

ESO / DSS2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POLYHEDRAL SEPARATION
Kepler's model of the solar system relied on Platonic solids — immutable polyhedra nested inside a series of spheres thought to carry the planets.

Governing the Planets

This year marks the 400th anniversary of Kepler's Third Law of Planetary Motion.

PHOTOS.COM / GETTY IMAGES PLUS

For the entirety of human civilization, roughly 6,000 years, most of the stars in the nighttime sky have seemingly retained the same relative positions. The stars are so far from us, and in most cases one another, that the motions we now know they possess are almost insignificant. Coupled with the "fixed" stellar background and easily noticeable to the earliest watchers of the heavens are five bright celestial dots of light — Mercury, Venus, Mars, Jupiter, and Saturn — which, like the Moon, move about in predictable yet at times complex ways. By 400 BC, and possibly as early as the 6th century BC, the ancient Greeks were articulating interpretations of their observations of the five objects, which they named *planētēs*, meaning "wanderer," from which the English word *planet* is derived. Underlying assumptions, promulgated chiefly by **Aristotle** (384–322 BC), were that all cosmic motions are circular and uniform, that the cosmos beyond the Moon is a finite, spherical, eternal, and changeless model of perfection, and that Earth occupies the center of the unchanging sphere, thereby implying that the planets revolve around us.

Contrary to the order inferred by Aristotle's suppositions was the puzzling observed "retrograde motion," occurring when the outer planets, Mars, Jupiter, and Saturn, are at *opposition* — opposite in the sky from the Sun when viewed from Earth — and temporarily appear to reverse course. Generally the outer planets move eastward with respect to the stars, but as the more rapidly orbiting Earth passes on the inside track, they temporarily veer westward. We now know this illusion results from the combined motions of Earth's revolution around the Sun with those of our more distant solar system neighbors.

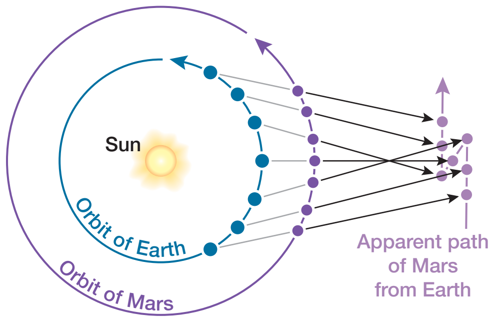
Continuing observations, which didn't necessarily fit theory, compelled unwieldy refinements of the models. Representations of circular orbits and spheres carrying the planets were the norm in ancient Greek astronomy. The development of such models culminated with **Claudius Ptolemy** (c. AD 100–170), a Greco-Roman astronomer working in the Roman city of Alexandria. The Ptolemaic model assumed each planet traveled on its own circular path called an *epicycle*. In turn, the epicycle orbited the Earth along a larger circle called a *deferent*. This interconnected system of circles addressed the varying speeds and occasional changes in direction of the planets observed by Earth-bound astronomers.

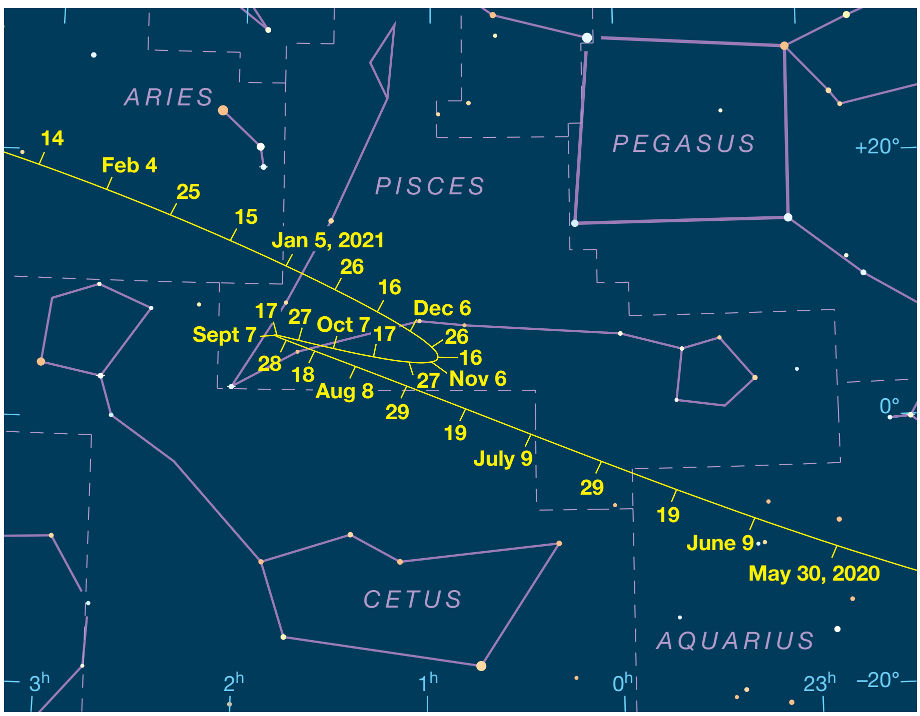
A Sun-Centered System

There things stood until the early 1500s, when **Nicolaus Copernicus** (1473–1543), a Polish cleric, physician, and astronomer, articulated a Sun-centered — or *heliocentric* — representation of the cosmos. This revolutionary idea countered the teachings of the then very powerful Catholic Church, which embraced Aristotle's Earth-centered — or *geocentric* — picture, which by then had prevailed with minor modifications for some 1,800 years. Copernicus completed work on his model in 1532 but didn't publish the treatise that outlined his ideas, *De revolutionibus orbium coelestium* (On the Revolutions of the Heavenly Spheres), until 1543. He built his system more on mathematical analysis and insight than on observations, and except for exchanging the positions of the Sun and Earth, his model, though a step in the right direction, didn't differ extensively from Ptolemy's. Both systems assumed circular orbits and both used epicycles, but Copernicus's, despite difficulties and inconsistencies, opened the door to modern astronomy.

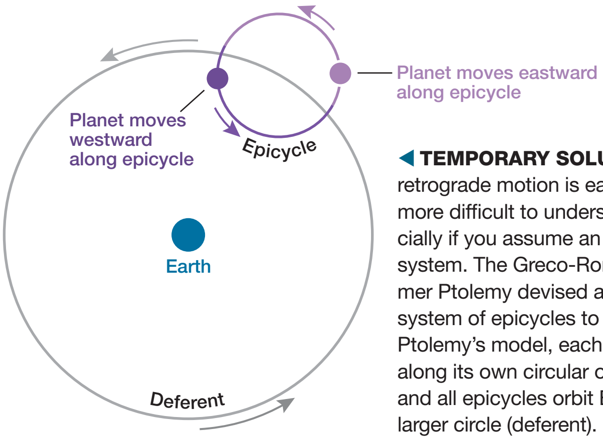
In the late 1500s, fate paved the way for a very improbable partnership between a wealthy, self-centered Danish nobleman, **Tycho Brahe** (1546–1601), and an underprivileged German mathematician with mystical tendencies, **Johannes**

MARS THE TRICKSTER When viewed from Earth, planets appear to travel from west to east — most of the time. When a planet is near opposition, it appears to move east to west, a phenomenon caused by the relative motion of Earth and planet. For superior planets (those that orbit the Sun outside of Earth's orbit), this apparent change of direction is relatively easy to observe, as is shown below in a chart of the position of Mars near the 2020 opposition.





RETROGRADE MOTION: GREGG DINDERMAN / S&T



◀ **TEMPORARY SOLUTION** While retrograde motion is easy to see, it's more difficult to understand, especially if you assume an Earth-centered system. The Greco-Roman astronomer Ptolemy devised a complicated system of epicycles to explain it. In Ptolemy's model, each planet travels along its own circular orbit (epicycle) and all epicycles orbit Earth on a larger circle (deferent).

Kepler (1571–1630). Their collaboration sparked a sweeping change in our understanding of the dynamics of the solar system, one we recognize to this day.

Tycho, backed by King Frederick II (1534–1588), constructed a state-of-the-art observatory on the then Danish island of Hven. The observatory housed several large pre-telescopic instruments, including a mural quadrant, several sextants, and an equatorial armillary sphere, all capable of making rigorously precise positional measurements. Supported by a staff of assistants, Tycho accumulated detailed records of the positions and movements of the planets, far exceeding the work done by astronomers of past eras.

While Tycho's equipment was as sophisticated as possible for the period, some of his analyses and ideas left much to be desired. In particular, he didn't fully subscribe to Copernicus's conception of the solar system. Rather, he blended it with Ptolemy's cosmology, centralizing Earth with the Sun circling it and placing the other planets in orbit around the Sun. It was an awkward model that he clung to until his dying day. However, he gave more clarity to other elements of the solar system. He concluded that an exceptionally bright star, a supernova that remained visible from November 1572 into early 1574, was far beyond the realm of our planetary system, contradicting Aristotle's tenet of immutability beyond the Moon. And after studying a comet's motion in 1577, Tycho correctly determined that comets were solar system entities, not atmospheric phenomena, as was believed by many of his predecessors.

Tycho thrived at Hven from the 1570s to the mid-1590s, at which time Frederick II's successor, his son Christian IV (1577–1648), began to withdraw support. The astronomer was forced to look elsewhere for patronage and went into exile in 1597.

New Ideas, New Models

Meanwhile, Kepler's inquisitive mind was processing thoughts and concepts regarding planetary motions. He was a devout Lutheran, and with the conflict between the Catholics and Protestants, as well as his sometimes poor health and many family issues, his life was awash with difficulty. Nevertheless, he was always productive. Over his career he authored approximately 20 works, many influenced by an overactive imagination and flights of fancy. A fervent Copernican, he attempted to find reason and divine purpose within the structure of the solar system and its then six known planets (Earth included).

In 1595, while teaching at a seminary school in Graz, Austria, Kepler envisioned combining the spacing of the planets with geometric structures, depictions of which appeared in much of his writing. At first, he separated the domains of each of the planets with equilateral two-dimensional figures: a triangle for the space between Saturn and Jupiter, a square between Jupiter and Mars, a pentagon between Mars and Earth, a hexagon between Earth and Venus, and a heptagon between Venus and Mercury. However, he soon realized that an infinite number of such forms existed and so sought something more manageable. His replacement incorporated symmetrical and congruent three-dimensional figures, of which only five exist, into the scheme of the solar system.

The Greeks knew well and systematically studied these five shapes, which we now refer to as the Platonic solids, after Plato (427–347 BC). The simplest of them are the tetrahedron, a pyramid consisting of four triangles, and the hexahedron, a cube with six squares. The icosahedron has the most sides, 20 triangles. The octahedron consists of eight triangles, and the dodecahedron has 12 pentagons. A sphere inscribed within a Platonic solid touches the center of the polyhedron's sides. A sphere circumscribed around a Platonic solid meets all corners of the shape.

Kepler reasoned that according to a heavenly plan, each of the five polyhedra separated two planets, which necessarily limited their number to six. (Of course, the discoveries of Uranus, Neptune, and Pluto in 1781, 1846, and 1930, respectively, would have severely undermined this picture, but such was the otherworldly nature of much of his thinking.) In 1596 Kepler published his cumbersome proposal in *Mysterium Cosmographicum* (The Cosmographic Mystery), which hung with him like an albatross for decades thereafter.

A Brief Partnership

After leaving Hven in 1597, Tycho found new sponsorship in 1599 through Rudolph II of the Holy Roman Empire and relocated to Prague, where he served as the Imperial Mathematician. Kepler, not willing to convert from Lutheranism, was consequently forced to leave the predominantly Catholic city of Graz. He moved to Prague in 1600, where he became Tycho's assistant.

The two astronomer-mathematicians needed each other. Kepler craved observational data to test his ideas, and Tycho desired a reliable associate to scrutinize his observations. Their time together was short, however, lasting only 18 months, during which each frequently traveled, and ended with Tycho's death in 1601. Even had Tycho lived longer, their collaboration may have ended quickly, as the relationship was difficult at best. Tycho, despite seeking an able assistant (the best available being Kepler), nonetheless was reluctant to open up

GREGG DINDERMAN / S&T

the complete store of his data, fearing that it might support Copernicus's system, not his own. Nevertheless, Tycho was forced to entrust the analysis of Mars's positions to Kepler as his previous assistant, Christen Longomontanus (1562–1647), had been unable to decode the riddle of its motions.

Tycho's death allowed Kepler greater but not always unrestricted access to the records, which remained under the custody of Tycho's family. Kepler was nonetheless able to meticulously evaluate the peregrinations of Mars. It was no easy task, and a complicating factor was the accompanying movement of the observing platform, Earth itself. After years of laborious trial and error, Kepler developed three relationships we now know as his "Laws of Planetary Motion," which were the first laws of nature expressible mathematically.

Kepler had struggled to fit Tycho's data into existing theories of the planets, repeatedly traversing the jungle of epicycles but never quite able to make things reconcile. In one instance, he found that his calculated position for Mars with respect to his mentor's work was within one quarter of the diameter of the full Moon. But he felt a need for greater precision, and so he discarded the associated hypothesis, believing that Tycho's observations couldn't be incorrect by even that small amount.

A New Astronomy

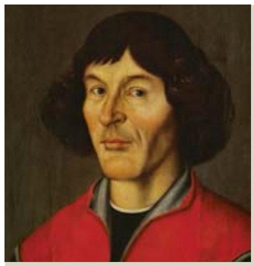
Because the assumed circular planetary orbits failed to match Tycho's exacting observations, Kepler contemplated other orbital shapes, which finally led to a positive result after several slow climbs up narrow theoretical stairways. He first considered an oval, even though he was aware that it lacked the perfect symmetry of spheres and circles. He attempted to transform the orbit into an egg shape, but after extensive and arduous calculations, he found that the orbit of Mars is an ellipse, which, like an oval, is basically a "stretched circle," but one precisely defined mathematically.

As well as a distinct center point, an ellipse possesses two *foci* — two points at the same distance from the center along an ellipse's *major axis* (the line drawn through the foci and center to the ellipse's perimeter). The locations of the foci depend on the extent of the "flatness" of the ellipse. The more stretched the ellipse, the farther apart the foci. For a nearly circular ellipse, the foci are very close together, and for a circle, which is a special case of an ellipse, they merge into the center. **Kepler's First Law**, presented in the 1609 treatise *Astronomia Nova* (The New Astronomy), states that *a planet follows an elliptical orbit and that the Sun occupies one focus of the ellipse.* The second focus is vacant.

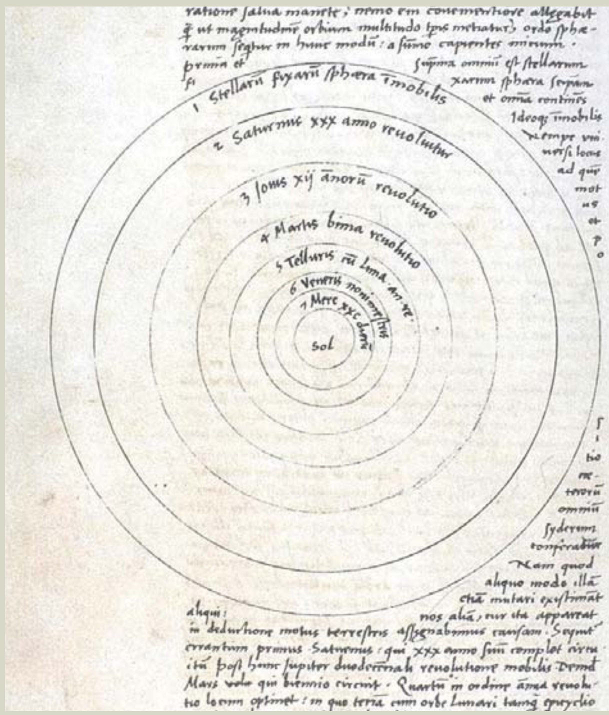
Kepler's Second Law, which he actually discovered before his first, explained how varying orbital velocities relate to varying distances of the planets from the Sun, the body which Kepler correctly suspected to physically control the planets. Conjecturing that the influential Sun should be centralized in the schema, he also surmised that the closer a planet to the Sun, the stronger the gravitational effect. Planets move more rapidly when nearer the Sun, a necessity to avoid being "pulled in" by its gravity, and more slowly when farther away, which prevents their escape from the solar system. This realization led to a second law, which states that *lines drawn outward from the Sun to points along a planet's orbit sweep out equal areas in equal times as the planet follows its course*.

When deriving the Second Law, which was also presented in *Astronomia Nova*, Kepler held tight to the old party line that planetary orbits were circular. Consequently, for areas swept out to be equal to each other in equal times — with the knowledge that observed planetary speeds varied — the Sun couldn't be in the center of the orbit. While the Second Law established the varying velocities, it didn't address orbital shape. With the subsequent formulation of the First Law and taking into account elliptical orbits with a non-centralized Sun, this problem vanished.

In 1619, Kepler published *Harmonices Mundi* (The Harmony of the World), a furtherance of his 1596 *Mysterium*

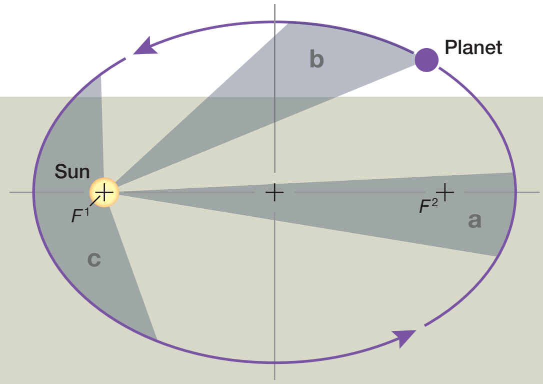


◀ **MULTITALENTED** Historians describe Copernicus as a taciturn man who talked little about his work. In addition to being a mathematician and astronomer, he was a cartographer, working with Bernard Wapowski to produce the first map of Poland. He also liked to paint (he studied painting at the University of Kraków) and write poetry.



▲ **REVOLUTIONARY THOUGHT** As this page from the 1543 treatise *De revolutionibus orbium coelestium* shows, Copernicus reordered the cosmos, placing the Sun ("Sol") at its center. Because the new model was still based on circular orbits, Copernicus continued to rely on epicycles (though fewer than deployed by Ptolemy) to explain retrograde motion.

◀ **SEARCHING FOR A CAUSE** Johannes Kepler was as much a mystic as a mathematician. Several chapters of his *Mysterium Cosmographicum* (1596) are dedicated to astrology and numerology, and the effects of other planets on Earth. This painting, an 18th-century copy of a now-lost portrait from 1610, shows Kepler holding a drafter's divider in his right hand.



▲ **THE SOLAR SYSTEM SORTED** Kepler demonstrated that all planets move in elliptical orbits, with the Sun occupying one focus (F^1) of the ellipse. (The other focus is unoccupied.) As a planet approaches the Sun, it moves more quickly through space, traveling through a longer section of the orbit than it would in the same amount of time when more distant from the Sun. A line drawn from the Sun to a planet sweeps out equal areas (a, b, and c) in equal times.

Cosmographicum. Several chapters were primarily mysticism, replete with attempts to associate human affairs with the planets, but the fifth and final chapter centered on **Kepler's Third Law**, which states that *the square of a planet's period of revolution around the Sun, its sidereal year, is proportional to the cube of its semimajor axis.* (The semimajor axis is half the length of the major axis.)

Here Kepler linked the distances of the planets with the Sun's force upon them, again invoking a quantifiable physical cause for the observed behavior. The relationship can be expressed with the following simple equation, which includes a constant of proportionality valid for all solar system planets:

$$P^2 = Ka^3$$

where P is the orbital period, K is the constant of proportionality, and a is the length of the semi-major axis. The law depends only on the relative, not specific, distances of solar system bodies from each other. The constant is the same for all bodies within a specific system, but differs from system to system.

Mathematical Representation of Kepler's Third Law

Planet	Sidereal Period P (yr)	Semi-major Axis a (a.u.)	P^2	$\propto$	a^3
Mercury	0.24	.39	0.06		0.06
Venus	0.62	.72	0.38		0.37
Earth	1.00	1.00	1.00		1.00
Mars	1.88	1.52	3.53		3.51
Jupiter	11.86	5.20	140.66		140.61
Saturn	29.45	9.54	867.30		868.25
Uranus	84.02	19.19	7,059.36		7,066.83
Neptune	164.79	30.07	27,155.74		27,189.44

While Kepler's stunning intellectual achievement ranks with the greatest of all time, his findings were empirical and limited to the observed motion of Mars as seen from Earth. At about the time Kepler published his first two laws, **Galileo Galilei** (1564–1642) was on the verge of the first astronomical breakthroughs using the newly invented telescope. Most celebrated was his 1610 discovery of Jupiter's four largest satellites, and, with the planet itself serving as a surrogate Sun, Galileo envisioned a miniature solar system analogue, which we now know dutifully obeys Kepler's laws. Galileo's discovery of Jupiter's satellites was significant, but as with Kepler's situation, it was confined to a special case.

In 1621 Kepler published the third volume of *Epitome Astronomiae Copernicanae* (Epitome of Copernican Astronomy), a lengthy exposition of his system. Although interspersed with much of the occult, it recapitulates his work and extends the three laws to the known planets, our Moon, and Jupiter's moons, but doesn't range beyond the solar system, remaining silent with regard to the realm of the stars.

In the 1660s **Isaac Newton** (1642–1727), armed with calculus, of which he was a co-inventor, developed laws of motion and gravitation, which encompassed the entire universe, more or less subsuming Kepler and Galileo. Kepler's laws retained a flavor of mutual independence, but with the new mathematics, Newton was able to derive enhanced versions of and unite the three. In his 1687 book, *Principia Mathematica*, he verified, as Kepler had strongly suspected, that they apply to all the solar system planets and by implication to everything everywhere. Newton modestly told the world that he stood on the shoulders of giants, and Johannes Kepler was certainly one of the giants.

■ **MIKE WITKOSKI** has been an avid sky observer for decades and has contributed articles to several publications over the years. He is an advocate for dark skies and volunteers at public events under the stars at Muddy Run Observatory in southeastern Pennsylvania.

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▲▶ **DOING IT ALL** Besides being powerful computers, the latest smartphones include cameras that can take exposures deep enough to record stars, bright nebulae, and even the Milky Way. This shot of our home galaxy over the Himalaya Mountains in Tibet was captured using a Meizu 16th Plus smartphone. Total exposure is 78 seconds at ISO 3200.

Smartphone Nightscaping

The ever-improving quality of cameras in smart devices makes nightscape astrophotography a snap.

We are on the cusp of a new revolution in astrophotography. Much like the digital revolution of the 1990s when CCD technology overtook film as the popular media for picture-taking, casual astrophotography is about to change forever. The device that is driving this change is probably in most every reader's pocket at this very moment — a smartphone.

The mobile-phone revolution is a booming business, creating some of the most valuable companies in the world. And as such, the pressure to produce better models is driving improvements at breakneck speed. Not only are smartphones becoming powerful computers that can do practically anything your old desktop model could do, but they also now boast remarkably versatile cameras that open up many possibilities for photography, particularly nightscape imaging.

A Pocket Camera and More

The app industry that grew in support of smartphones has long provided users the ability to run planetarium programs and observing-planning apps, as well as to take some rudimentary control of a device's camera when the standard controls are inadequate for astro-imaging. And for quite some time, intrepid amateurs have been recording good close-ups of the Moon and planets by attaching their device to a telescope and snapping away (see last month's issue, page 28).

Only recently have cameras in the newest smartphones been able to take exposures lasting longer than a second or two. And while some of these may be a bit pricey, you can often greatly mitigate the cost by upgrading the phone through your service provider. You usually don't need to spend much more than a few hundred dollars to get the latest iPhone or Android model this way.

What to Look For

If you're on shooting scenic landscapes crowned by stars and the Milky Way with your smart device, you'll need to

UNLESS NOTED, ALL PHOTOS PROVIDED BY AUTHOR choose a phone with built-in manual controls for the camera. Recent high-end models by Huawei, Meizu, and Samsung, among others, include manual mode to control the camera's electronic shutter, ISO speed, focus, and white balance. Some also offer the option to save files in RAW format, which is essential for getting the best results.

Unfortunately for iPhone users, its camera automatically determines most settings, and it currently cannot take true long exposures. Several apps are available to get around most of these limitations, particularly *NightCap Camera* (**nightcapcamera.com**), which can bypass the camera's exposure limit by automatically stacking short exposures, with a result that's similar to a single long exposure.

When choosing a smartphone for nightscape photography, be sure to look for a model with a large CMOS detector. I use a Meizu 16th Plus that incorporates a Sony IMX380 Exmor CMOS sensor, which provides moderately low-noise images under low-light conditions and 20-megapixel resolution. But new and better models are announced often, so look carefully at the specifications of the model you're interested in before making a decision.

▲ **ARCHING REFLECTIONS** A still lake mirrors the star trails in this shot with the author's Meizu 16th Plus smartphone taken from the ancient Xiate trail in Xinjiang, China.

Additional Accessories

After choosing your device, you'll still need a few accessories to get you shooting. Since photographing the night sky requires long exposures, a tripod is an essential. You can use any standard photo tripod to mount your phone, though I suggest a heavier professional-quality tripod. Smartphones, unlike DSLR cameras, are extremely light, so a heavier tripod will hold your phone steady even under a good breeze.

Next, you'll need a special tripod mount to attach the camera. This is the easy part. Due to the popularity of the "selfie," you can now purchase a cheap selfie stick in discount stores, often for only a few dollars! These are extremely useful because the phone clamp is attached using a standard ¼-20 tripod thread. Simply unscrew the clamp and attach it to your photo tripod.

Another important accessory you'll need is a Bluetooth shutter remote. Simply clicking on your device's screen to take the picture will cause the phone to shake, immediately trailing the stars in your photo. A Bluetooth shutter remote, some costing less than $2 online, will eliminate this problem. More advanced models offer a time-delay feature or even a voice-controlled trigger. The more you avoid touching your phone while taking photos, the better your results will be.

The final accessories I recommend aren't essential but will increase the variety of your nightscape results and let you shoot longer. Unless you have one of the few dual-lens models that recently entered the market, your smart device probably has only one lens with a fixed focal length. This may not be wide enough to capture the Milk Way in one exposure. Fortunately, there are many decent clip-on lens kits that offer a variety of focal lengths, which permit you to tailor your field of view to match your subject.

Note that some of the latest cellphones have a built-in wide-angle lens. Keep in mind the CMOS behind the lens is very small with extremely tiny pixels, which may not be good for taking images of stars.

Finally, add an external power source, such as a

SELFIE STICK AND MOUNT: SEAN WALKER / *S&T*

◀ **INEXPENSIVE BRACKET** Mounting your device on a tripod is cheap and easy. Simply purchase a selfie stick (often costing $5 or less) and unscrew the phone clamp (right). Because the clamp connects using a standard ¼-20 tripod thread, you can attach it to any standard photo tripod (left).

small rechargeable battery pack with USB output, along with your phone's charger chord to keep you running most of the night.

In the Field

Once you're ready to get out under the stars, you should keep a few things in mind to get the best results. First, activate "airplane mode" to reduce your smartphone's power consumption. The camera draws a lot of power, as does the device's network connection, particularly if you are out of range of a cell tower. The fewer activities your device is performing while shooting, the more exposures you can take before depleting its battery.

Make sure your device's Bluetooth is enabled and pair your trigger device so it can fire the shutter. Set your smartphone to record in RAW mode and its camera to "pro" or "expert" mode, which is often where all the manual controls reside. This lets you change the shutter speed, ISO, white balance, and, most importantly, focus to infinity. With my Meizu 16th Plus, I often change the exposure in "expert" mode to 20 seconds, ISO 3200, and focus at infinity, with a white balance of 3500K.

This is only a suggestion, as you may need to try different settings depending on lighting conditions, such as when the Moon is up or if you are shooting under light pollution.

Targets

Now that you're ready to shoot, here are some ideas on what to shoot. Star-trail images are perhaps the easiest entry point into nightscape photography. Simply set your phone to shoot a series of exposures lasting 15 minutes or more. You can then either transfer the images to a desktop computer and stack the results, or use an app that does this right in your phone. Some smartphones even include this action in their native camera-control apps!

Keep in mind that star trails appear different depending on the direction you aim your camera. Pointing north will produce an image in which the stars arc around the north celestial pole near Polaris. Aiming east or west, the stars appear to move in nearly straight lines.

Another favorite target for nightscape imagers is the Milky Way. As seen from the Northern Hemisphere, the central bulge of our home galaxy rises from the east after midnight in spring and is visible through late autumn. The best time to capture it is under a moonless sky in the mid-summer months. Be sure to use a high ISO setting and exposures lasting 20 seconds or more. Adding a small tracking head to your tripod will permit you to

◀ **NO TOUCHING** Avoid touching your device and trailing your exposure when firing off exposures by using a Bluetooth remote shutter release, like the model offered by Kodak seen here.

SHUTTER RELEASE: KODAK.COM

▶ **REACH FOR THE STARS** A field of sunflowers appears in this 60-second exposure captured during a moonlit night in Thailand.

NORTHERN LIGHTS Bright aurorae are well within the exposure range of modern smartphone cameras. The author captured this display from the arctic coast in Murmansk, Russia.

▲ **IPHONE CONTROL** Although iPhones currently cannot record exposures longer than ¼ second, the popular app *NightCap Camera* performs live stacking to simulate long exposures and also includes other important manual controls for ISO speed, focus, and exposure duration.

shoot longer exposures, or even multiple exposures that you can later stack to produce an even smoother result.

The Milky Way is so large that it will most likely be bigger than your camera's field of view. Here you may want to shoot a panorama of several images by rotating your tripod between each exposure, and then stitch the results together later using an app or a desktop stitching program. Be sure to include lots of overlap between each image so that your stitching software can recognize matching foreground objects as well as star patterns.

Another good target for your smart device is aurorae. The northern (or southern) lights are one of the most beautiful and rapidly changing events you can see with the naked eye.

Because bright aurorae change appearance very quickly, I suggest using the highest ISO and a short exposure, but you'll need to experiment to determine the shortest shutter speed to adequately record the changing details in these glowing curtains of light. Some bright aurorae record well in exposures of just a second or two.

A final consideration when capturing nightscape images is your foreground. Some basic knowledge about astronomy is helpful so that you can plan, say, to record a particular constellation or the Milky Way rising over a snow-capped mountain or a glassy-smooth lake. You'll need to plan precisely where you will need to be set up in order to capture both in the same image, to give the picture artistic depth and a good composition. Several apps and websites such as the Photographer's Ephemeris (**photoephemeris.com**) can help you plan where to set up to capture both your subject and foreground long before you head out under the stars.

Once you have your images, you'll need to perform some post-processing to bring out the Milky Way, brighten the foreground, or stitch together panoramas. You can do some basic processing with the photo-editing app included with your smartphone. For more advanced processing, which almost certainly will produce better results, bring your images onto a desktop computer and use photo-editing software such as *Adobe Photoshop*. A great tutorial on processing nightscape photos can be found in *S&T:* Jan. 2018, p. 36.

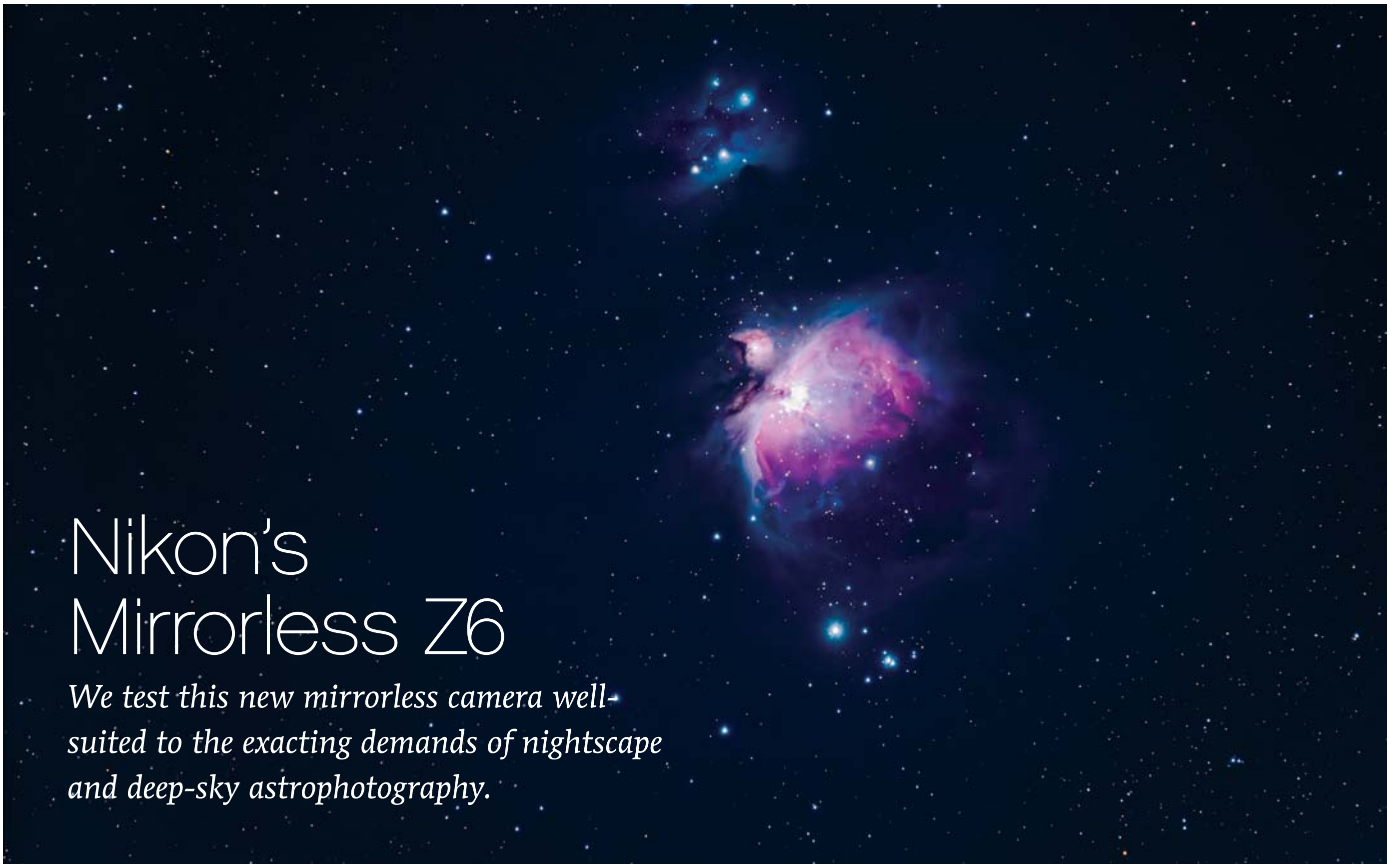
With the rapid development of smartphone technology, soon you'll no longer need a heavy pack full of cameras and lenses to take stunning nightscape images. These devices can drastically reduce the threshold required to enter the world of astrophotography, inspiring those with just a casual interest get give it a shot.

■ The World at Night (TWAN) photographer **JEFF DAI** travels around the globe to take breathtaking images of the night sky over picturesque landscapes.

▼ **CLEVER COMPOSITION** Nightscape photography is all about creating a composition that includes an interesting foreground with the stars above. This view captures stars through radio telescope dishes at Beijing Observatory in China.

▼ **LIMITED GEAR** Using your smartphone for nightscape photography doesn't add more than a tripod and trigger device to your gear, making scenes like this campsite silhouette under the Milky Way a snap.

CAMERA CONTROL: NIGHTCAPCAMERA.COM



Nikon's Mirrorless Z6

We test this new mirrorless camera well-suited to the exacting demands of nightscape and deep-sky astrophotography.

Nikon Z6

U.S. Price: $1,799.95
nikonusa.com

What We Like

Low noise at high ISO settings

Long exposures free of artifacts

Low-noise 4K video

What We Don't Like

Requires costly XQD memory card

Incompatible with some control and processing software

◀▲ As in all mirrorless cameras, the Nikon Z6's sensor is set back from the new Z-mount flange by a much shallower distance than with DSLRs, in this case only 16 mm, compared to the 46-mm flange distance of Nikon's classic F-mount bayonet. *Top:* This stack of four 8-minute exposures of the Orion Nebula taken in moonlight at ISO 200 through a 105-mm refractor shows the Z6's effectiveness for long-exposure deep-sky imaging.

THE MIRRORLESS CAMERA WARS ARE ON. With the recent introduction of Canon's EOS R and Nikon's Z series, the two major camera manufacturers finally challenge Sony's lead in the mirrorless, full-frame camera market. These new models establish the mirrorless design as the future for serious consumer cameras.

Not that DSLRs, cameras that use reflex mirrors for framing and focusing, are going away anytime soon. But the new generation of mirrorless models, with their larger lens mounts and shorter required distance from lens to sensor, allow greater freedom in lens design. The camera bodies are smaller and lighter, in contrast to DSLRs that, in top-end models at least, have become larger and heavier.

But are the upstart mirrorless cameras as good as our tried-and-true DSLRs for the demands of astrophotography? We tested Sony's much-acclaimed α7 III (*S&T:* Apr. 2019, p. 60) and found it superb for nightscape, time-lapse, and low-light 4K videos, but with deficiencies when used for deep-sky imaging.

Almost identical in key specifications and price to the 24-megapixel α7 III is Nikon's new Z6. Using a unit on loan from Nikon's marketing firm in Canada, I was able to test how well the Z6 performs at high ISO speeds on actual night scenes and deep-sky objects. Such tests can reveal issues that go unnoticed in daylight photography and in reviews by YouTube mavens.

The Nikon Z6

The Z6, a 24-megapixel camera, yields an image of 6,048 × 4,024 pixels, nearly

ALL PHOTOS BY THE AUTHOR

identical to that of Nikon's popular D750, a favorite DSLR camera of mine for astrophotography. Pixels in both cameras are 5.9 microns square, providing a good balance of noise vs. resolution. However, the sensor in the Z6 is a new back-illuminated CMOS design, which, along with Nikon's latest *Expeed 6* firmware, promises to yield lower noise than the four-year-old D750.

I selected the Z6 for testing over Nikon's more expensive Z7 mirrorless because the latter model, while providing higher resolution with 46 megapixels, will inevitably exhibit higher noise due to its smaller 4.3-micron pixels.

For my testing, I shot with the Nikon Z6 alongside both the D750 and the Sony α7 III, to compare noise levels, live view modes, movie capability, and battery life.

Noise Levels

Key to performance for astrophotography is how well cameras perform at the high ISO speeds we typically employ for most nightscape and deep-sky images. In side-by-side tests of a sample nightscape scene (my rural backyard) on both moonless and moonlit nights, the Z6 exhibited nearly identical noise levels at ISO 3200 to 12,800 as the veteran D750, seen below.

Luminance (overall grittiness) and chrominance (color speckling) noise levels looked very similar, with Z6 images appearing a bit lower in noise, especially at ISO 12,800, but certainly not by as much as even a half-stop improvement. Comparing it to the Sony α7 III also revealed nearly identical high-ISO noise performance. All three cameras were excellent, with no clear winner in still images.

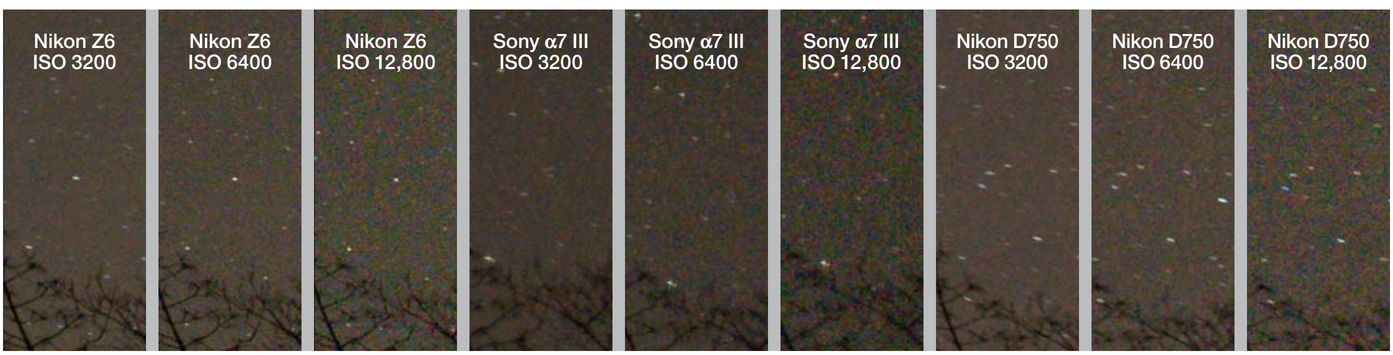
▶ The Z6 can provide a very bright Live View image by switching to its Movie Mode using the dedicated lever at top, with the ISO set to Hi1 or Hi2. This is a scene lit only by moonlight.

The Z6 sensor employs a signal path design that is "ISO invariant." The benefit is that a nightscape image shot at a low ISO speed and therefore underexposed, then boosted later in exposure at the computer should look nearly identical to a properly exposed image shot at a high ISO speed to begin with.

ISO invariant sensors allow you to increase shadow details in nightscape foregrounds during processing without introducing ugly artifacts such as excessive noise, fixed-pattern banding, and magenta casts. A test dark-sky nightscape shot at ISO 100, and so underexposed by a full five stops, did exhibit more random colored pixels when boosted later in processing, but overall it looked similar to a properly exposed image. I did not see any of the banding artifacts reported by other Z6 reviewers when shadows are boosted by extreme amounts.

The Nikon Z6 provides as low a noise level as you'll find in a 24-megapixel camera, with larger pixels and good ISO invariant performance. Both traits make the Z6 excellent for nightscape and time-lapse photography.

▲ Nightscape images underexposed by as much as 5 EV by shooting at slow ISO speeds then boosted later in processing looked similar to well-exposed images shot at a high ISO at the camera. This demonstrates the Z6's good "ISO invariant" sensor design, which is similar in performance to that of the D750 and Sony α7 III.



▲ At the ISO 3200 to 12,800 speeds commonly used for nightscape images, the Nikon Z6 showed similar noise levels as the Sony α7 III and Nikon D750, with the latter older camera marginally worse for noise at the highest ISO setting.

Live View

The Z6's Live View offers three levels of magnification, permitting users to zoom in on a star by up to 15× for precise focusing. That's not quite as good as the D750's 20× zoom level, but it worked sufficiently, especially when combined with a Bahtinov focusing mask on a telescope.

A bright Live View image, helpful when framing with a DSLR, is essential in mirrorless cameras as they lack any optical viewfinder. The D750 has an Exposure Preview option hidden in the "*i*" button Menu with Live View activated. Turning that on brightens the Live View image. The mirrorless Sony α7 III has an even more effective "Bright Monitoring" mode equally well hidden in its Custom button assignments.

The Z6 can achieve a significant boost in its live image brightness similar to the Sony's by switching the Z6 to its Movie mode with the ISO set to Hi1 (ISO 102,400) or Hi2 (ISO 204,800). Like most Nikons, the Z6 remembers settings separately for its Still and Movie modes, making it easy to employ the Movie mode as a quick and temporary means of brightening the Live View image for framing nightscape scenes. That's very handy and produces a much brighter Live View image than the D750's.

▲ *Left:* The rear screen is also a touchscreen, with an "*i*" menu that can be customized to include favorite functions conveniently accessible by touch. *Right:* An "always-on" top OLED screen provides helpful exposure and battery life information during a long shoot. The rear LCD screen tilts up for ease of use on a telescope when aimed high in the sky.

Movie Mode

Where the Z6 really pulled ahead of its DSLR equivalent, the D750, is in shooting movies. For one, the Z6 can shoot 4K movies (3,840 × 2,160 pixels) at 30, 25, or 24 frames per second. The older D750 is HD (1,920 × 1,080) only.

The Z6 shoots movies using the full width of the sensor, downsampling the pixels in the process. When shooting 4K video, lenses therefore provide the same field of view as they do when shooting stills. That's also true of Sony's mirrorless cameras but not of Canon's new EOS R and RP mirrorless models, which crop 4K movies by 1.8× or 1.7×, respectively.

But the huge improvement in movie performance is in its noise levels. Even at ISO 51,200, the Z6 looks acceptably clean, unlike the D750, which is unusable at its top speed of 51,200. At ISO 25,600 the D750 is still very noisy in movies, far more than the Z6.

This improvement is important if you would like to shoot real-time videos of aurorae or of other nighttime events such as star parties.

That said, the Sony α7 III is still the winner for real-time low-light movies, as it can shoot at "dragged" shutter speeds as slow as ¼-second, providing a 2.5-stop increase in light input over the Z6, which can shoot only as slow as 1/25-second at 24 frames per second. The Sony remains my choice for real-time aurora movies, but the Z6 will work very well on bright aurorae.

▼ This series compares screen grabs from movies of the same moonlit scene shot with the three cameras. The Z6 far outstrips the older D750 for movie performance, providing much lower noise at the ultra-high ISOs required for low-light movies. However, the Sony α7 III provides slightly lower noise than the Z6 and can shoot movies with shutter speeds as slow as 1/4-second, allowing even slower and less noisy ISOs.

Silent Shooting

Mirrorless cameras still have mechanical shutters that close then re-open quickly every time a photo is taken. The Z6, as do other mirrorless cameras, has a "Silent Shooting" mode that employs an electronic shutter that is absolutely quiet. Wedding photographers will love it. For astrophotographers it can be handy for completely eliminating vibration when taking high-magnification stills of the Sun and Moon.

I found telescopic images of the Moon taken with Silent Shooting did look ever so slightly sharper than those taken with the mechanical shutter. Combined with the Z6's Continuous Extended drive rate, which allows burst rates of up to 8 frames per second with uncompressed raw files, Silent Shooting should be great during total solar eclipses for recording sharp diamond rings, Baily's Beads, and prominences.

▲ The Z6's Silent Shooting mode employs an electronic shutter to eliminate noise and vibration, which is particularly helpful for getting sharper solar and lunar images shot through a telescope.

Deep-sky Imaging

The tough test is long-exposure deep-sky imaging. Problems that can remain hidden even in nightscape images can become visible in exposures lasting many minutes, especially after applying the high levels of contrast required to bring out deep-sky targets.

However, the Z6 passed the test admirably. I saw no edge shadows from masks or mechanical obstructions in front of the sensor, which is as a mirrorless sensor should be. By comparison, DSLRs produce a darkening along the bottom of the frame due to shadowing from the upraised mirror.

Unlike in the Sony α7 III, I saw no discoloration or oddly colored glows created by internal heat or light sources. Stars also appeared neutral, with no strange green stars or anti-aliasing effects. In comparing Z6 images to ones taken with the Nikon D750, stars were not "eaten" or smoothed out by internal firmware routines.

Using Long Exposure Noise Reduction to apply dark frames internally by the camera did not introduce any image artifacts, such as blurred or discolored stars.

The limited loan period didn't allow me to test the Z6 on a moonless night targeting nebulae to check its red sensitivity, but I would not expect it to be any better than other stock DSLRs for picking up faint H II regions. LifePixel (**lifepixel.com**) and Spencer's Camera&Photo (**spencerscamera.com**) both offer services to modify the Z-series cameras with a filter that transmits more Hα signal.

File Compatibility

The Z6 writes raw files in Nikon's NEF format. However, as with all camera brands the exact file protocol varies from model to model. As of this writing in early 2019, the mainstream raw developers from Adobe, Affinity, DxO, Luminar/SkyLum, and ON1 opened Z6 files without problems.

However, specialized astronomy image-processing programs, often reliant on the good graces of independent developers, are slower to catch up and might not open Z6 raw files. For example, *PixInsight* v1.08.06.1473 (issued in May 2019) did not, even with the new LibRaw module installed.

Fortunately, the free open source raw developers *Darktable* v2.6.0, *LightZone* v4.1.9, and *Raw Therapee* v5.6 all opened Z6 files, though doing so might require also updating your computer operating system to the latest version.

Control Options

New cameras also often come with unique protocols for allowing external hardware and software to control the camera. Just because you have software that will run Nikon cameras doesn't mean it will run a Nikon Z6, or any new Nikon for that matter. For example, *BackyardNIKON* v1.0 did not work with the Z6.

AstroPhotography Tool (*APT* v3.63) did run the Z6 just fine, using the USB-C to USB-A cable that comes with the camera. That connection allows *APT* to shift shutter speed, ISO, and even lens aperture using its scripting function. For other programs, best check with the developer for compatibility.

However, to keep things simple at the telescope, I usually prefer to control


▲ Long exposures taken with the Z6 were free of amplifier glow and sensor shadowing, yielding clean images. This is a single 4-minute exposure at ISO 400 taken in moonlight to show field illumination. The vignetting is inherent in the 105-mm refractor and field flattener employed (no flats or lens correction were applied here). The blue glow at the top right is from a star just off the frame.

Nikon's optional FTZ lens adapter is required to attach "legacy" F-mount lenses, such as this Sigma Art lens (far left), or to attach the Z6 to field flatteners (left) and telescope adapters equipped with a standard Nikon F-mount T-ring. The FTZ then places the Z6 sensor at the correct distance from the field flattener for optimum correction.

cameras using just a hardware intervalometer. The Z6 uses the same DC-2 connector as the D750 for a shutter release cable. As such, the Z6 will work with any time-lapse controllers that connect through just the shutter port. Devices that control a camera through its USB port to shift shutter, aperture, and ISO might need their firmware updated before they will run a Z6.

Battery Life

All the attractive features are for naught if the camera draws so much power its batteries don't last long enough to be practical. We need cameras to last several hours at least to complete a night-sky shoot without interruption and battery swaps.

While the Z6 is rated as having poorer battery life than the D750, I found otherwise. It held out very well, using its EN-EL15b battery, compatible with the batteries in many other Nikon DSLRs. At room temperature the battery lasted for 1,500 photos, as good as the D750 in a side-by-side endurance test.

At night in the cold, the Z6 lasted nearly three hours at -10°C (14°F) on its internal battery when shooting the multi-minute deep-sky images shown here, again matching the D750. On another night at -15°C (5°F) the Z6 again lasted three hours, enough for 675 frames in a test time-lapse using its built-in intervalometer.

The Z6 should be just as good as most DSLRs for long time-lapses and deep-sky shoots, provided the rear screen and electronic viewfinder are turned off. The Z6 has a handy physical button for doing just that.

Recommendations

If you are happy with your full-frame Nikon DSLR now, switching to the Z6 to "go mirrorless" might not yield a significant improvement in still-image quality. It will, however, provide excellent 4K video, a feature only available on Nikon's high-end D850, as well as the cropped-frame D500 and D7500 DSLR cameras.

If you're using an APS-format Nikon now and want to upgrade to a full-frame camera, then choosing a Z6 rather than a DSLR would be an excellent choice. It yields lower noise than your existing camera, provides full-frame 4K video capability, a large, convenient touchscreen, and brighter Live View, all in a more compact and lighter body than any of Nikon's full-frame DSLRs. Just be sure to figure in the additional costs of its unique XQD memory cards, a card reader for them, a lens or two, and the FTZ lens adapter. The latter allows you to use all your existing Nikon F-mount lenses, provided they will properly cover a full-frame Nikon.

I was impressed with the Z6. If I were shopping for a Nikon full-frame camera now for astrophotography, it's the model I would definitely purchase.

The Z6 only accepts Sony's new XQD memory cards, not the more common SD or CF cards. While XQD cards can be more expensive, they are fast at writing and reading large 4K video files.

Like Nikon's high-end DSLRs, the Z6 offers options for shooting in smaller raw formats. However, unlike CCD cameras, this only down-samples the image, it does not bin the pixels to significantly reduce noise. While the smaller images reduce resolution, the smaller file sizes might be useful for some time-lapses intended only for HD or 4K-resolution final movies.

Contributing Editor **ALAN DYER** maintains his blog at **amazingsky.net** with tales of image-taking, time-lapse videos, tutorials, and test reports.

Better Balance Weights

Fine-tune your scope's balance with these simple weights.

LIGHTWEIGHT TELESCOPES are a joy to use, but they have one common drawback: The eyepiece contributes a significant fraction of the scope's total weight. And eyepieces range anywhere from a couple of ounces to a couple of pounds, so when you finally track down an elusive planetary nebula and remove your wide-field eyepiece to switch to a higher power, the unbalanced scope often takes off for the zenith, undoing all your work.

In our November 2016 issue I described a disk brake system for locking down a scope while changing eyepieces, but New Hampshire ATM Joe Dechene has developed a simpler, more versatile way of accomplishing the same thing: adjustable weights.

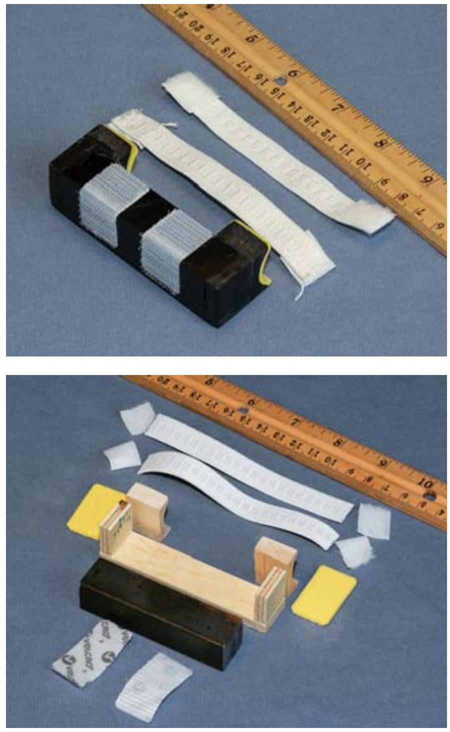
▲ Joe Dechene's adjustable weights attach tight to the telescope's trusses, yet can be easily slid up and down to fine-tune the balance.

Moveable weights are nothing new, but Joe's implementation of them is the most user-friendly I've seen. He didn't need to screw any rails to his telescope, and he doesn't need to loosen any locking screws to slide a weight forward or back. He simply attaches the weights to his telescope's trusses, where they can be moved up and down as necessary.

If I were designing such a system, I would have stuck long strips of Velcro hooks on the trusses and put some loops on the weights, but that's why I'm writing about Joe's design and not mine. Joe realized that tugging Velcro loose and sticking it back down would knock a telescope off target just as easily as changing an eyepiece (not to mention there's the danger of dropping a weight on the primary while attempting to move it). So he came up with a better way. The hooks go on the weights, and the loops go on the ends of stiff elastic bands. When you wrap the elastic around the trusses and stick the Velcro together, the weights can be slid up and down the trusses smoothly and easily without disturbing the scope's aim.

The weights can be constructed of pretty much anything heavy. To make them easy to grip and slide, Joe used ¾-inch-square steel bar stock. In order to prevent damage to the primary mirror if he did accidentally drop one, he put soft wooden caps on either end. On the sides he made curved wooden surfaces that match the truss diameter, with 1⁄16-inch hobby foam lining the inside of the curve so the wood doesn't contact the truss poles directly.

Joe reports that "Operation cannot be easier. Simply attach to the truss poles as needed and slide to compensate for various eyepiece or camera weights. It's a joy to use, being easy to slide and precisely balance the scope."



▲ *Top:* Velcro hooks go on the weights, and loops on the elastic straps. Curved contact surfaces lined with hobby foam ensure a snug fit against the telescope's trusses. *Bottom:* Each of the weight components is laid out for assembly.

Balancing the scope in all positions between horizon and zenith may require weights on more than just one truss, so make a couple while you're at it.

That solved the problem nicely for his truss-scope. But what about his equatorially mounted refractor? He could set the initial balance on each axis by counterweight position and dovetail position, but he still had the same problem when he removed a heavy wide-field eyepiece to put in a lightweight high-power eyepiece. Trouble was, there were no trusses to mount weights to.

The solution was a drawtube weight. Joe made a U-shaped weight with two pieces of the same steel bar stock he

JOE DECHENE (4)

used for his truss weights, separated by a wooden crossbar. He purposely proportioned the stock to make the weight naturally balance in the upside-down position when draped over the focuser's drawtube, but since rapid meridian reversal when slewing could make the weight fall off, he added a small rotating tab on the bottom of one bar to lock it in place until it rights itself.

▲ A U-shaped drawtube weight works well for balancing refractors.

This weight isn't as adjustable as the truss weights, but it doesn't need to be. If it weighs the difference between a high- and low-power eyepiece, you simply take it off when using the heavy eyepiece and put it on when using the light one. Your scope remains balanced in either case.

Joe says, "Now I can swap eyepieces with much more confidence on the refractor, too."

Attention to small details can add up to a big difference in a successful night out observing. Joe's eyepiece compensating weights are a great step in that direction.

For more information, contact Joe at **Joseph.Dechene@se.com**.

■ Contributing Editor **JERRY OLTION** hangs fishing weights from some of his scopes. He likes Joe's idea better.

SHARE YOUR INNOVATION
Do you have a telescope or observing accessory that *S&T* readers would enjoy knowing about? Email your projects to Jerry Oltion at j.oltion@gmail.com.

▷ GALACTIC MASHUP

Kent Wood

The distorted appearance of spiral galaxy NGC 3718 in Ursa Major is thought to be the result of gravitational interactions with NGC 3729 outside of the frame, rather than with the more distant galaxy group Hickson 56 at lower left.

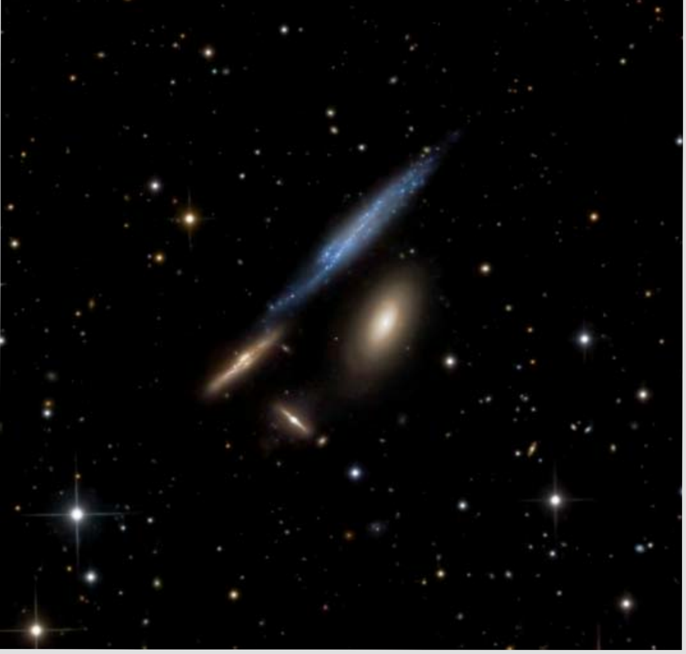
DETAILS: *Astro-Tech AT 16RC Ritchey-Chrétien telescope with an Atik camera. Total exposure: 20 hours through color filters.*

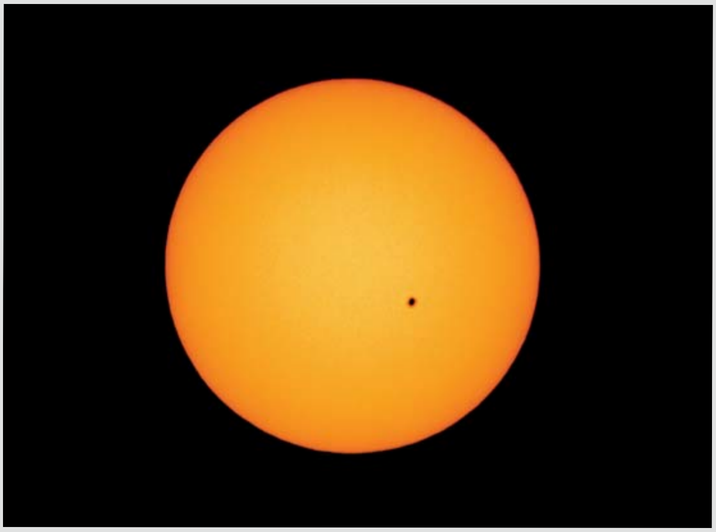
▽ CANYON COLORS

John Vermette

The Milky Way crowned with brilliant Vega stands high above Bryce Canyon National Park in Utah. Subtle green and red airglow adds additional color to this scene captured in the pre-dawn hours of early April.

DETAILS: *Canon EOS 6D DSLR camera with Rokinon 24 mm f/1.4 lens. Panorama of 39 images consisting of 15-second exposures for the sky and 30-second exposures for the foreground recorded at ISO 3200.*





△ RECTANGULAR GATHERING

Bruce Waddington

Nicknamed "The Box," the compact galaxy group Hickson 61 includes (clockwise from top) NGC 4173, NGC 4169, NGC 4174, and NGC 4175.

DETAILS: *PlaneWave 12.5-inch CDK with a QSI 640ws CCD camera. Total exposure: 10.3 hours through LRGB filters.*

△ BIG SPOT

Barry Burgess

After more than a year of scant solar activity, large sunspot group AR2738 appeared in mid-April, putting on a wonderful show for patient solar observers.

DETAILS: *Canon 7D Mark II DSLR camera with Rubinar 1,000-mm f/11 mirror lens with solar filter. Total exposure: 1/125 second at ISO 800.*

IN THE KEYHOLE

José Joaquín Pérez

Deep in the middle of NGC 3372, the Carina Nebula, lies the variable star system Eta Carinae (center). North is toward the top right.

DETAILS: *f/3.8 Newtonian Astrograph with a Moravian G316200 CCD camera. Total exposure: 32 hours through color and narrow-band filters.*

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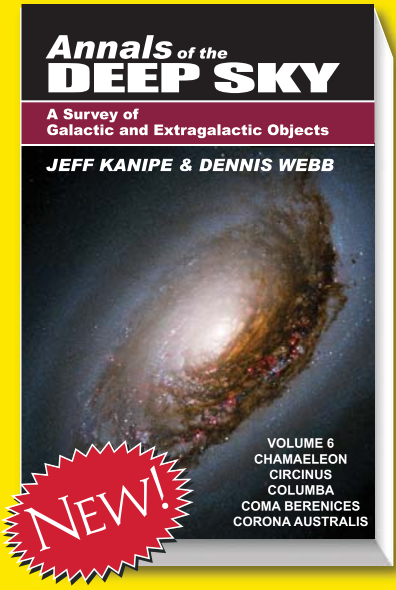

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LOOKING FOR PARTNER: to share time on PlaneWave CDK24 telescope situated 20 miles south of Cerro Tololo in Chile. Email dunckelnick@earthlink.net for more information.

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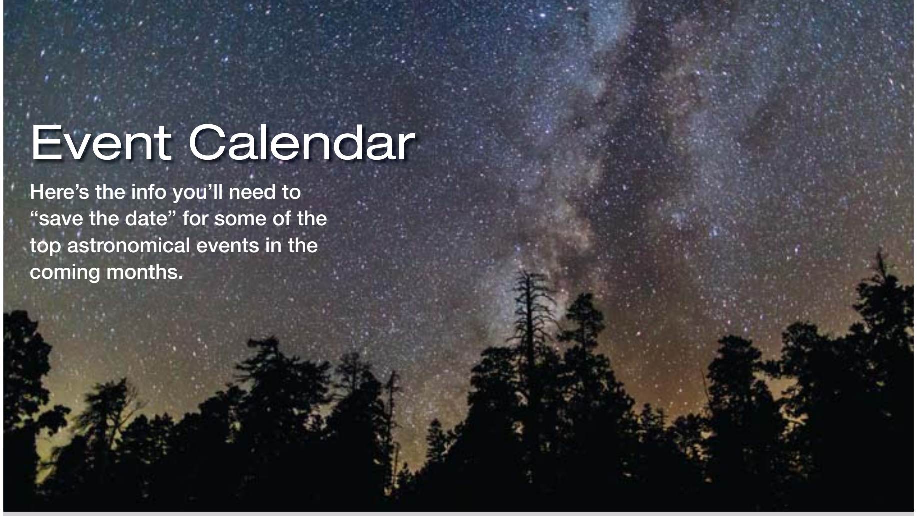

Event Calendar

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

July 26–August 4
SUMMER STAR PARTY
Plainfield, MA
rocklandastronomy.com/ssp

July 27–August 4
MOUNT KOBAU STAR PARTY
Osoyoos, BC
mksp.ca

July 28–August 2
NEBRASKA STAR PARTY
Merritt Reservoir, NE
nebraskastarparty.org

July 30–August 3
TABLE MOUNTAIN STAR PARTY
Oroville, WA
tmspa.com

July 30–August 4
OREGON STAR PARTY
Indian Trail Spring, OR
oregonstarparty.org

August 1–4
STELLAFANE CONVENTION
Springfield, VT
stellafane.org/convention

August 22–25
STARFEST
Ayton, ON
nyaa.ca/starfest.html

August 24–31
MERRITT STAR QUEST
Merritt, BC
merrittastronomical.com

August 30–September 3
ALMOST HEAVEN STAR PARTY
Spruce Knob, WV
ahsp.org

September 19–22
RTMC ASTRONOMY EXPO
Big Bear City, CA
rtmcastronomyexpo.org

September 21–29
OKIE-TEX STAR PARTY
Kenton, OK
okie-tex.com

September 26–29
GREAT LAKES STAR GAZE
Gladwin, MI
greatlakesstargaze.com

September 27–29
EASTERN IOWA STAR PARTY
Dixon, IA
https://is.gd/EIowa

September 27–29
BLACK FOREST STAR PARTY
Cherry Springs State Park, PA
bfsp.org

October 20–27
PEACH STATE STAR GAZE
Deerlick Astronomy Village, GA
atlantaastronomy.org/PSSG

October 21–26
ELDORADO STAR PARTY
Eldorado, TX
eldoradostarparty.org

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

Encounters With Police

A criminal justice expert who also stargazes offers safety tips for amateur astronomers.

AMATEUR ASTRONOMERS NEED dark skies and a minimum of stray light. Yet many of us live in metropolitan areas, with their light-polluted skies. Observing closer than one might wish to people and their homes can create extra safety concerns for the stargazer. As we're all aware, unfamiliar noises or suspicious figures in the dark can result in calls to the police to investigate.

Amateur astronomers pose a special challenge to law enforcement because they work at night and engage in practices that might be unexpected and unclear to non-astronomers. No human being is really good at rapidly assessing ambiguous situations in the dark, not even a police officer.

I might best sum up the following pointers for amateurs with this overall recommendation: *Make your activity as clear as possible.*

Some specific suggestions:

- Have any star charts or atlases clearly visible. Also, if you're observing with binoculars, you might wish to have a book about binocular astronomy on hand. Most people, including police officers, don't know that binoculars can be used for astronomy, so you could be mistaken for a stalker or window peeper.
- If you park at a site away from home, leave a paper or cardboard sign on your dashboard that says "Amateur Astronomer at Work."
- If your telescope has an unconventional design, you might want to put some reflective tape on your tube or mount. Remember, most people, including police officers, think that a telescope only looks like a classical refractor. Reflective tape might prevent the police from thinking your rig is a weapon. (I don't know anyone who would put reflective tape on a weapon.) As an added benefit, reflective tape on your mount might help you avoid tripping over it in the dark!
- If you're using a device with a light screen, write or tape something on the outside of the screen related to astronomy. It could quickly answer the question as to why you're, say, crouched behind a wall at night.
- Don't observe in totally unconventional locations such as unsecured cemeteries or abandoned properties. The police are more likely to assume in advance that anybody encountered at such sites is up to no good.
- If possible, wear clothing or other indicators that identify you as an amateur astronomer. Some astronomy clubs now issue patches, cards, and clothing, which serve that purpose nicely.

Two final issues worry me the most, but I have no answer for them. Many telescopes have red dot finders, and many amateurs use green laser pointers, either of which police could confuse with being part of weaponry. Another issue is flashlights, many of which can look like gun barrels in the dark.

Police aren't out to frighten or hurt amateur astronomers. But only a hermit on a desert isle would be unaware of the many recent cases of unarmed citizens who have been shot by police. As amateur astronomers, if we leave a path of "cookie crumb" clues for law enforcement to make instantly obvious what we're doing, hopefully they won't notice that red dot finder until after they ask for a quick view through your scope!

SEAN WALKER / *S&T*

■ **DENNIS KELLY**, an amateur astronomer for most of his life, holds two criminal justice degrees, a B.S. from Northern Michigan University and an M.S. from Michigan State University.

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SVX130T-WR35 shown with MoonLite NiteCrawler-WR35 Focuser.

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