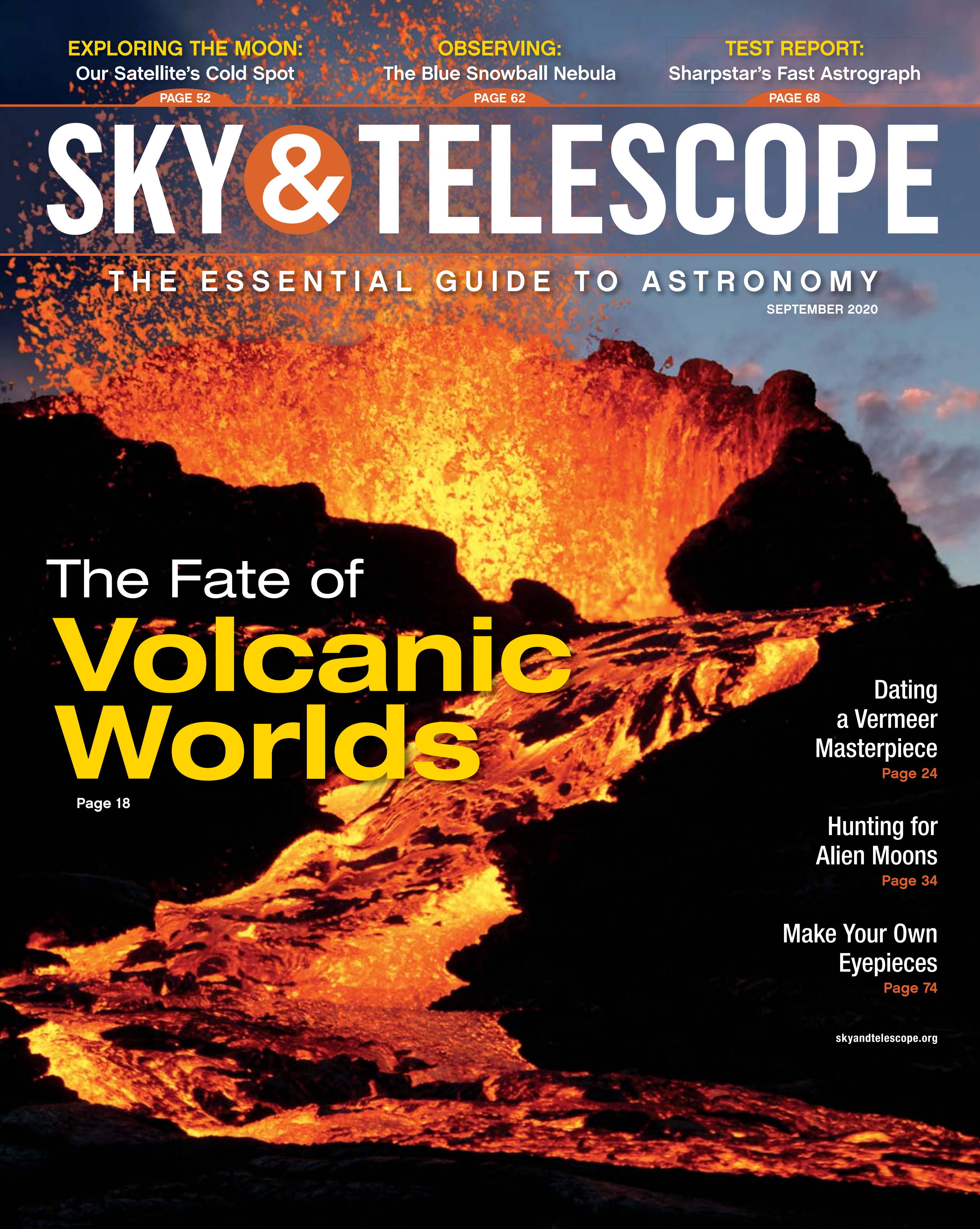

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SKY & TELESCOPE

THE ESSENTIAL GUIDE TO ASTRONOMY

SEPTEMBER 2020

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The Wages of Obsession

YOU REALLY HAVE TO SYMPATHIZE with astronomers who are seeking the first confirmed moon outside our solar system, or *exomoon*. Reading Shannon Hall's feature on page 34, you quickly feel their pain. At times they seem like a pool of lottery players who suddenly think they might have won the jackpot, only to discover that the last number in their long string is off by one.

It's hard enough to pinpoint exoplanets, though we've now verified the existence of more than 4,000 of those. But exomoons embody longer odds. A moon is generally defined as a celestial body that orbits a planet (or asteroid) and is small enough that the two orbs' shared center of gravity lies inside the surface of the planet. So you can imagine that if an exoplanet's signal in observational data is small, an exomoon's is minuscule. Teasing apart its signal from that of its host planet will be exquisitely challenging.

Patently obvious to frustratingly elusive: our Moon vs exomoons

SEAN WALKER / S&T

Astronomers have tried to sniff out exomoons by the effects they have on objects around them, such as planetary rings. They've also proposed multiple techniques they might use to try detecting them, including direct imaging, microlensing, pulsar timing, and the transit method. But exomoons remain frustratingly elusive.

This is oddly counterintuitive considering that the biggest, baddest celestial object in our own sky is the Moon. Ours can't be missed; theirs can't be found.

Yet, anyway. For most astronomers would likely agree that it's only a matter of time before they validate the discovery of the first exomoon.

What will these alien moons be like? It's hard to know, having only those in our own solar system to draw from. But if ours are any indication, moons come in a wide variety of styles. Most exciting of all is that some might be habitable.

Certain exomoons might even be "super-habitable," scientists say, by enjoying a diversity of energy sources from which to sustain a possible biosphere. They could receive heat not only from their star but from their host planet in the form of emitted heat, reflected light, and gravitationally induced tidal forces. In fact, it's not inconceivable, as one researcher quoted in Hall's article notes, that a moon ejected from an extrasolar system with its host planet and wandering, the two of them, alone in space might *still* harbor life because of its planet's resident heat. Imagine: a habitable zone not requiring a star!

So, we wish the exomoon hunters the best in snagging their quarry — not just the first confirmed extraterrestrial satellite, but all those to follow. Though, let's face it, that first one might well have us over the Moon.

Peter

Editor in Chief

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The Essential Guide to Astronomy

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Global view of Pluto created from images taken by NASA's New Horizons spacecraft during its July 2015 flyby. Courtesy NASA / JHUAPL / SwRI

These images of Jupiter and its four planet-size moons were photographed by Voyager 1 and assembled into this collage. They are not to scale.

The Galilean Moons

In F. Michael Witkoski's interesting article about "Finding Jupiter's Moons" (*S&T:* May 2020, p. 60), I was glad to see him give Simon Marius the deserved credit for his independent discovery of the Galilean satellites. But aside from using the Julian calendar, which placed Marius's observations in 1609 instead of Galileo's 1610, he didn't directly claim to "have observed the satellites first."

As Witkoski writes, the date confusion "angered Galileo." In fact, Galileo's diatribes ruined Marius's reputation for hundreds of years, even though today we use Marius's names for those four moons. The Simon Marius Portal, **simon-marius.net**, contains a collection of documents in several languages.

Jay M. Pasachoff
Williamstown, Massachusetts

F. Michael Witkoski describes Jupiter's moons as supporting heliocentrism. While Galileo said so, other astronomers did not necessarily agree. Consider Simon Marius, who concluded that observed variations in the motions of the moons could only be explained if Jupiter indeed orbited the Sun. Still, Marius denied heliocentrism in his *Mundus Iovialis*, writing, "I assume that the Sun himself moves in a sort of concentric orbit round the Earth," as in Tycho Brahe's model of the universe. Astronomers Johann Georg Locher and Christoph Scheiner also reported in detail on Jupiter's moons in 1614, in their book *Disquisitiones Mathematicae, De Controversiis Et Novitatibus Astronomicis*. They saw the moons as supporting the ancient epicycle theory that explained the observed motions of the planets in terms of one circle turning upon another. But as their book noted, epicycles had never been directly observed until Jupiter's moons.

Witkoski emphasizes religious opposition to heliocentrism. But when Marius, Locher, and Scheiner endorsed Brahe's ideas over Copernicus's, they appealed to the stars. Stars were observed to have measurable diameters. No one knew then that these were spurious Airy disks, artefacts of optics. Stars would have to be huge to show such diameters at the distances heliocentrism required, so Locher and Scheiner calculated that every visible star would be larger than Earth's orbit.

They admired Galileo's work and supported him against Marius. They just disagreed with his interpretation of the data.

Christopher M. Graney
Louisville, Kentucky

Pipe Mounts

I have been a subscriber since 1969 and have seen many things come and go, but the pipe mount never totally went away, as seen in Astronomer's Workbench (*S&T:* May 2020, p. 72). I built mine in 2006, mostly for my Jaeger 5-inch f/5 refractor. It's straight from Sam Brown's *All About Telescopes,* published in 1967 by Edmund Scientific. It's based on 2-inch galvanized pipe. I enlarged the legs for the refractor column height and inserted a dogleg with 45° elbows to reduce the lateral offset of the telescope. I also built an alternate platform for holding large binoculars from hardwood and a steel angle brace.

John F. Rusho
Chaumont, New York

▲ John Rusho built this pipe mount for his 5-inch refractor.

Traveling on Spaceship Earth

"My Immense Journey" by Dan Rinnan (*S&T:* Apr. 2020, p. 84) prompted a lively discussion at the supper table. Our 10-year-old son, Pascal, asked whether the distance traveled by the Voyager 1 space probe should also include the motion of the Milky Way toward the Andromeda Galaxy, the Local Group of galaxies toward the Virgo Cluster, and the Laniakea Supercluster toward the attractors. And shouldn't the motion of orbiting the Sun be added in? However, we weren't sure about the Sun's orbital motion around the Milky Way's center. As often happens, lacking coffee, the grown-ups in the room hadn't considered that possibility.

Daniel and Pascal Crane
Dexter, Michigan

In order to make a valid comparison of the motion of the author to the motion of the Voyagers, we need to put them in the same frame of reference. The article described the author's motion relative to the cosmic microwave back-

JUPITER AND MOONS: NASA / JPL; MOUNT: JOHN RUSHO ground but only considered Voyager 1's motion relative to the Sun. The Voyagers nearly share the Sun's motion relative to the microwave background, so neither the author nor the Voyagers are being "left in the dust."

Nancy Morrison
Newton, Massachusetts

Dan Rinnan replies: *Voyager 1 has broken free of Earth's gravity, but it's still within the gravitational frame of our Sun. For a long time, it will share the Sun's motion through the Milky Way, and our galaxy's movement through the universe itself. But in about 40,000 years Voyager 1 will fly within 1.6 light-years of AC+79 3888, a star in the constellation Camelopardalis. The probe may then be captured by that star's gravitational frame, and change direction, but continue to orbit around the center of our galaxy. So, yes, Voyager 1 shares my own motion through space. But I've still traveled a lot farther because, being older, I've had 33 years more travel time.*

Photographing the Jet

I really enjoyed Howard Banich's "A Curious Straight Ray" (*S&T:* Apr. 2020, p. 30). It was interesting to read about his visual impressions in instruments over the impressive aperture range of 12 to 90 inches! I've also wondered about the visibility of this object. I decided to see how well it could be photographed using a more modest telescope. Last year, I tried my luck — and succeeded — with my 6-inch f/9 Ritchey-Chrétien. Now, I wonder what the smallest aperture capable of photographing this object would be?

Dave Billesbach
Lincoln, Nebraska

An Oldie But a Goodie

Last year, I required cataract surgery. In my collection of old issues, I found "Clearing the Clouds: Cataract Surgery for Astronomers" by Kathy and Jerry Oltion (*S&T:* Sept. 2014, p. 34). The article helped me navigate through the process — eventually with a happy result.

I went through three different surgeons. The second did the cataract surgery, but my eyes had diffraction spikes like the ones described in the article. My third surgeon saw the issue and fixed it.

Many thanks to *S&T* for an article that is still relevant and available to astronomers facing cataract surgery.

Allen Jensen
Ellijay, Georgia

FOR THE RECORD

- In the sidebar of "A Curious Straight Ray" (*S&T:* Apr. 2020, p. 33), under "Making simplifications," the editors oversimplified, and *c* is missing from the numerator of the first equation's right side. It reappears, though, in the solutions beneath.

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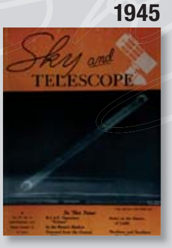
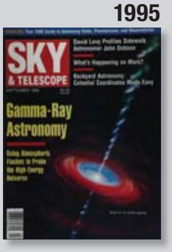
75, 50 & 25 YEARS AGO by Roger W. Sinnott

1945



1970

1995



September 1945

Novae as Yardsticks "In recent years, the luminosities of new stars have been established with considerable accuracy, and our knowledge of the absorption of light in space has improved so much that Dr. Dean B. McLaughlin, of the University of Michigan Observatory, has made a study of the space distribution for some 100 novae for which reasonably good data are available. . . .

"The space co-ordinates of these novae locate most of them within 3,000 parsecs of the sun and within about 500 parsecs of the galactic plane. . . .

"[T]he Sagittarius novae are at the distance of the star cloud in that region of the sky. [But, writes McLaughlin,] 'The present investigation . . . gives no definite answer to the question whether the brightest star clouds in Sagittarius are truly parts of the central nucleus of the galaxy.'"

September 1970

Diffuse Interstellar Bands "The spectra of distant, strongly reddened early-type stars often contain certain broad, diffuse absorption bands. . . . They clearly originate in interstellar space, but the identification of the material causing these absorptions has puzzled astronomers for decades.

"A startling but well-documented identification was announced by Fred M. Johnson, Electro-Optical Systems . . . After a laboratory survey of spectra of hundreds of complex organic compounds, he found that the diffuse interstellar bands were closely matched by bispyridylmagnesiumtetrabenzoporphine . . . How so complex a molecule could be formed in interstellar space in large amounts is not explained. Once formed, its survival would be aided by its extreme thermodynamic stability."

A century after the pioneering work of William and Margaret Huggins, the analysis of deep-sky spectra was truly coming into its own.

September 1995

Heavenly Brew "Ethyl alcohol, or ethanol (CH_3CH_2OH) — the organic compound that gives beer, wine, and liquor their intoxicating powers — reveals itself . . . by emitting discrete spectral lines at millimeter wavelengths. Although first detected toward the galactic center in 1975, ethanol has eluded subsequent searches of its expected habitat . . . Now, however, a British team has located a huge reservoir of the evasive compound on the outskirts of a young star-forming region. . . .

"Thomas J. Millar [and two colleagues] identified 14 spectral lines [betraying] ethyl alcohol in the molecular cloud around G34.3+0.15, a compact ionized-hydrogen region near the border of Aquila and Serpens Cauda. The features arise when an ethanol molecule jumps between differing quantum states of rotation. . . .

"[They] suggest that G34.3+0.15's abundant ethanol is formed on . . . the dust grains that cocoon the system's newly formed stars."

STARS

Milky Way Magnetar Explodes as Fast Radio Burst

▲ An artist's concept of a *magnetar*, a highly magnetized neutron star

FAST RADIO BURSTS are brief, powerful, and mysterious flashes of radio waves (*S&T:* July 2016, p. 24). Now we've found one of these flashes originating in our own galaxy.

Two observatories independently detected the burst of radio waves coming from a *magnetar* some 30,000 light-years away. Its radio signature looked just like the fast radio bursts (FRBs) that astronomers have discovered in increasing numbers over the past few years in other galaxies. Those bursts unleash a vast amount of energy in the blink of an eye, but what causes them remains unknown. The new detection, not yet published but posted on *The Astronomer's Telegram*, promises to shed light on the powerful mechanism.

The new observations suggest that magnetars may produce some FRBs. Magnetars are ultra-magnetized versions of neutron stars, the collapsed cores that remain after supernovae explode. These exotic objects are already known to flash and sputter gamma rays and X-rays but had never been seen emitting an FRB.

Astronomers discovered a magnetar in our galaxy in 2014 known as SGR 1935+2154, which they have monitored since then. So they were watching when, on April 28th, the Canadian Hydrogen Intensity Mapping Experiment (CHIME) and the STARE2 radio array both observed a distinctive flash of radio waves coming from the magnetar's direction. Nearly simultaneously, the source burped out a short X-ray flash spotted by several X-ray telescopes. The multiple independent detections helped astronomers pinpoint a more exact location for the source.

"The luminosity implied by the STARE2 analysis is really astounding," says Geoffrey Bower (Academia Sinica, Taiwan), who wasn't involved in the new observations. "It does suggest that bursts from magnetars could be detected at enormous distances."

The discovery could also help astronomers understand the process behind the flashes. Snapping magnetic field lines could release enough energy to power the radio bursts we see.

Bower adds that this discovery doesn't mean that all FRBs come from magnetars. "There may very well be other mechanisms or sources at work producing FRBs," he says.

■ **MONICA YOUNG**

SOLAR SYSTEM

Did Asteroid Ryugu Skirt Close to the Sun?

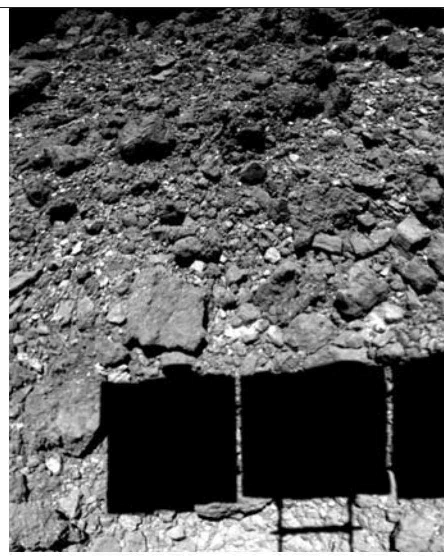
A COMBINATION OF CRATERS and surface color suggests that the near-Earth asteroid 162173 Ryugu was cooked by the Sun between a few hundred thousand and several million years ago — and that the die-shaped world might be remarkably younger than previously thought.

The Japanese spacecraft Hayabusa 2 (*S&T:* May 2020, p. 14) revealed Ryugu to be oddly striated, its equator and poles tinged blue while mid-latitudes are darker and reddish.

As Tomokatsu Morota (University of Tokyo) and colleagues write in the May 8th *Science*, Ryugu's boulders likely start out bluish before solar wind exposure, meteoroid impacts, and solar heating redden them. The redder stuff migrates to the asteroid's mid-latitudes over time because they are topographically the lowest parts of Ryugu's surface.

Surface reddening is common on asteroids, but the authors argue that

▶ Hayabusa 2 observes Ryugu just before its first touchdown on the surface.



MAGNETAR: NASA'S GODDARD SPACE FLIGHT CENTER / S. WIESSINGER; RYUGU'S TOUCHDOWN: JAXA / U. TOKYO / KOCHI U. / RIKKYO U. / NAGOYA U. / CHIBA INST. TECH. / MEIJI U. / U. AIZU / AIST

STARS

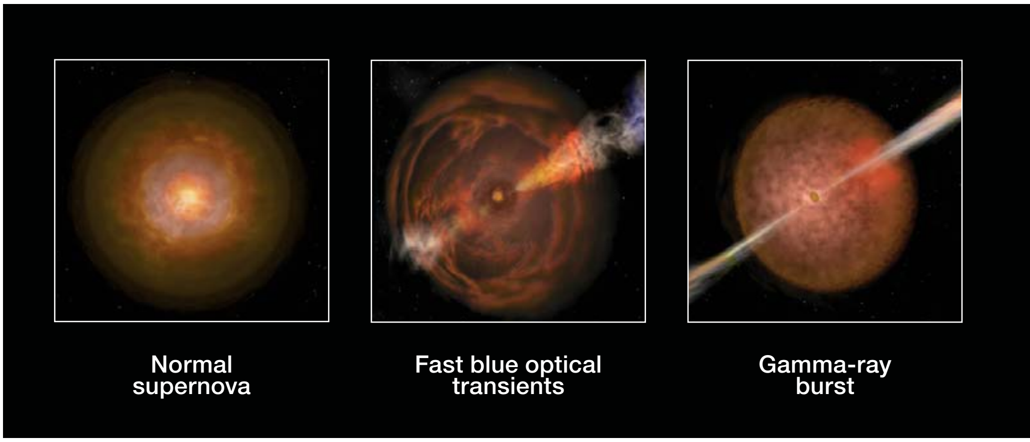
Two New Beasts for an Explosive Menagerie

ASTRONOMERS HAVE ADDED two explosive events to a class dubbed Fast Blue Optical Transients (FBOTs), named for its members' sudden appearance and blue-hot colors.

One of the first real-time discoveries occurred in 2018. Officially designated AT2018cow, this explosive source earned the nickname "the Cow" (*S&T:* May 2020, p. 10). Its proximity enabled detailed follow-up observations, which made it the prototype FBOT.

Before then, in 2016, the automated Catalina Sky Survey and the All Sky Automated Supernova Survey had independently discovered another source, designated CSS161010. But according to Raffaella Margutti (Northwestern), "It took almost two years to figure out what we were looking at, just because it was so unusual."

Visible light from CSS161010 peaked in a matter of days, glowing from a dwarf galaxy some 500 million light-years away. In the years that followed, Deanne Coppejans (also at Northwestern), Margutti, and colleagues followed up with radio and X-ray observations, presented in the May 20th *Astrophysical Journal Letters*. The researchers interpret the data as a blast that ejected twin jets of plasma shooting out at half the speed of light and carrying up to 10% of the Sun's mass.



▲ Astronomers think FBOTs (*center*) may be a type of explosion in between regular core-collapse supernovae (*left*) and more extreme gamma-ray bursts (*right*).

BILL SAXTON / NRAO / AUI / NSF

Meanwhile, the Zwicky Transient Facility recorded a similarly luminous burst in 2018, whose light traveled for 3 billion years to Earth. Officially, the event is ZTF18abvkwla but astronomers couldn't resist dubbing it "the Koala." (Soon there may be a whole zoo!) In the May 20th *Astrophysical Journal*, Anna Ho (Caltech) and her colleagues followed up on the Koala with radio observations, finding evidence of fast-moving material that had blasted into thicker surroundings. The radio waves rivaled gamma-ray bursts in their luminosity.

Most astronomers believe that these new beasts are massive stellar explosions. Ralph Wijers (University of Amsterdam), who was not involved in these studies, thinks FBOTs could help fill the gap between regular supernova explosions and the most energetic gamma-ray bursts. In the case of FBOTs, thick, dense clouds of material may surround the supernovae, absorbing and re-radiating the explosive power.

But other ideas remain in play. Maybe FBOTs are not supernovae but *tidal disruption events*, where intermediate-mass black holes rip apart and consume unlucky stars.

Whatever produces these hot, brief, and energetic outbursts, one thing's for sure: Now that astronomers know what to look for, these events are likely just the tip of an explosive iceberg.

■ GOVERT SCHILLING

Ryugu's reddening reaches too deep to be caused by normal space weathering. Red ejecta dug up by impacts streak the surface, and some small craters are actually redder than their surroundings, suggesting the red materials are at least a few meters deep. Furthermore, the team found that craters are either red or blue, with few in between. The dichotomy suggests that the reddening was an event, not a continuous process, and that it happened before the blue craters had formed.

Putting these data together, Morota and colleagues propose that Ryugu baked when it ventured too close to the Sun, between 300,000 and 8 million years ago.

They also estimate that the heating happened some 8.5 million years after the asteroid's formation, making Ryugu at most about 17 million years old.

This age is surprisingly young. Based on Ryugu's orbit, scientists thought the little world was built from the debris of a main-belt asteroid smashup that happened a few hundred million years ago. Maybe multiple generations of asteroids formed and broke up before Ryugu coalesced, the authors suggest.

But the age estimates are far from certain, cautions OSIRIS-REX scientist Daniella DellaGiustina (University of Arizona). It's possible that space weathering, pulverization, and even carbon could redden the rocks, she explains. Researchers will be able to confirm Ryugu's surface age once they test Hayabusa 2's samples, which are scheduled to drop in Australia this December.

Interestingly, the scientists say the proposed heating event *couldn't* explain why Ryugu's minerals show so little evidence of interacting with water (*S&T:* July 2019, p. 8). The bluish regions are just as dry as the reddish ones.

■ CAMILLE M. CARLISLE

● Read more at **https://is.gd/ryugu.**

An artist's concept of the Wolfe Disk

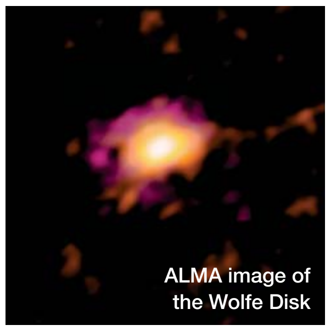
GALAXIES

Astronomers Find Rotating Disk in Early Universe

ASTRONOMERS HAVE DISCOVERED a stably rotating disk galaxy just 1.4 billion years after the Big Bang. It represents the best indicator yet for how galaxies like the Milky Way formed.

In the May 21st *Nature*, Marcel Neeleman (Max Planck Institute for Astronomy, Germany) and colleagues report observations of the galaxy DLA0817g, nicknamed the Wolfe Disk for late astronomer Arthur M. Wolfe. Atacama Large Millimeter/submillimeter Array (ALMA) images reveal details as small as 4,200 light-years across in the galaxy, whose light traveled 12.3 billion years before arriving at Earth.

Combined with Hubble Space Telescope images, the data provide solid evidence that the dust, gas, and stars within the galaxy rotate on a plane.



ALMA image of the Wolfe Disk

The formation of a stable disk in the early universe does away with some early ideas of galaxy formation, which suggested that infalling gas growing an infant galaxy would be too hot to settle into a disk until much later on. Likewise, major mergers between galaxies would toss stars and gas around, creating a writhing mess rather than an orderly disk.

Instead, the Wolfe Disk supports *cold-mode accretion*, in which galaxies grow by feeding on gas flowing in along filaments of the cosmic web (*S&T:* Sept. 2015, p. 16). The study doesn't rule out mergers altogether, though; smaller mergers may have occurred without creating too much of a mess.

The ALMA image shows that within its 14,000-light-year extent, the Wolfe Disk contains the mass of some 72 billion Suns and rotates at about 300 km/s (600,000 mph). When put in comparable terms, this makes the disk half the size of the Milky Way and about 70% its mass, Neeleman says.

The Wolfe Disk isn't the first rotating disk galaxy to be discovered in the universe's early years (*S&T:* Nov. 2015, p. 12; Apr. 2018, p. 12). But this is the first one in which the observations are on a firm enough footing to rein in theoretical scenarios.

■ **MONICA YOUNG**

SOLAR SYSTEM

Jupiter Has Trapped a Comet in a Bizarre Orbit

JUPITER HAS CAPTURED an icy comet from the outer solar system, and its bizarre orbit will — in 2063 — bring it back for a close swing by the giant planet.

NASA's asteroid-hunting ATLAS project in Hawai'i discovered 2019 LD_2 a year ago; further observations revealed it to be a comet (changing its designation to P/2019 LD_2). Then, this past May, multiple teams of astronomers confirmed it as a Jupiter-family comet.

Amateur astronomer Sam Deen was the first to realize the comet's bizarre orbit after using software on the JPL Solar System Dynamics website. He reported his calculations May 21st on the Minor Planet Mailing List (MPML). He found that P/2019 LD_2 had recently had a close encounter with Jupiter that left its orbit unstable. Fellow amateur and MPML member Tony Dunn confirmed this recent change, as did Theodore Kareta (University of Arizona) and colleagues in the May 27th *Research Notes of the AAS*.

The model showed that the comet had likely been a Centaur, part of a family of outer solar system bodies, before it passed about 14 million km from Jupiter on February 17, 2017. The encounter inserted the comet into an orbit 21° ahead of the giant planet. The model predicts the comet will drift no more than 30° ahead before the two begin converging again.

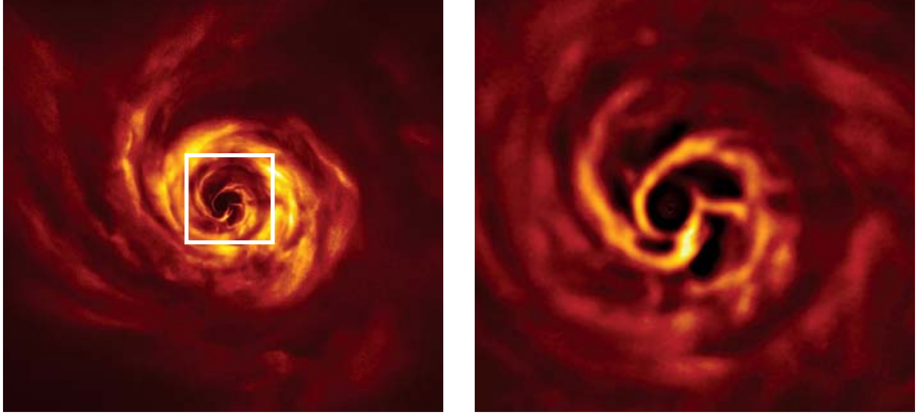
On May 13, 2028, the comet will again pass close by Jupiter, shifting its orbital resonance with the giant planet from 1:1 to 3:2. But the new orbit won't last, either, because it will put P/2019 LD_2 on course for a much closer encounter: In January 2063, the comet will pass only 3 million km from Jupiter, near the orbits of the Galilean satellites — and close enough to cause a major redirection. Where it goes from there is unclear. "It could get tossed almost anywhere," says Bill Gray (Project Pluto).

■ **JEFF HECHT**

EARLY DISK GALAXY ILLUSTRATION: NRAO / AUI / NSF / S. DAGNELLO; ALMA IMAGE: ALMA (ESO / NAOJ / NRAO), M. NEELEMAN / NRAO / AUI / NSF / S. DAGNELLO

EXOPLANETS

Astronomers Snap Baby Planet's Picture



▲ *Left:* In this SPHERE image, AB Aurigae is blocked out at the center, revealing the disk around it. *Right:* Astronomers think a planet is forming in the bright yellow swirl, seen just below the center in this close-up of the system.

ASTRONOMERS HAVE WITNESSED the turbulent swirls of planet formation around the several-million-year-old star AB Aurigae, 530 light-years away in the constellation Auriga, the Charioteer.

Previous observations with the Atacama Large Millimeter/submillimeter Array (ALMA) in Chile had shown spirals within a vast, 120-a.u. gap in the disk of dust and gas surrounding the central star. The gap, and the gaseous spirals within it, had hinted at fast-growing newborn planets, but they didn't provide definitive evidence of their existence.

Now, Anthony Boccaletti (Observatory of Paris) and colleagues have taken closer-in and more sensitive observations using the Spectro-Polarimetric High-contrast Exoplanet Research (SPHERE) instrument on the European Southern Observatory's Very Large Telescope, showing the suspected planet formation in action. The results appear in the May *Astronomy & Astrophysics*.

SPHERE uses a coronagraph and special techniques to negate the light coming from the bright central star, revealing fine detail in the dust-and-gas disk around it. SPHERE's image shows that the spiral arms previously seen by ALMA continue inward toward the star. Nestled within one of these arms is a smear of light — a planet likely several times Jupiter's mass that's coming together within the *S*-shape swirl.

The actual mass depends on how fast the object is growing, though; the forming object might be too massive to be a planet.

Whatever the forming object is, it's at 30 a.u. from its star, putting it at roughly the same distance that Neptune orbits the Sun. Indeed, comparison with the ALMA images from four years ago shows that the smear appeared there, too — and it has since then rotated around its star in a way that's consistent with it being in orbit.

"The twist is expected from some theoretical models of planet formation," explains coauthor Anne Dutrey (Laboratory of Astrophysics of Bordeaux, France). "It corresponds to the connection of two spirals — one winding inwards of the planet's orbit, the other expanding outwards — which join at the planet location."

The researchers say that, because the gap in the disk around AB Aurigae is so vast, there could be more planets, as yet unseen, forming within the cavity.

■ MONICA YOUNG

SPACE BRIEFS

SpaceX Lofts "VisorSat"

SpaceX has revealed details on its plans to darken its Starlink megaconstellation, which will ultimately contain up to 42,000 satellites. The document, posted on the Starlink website, clarifies which parts make the satellites so bright (the solar panels, though shiny, are not the culprit). SpaceX had attempted to darken one of its satellites with a specialized coating on its phased array and parabolic antennas, but it did not reduce the reflections enough. The company is now implementing two different fixes: a software change will dim satellites raising their orbits by turning their solar panels to reflect less sunlight, while additional hardware — a deployable visor — will prevent sunlight from reflecting off other parts of the satellites once they reach their operational altitude. The first "VisorSat" launched on June 3rd.

■ MONICA YOUNG

U.S. Launches Space Crew

On May 30th, a SpaceX Falcon 9 rocket carried the new Crew Dragon capsule on its first crew-carrying flight — and the first launch to come from American soil since the retirement of NASA's Space Shuttle program in 2011. NASA astronauts Robert Behnken and Douglas Hurley, both shuttle veterans, flew to the International Space Station (ISS). The first non-test flight, slated for August 30th, will carry four expedition crew members. NASA has contracted commercial flights with both SpaceX and Boeing, offering them $2.6 billion and $4.2 billion, respectively. Each company is to fly six operational missions to the ISS. SpaceX will carry out its assigned missions through 2021. Boeing launched and landed an uncrewed Starliner capsule in late 2019, but it failed to reach the station. The company plans to carry out a second uncrewed demo flight in the fall.

■ DAVID DICKINSON

The Roman Space Telescope

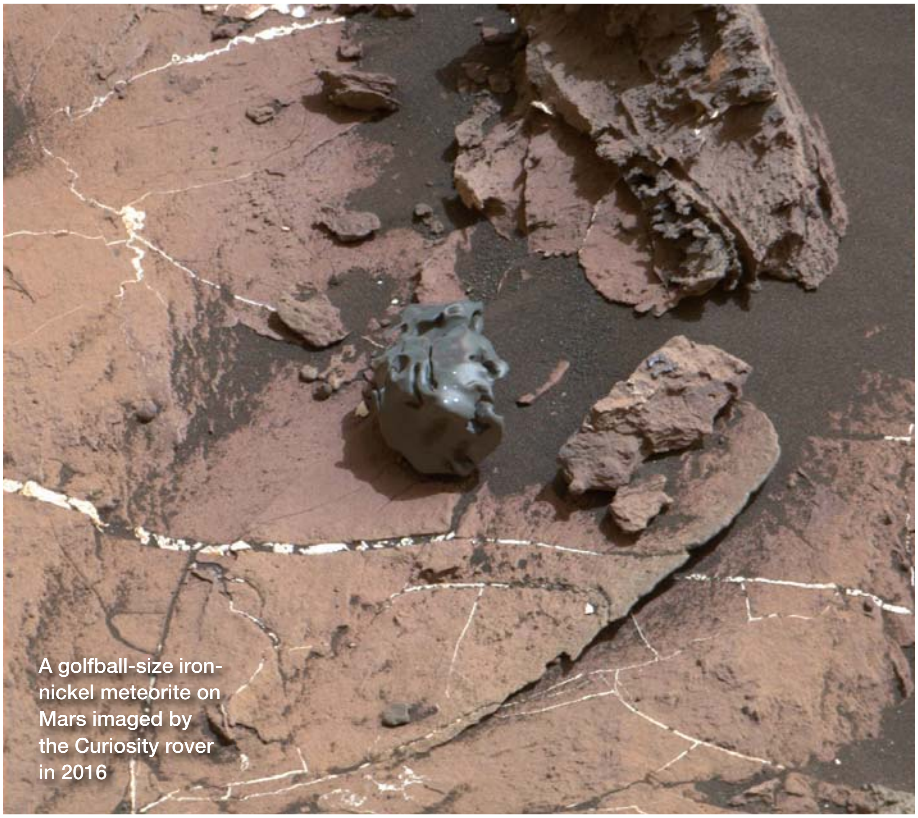
NASA has renamed its Wide Field Infrared Survey Telescope (WFIRST) the Nancy Grace Roman Space Telescope, the first space telescope to honor a woman in the field. Known as the "Mother of Hubble," Roman (1925–2018) was NASA's first chief astronomer. Under her leadership, NASA launched several astronomical observatories. She played a key role in developing the International Ultraviolet Explorer and the Cosmic Background Explorer. Her primary legacy, though, was paving the way for the Hubble Space Telescope. Now, the Roman Space Telescope is set to follow the James Webb Space Telescope into orbit, using infrared light to probe the nature of dark energy as well as hunt for exoplanets. The $3.2 billion mission is currently only funded through September 2020. It is not included in the president's FY2021 budget request, which Congress has not yet approved.

■ DAVID DICKINSON

ESO / BOCCALETTI ET AL. (2)

Not From Around Here

NASA's rovers have found meteorites on Mars that came from elsewhere. What secrets do they hold about Martian history and climate?



A golfball-size iron-nickel meteorite on Mars imaged by the Curiosity rover in 2016

WHEN THE OPPORTUNITY ROVER discovered the first extramartian rock in May 2004, it seemed like such a delightful novelty. To travel all that way from our home planet to explore the Martian hills, dunes, and craters only to stumble upon a rock that is not from that world! What are the chances that among all the places we could have roved we'd roll right up to this interloper on Mars?

The chances are not all that poor, as it turns out. Between Spirit, Opportunity, and Curiosity, we've so far encountered more than 20 of these aliens. How did Opportunity recognize that first outsider? It has the look of many iron meteorites on Earth — shiny, metallic, and eroded with *vesicles*, or pits.

Astute observers noticed that, strangely, these rocks seem to have the same infrared spectrum as the Martian sky. Their shiny, metallic surfaces act as mirrors, reflecting sky light back to rover instruments. Once scientists correctly interpreted this, the spectra became a tool to find more meteorites.

Most meteorites we've spotted on Mars are iron or stony iron. On Earth these make up about 80% of finds but only 6% of witnessed falls, most of which are stony meteorites called chondrites. So far we've found no chondrites on Mars. Therein lies a mystery that we're still trying to work out.

Our rovers have collectively logged only about 95 kilometers (60 miles) on Mars, and we've discovered an average of about one meteorite every 5 km. That would be ridiculous luck on some random drive on Earth, even in deserts akin to the surface of Mars. Has some process concentrated meteorites in the regions the rovers have explored?

Our own planet has places that naturally concentrate meteorites. In Antarctica's Alan Hills, for instance, the flow of ice acts like a conveyer belt, depositing old rocks in a relatively small area. Could something similar have happened where our Mars rovers have made their meteorite sightings?

I asked my colleague Barbara Cohen (NASA Goddard Space Flight Center), who has led the effort to catalog the meteorites seen on the Red Planet. (They're now listed in the official database of meteorites at **lpi.usra.edu/meteor**.) The surfaces where both Spirit and Opportunity roamed are *deflationary*, Cohen told me. "It's similar to the Sahara Desert, where meteorites fall onto sand dunes, then as the dunes blow away you get these lag deposits of meteorites." The dryness preserves them for hundreds of millions of years. To get similar concentrations on Mars, she said, "you have to infer that both things are in effect — there's a way to concentrate them and a way to preserve them."

Could the relative lack of stony meteorites we've found on Mars, at least so far, simply be because irons resist erosion better? Perhaps, but Cohen notes that chondritic meteorites might not stand out as well from Martian rocks and thus might have escaped notice as the rovers passed by. Or maybe Mars, being farther from the Sun and closer to the asteroid belt, receives a different mix of space rocks.

Further examination of these fortuitous finds on Mars has revealed that multiple erosional processes have affected their surface chemistries, including some modification by water. These and other meteorites may therefore become important probes of Martian history, even climate change.

■ Contributing Editor **DAVID GRINSPOON** is a senior scientist at the Planetary Science Institute in Tucson, AZ.

NASA / JPL-CALTECH / MSSS

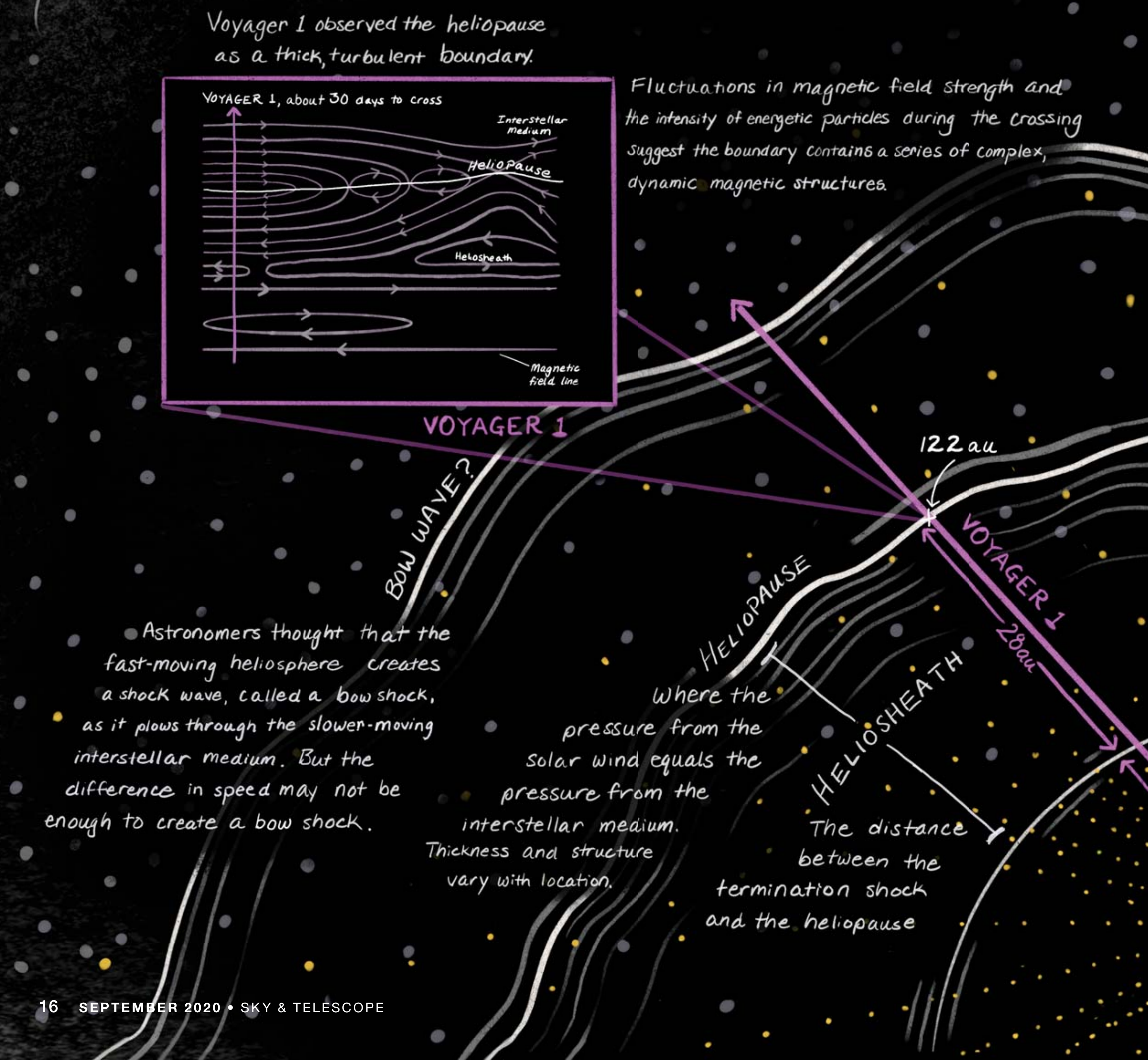
Crossing the Edge of Our Solar System

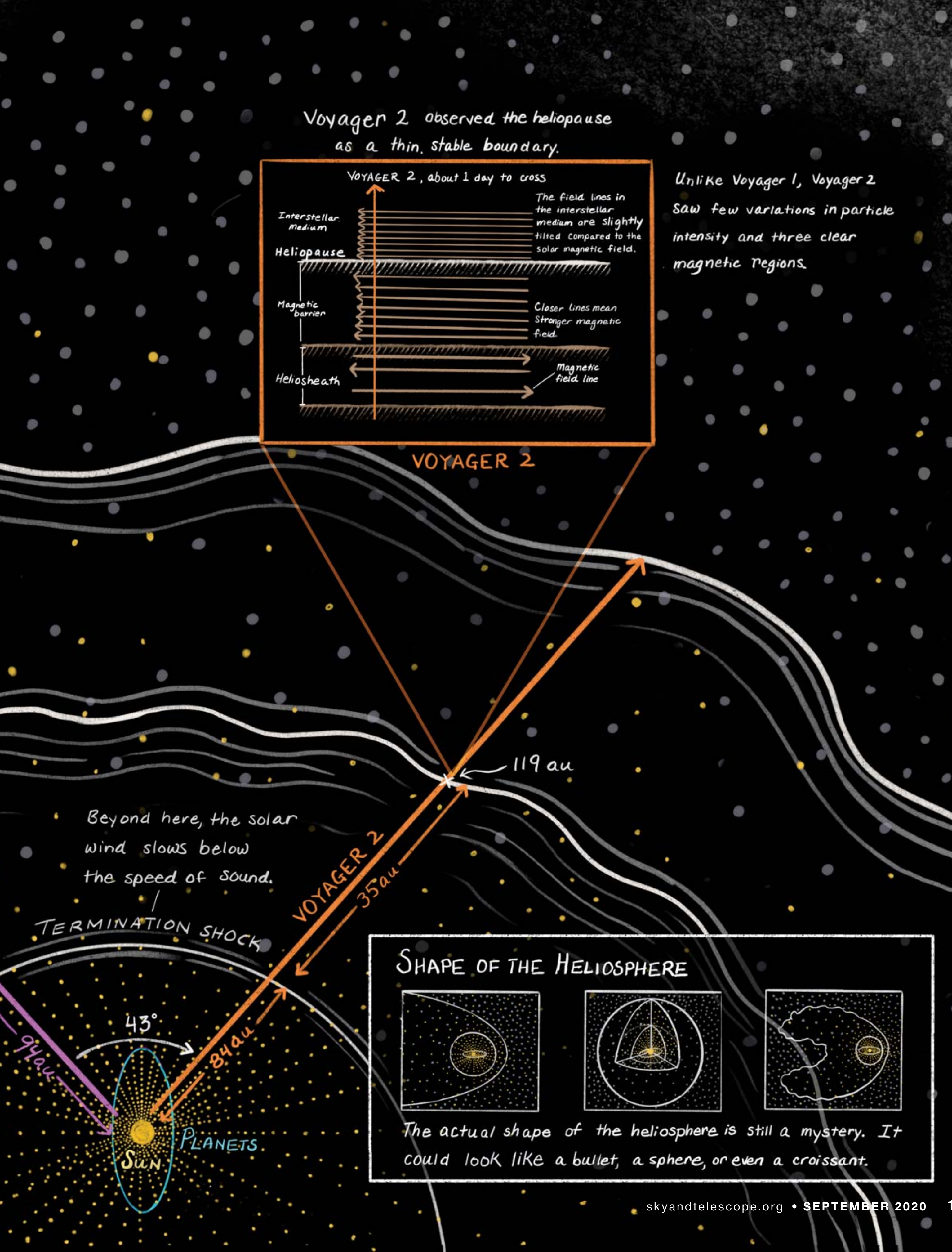
The Voyager 1 and 2 spacecraft have now both left the *heliosphere*, the bubble containing the Sun's magnetic field. Outside lies the interstellar medium, full of particles and magnetic fields from other stars. The edge between these two regions is the *heliopause*.

Many think of the heliopause as a sharp, static boundary. That's not true. Not only do its thickness and structure vary with location, its distance from the Sun changes based on the solar cycle and the solar wind's dynamics.

Voyager 1 crossed the heliopause in 2012 near solar maximum and found a thick, turbulent boundary. Voyager 2, on the other hand, encountered a thin, stable region when it crossed during solar minimum in 2018.

MONICA BOBRA is a solar physicist at Stanford University. NICOLLE R. FULLER at Sayo Studio is a science illustrator whose art invites visual exploration of the science and technology in the world around us.





VOYAGER 1 CROSSING: M. SWISDAK ET AL. / *ASTROPHYSICAL JOURNAL LETTERS* 774:1 (2013)

 by Paul Byrne

The Fate of Volcanic Worlds

Comparing the volcanic histories of the inner solar system worlds tells us how rocky bodies age — and where else we can look for volcanic worlds.

▲ **PLANETARY GOO** Lava flows like this one in Hawai'i appear in many places on Earth, created by our planet's escaping heat. Similar flows have also erupted on all large worlds in the inner solar system.

SARAPORN / SHUTTERSTOCK.COM

The eruption of Eyjafjallajökull in 2010. The explosion of Krakatau that sent pressure waves circling Earth in 1883. Vesuvius's devastation of Pompeii and Herculaneum in 79. Lava flooding 7 million square kilometers in Siberia 250 million years ago, during the largest mass extinction in Earth history.

Volcanic activity has shaped our world's surface for billions of years, defining key moments in Earth's geological history and helping build our atmosphere and oceans via the gases released. But outpourings of gas and melted rock from the interior to the surface are not unique to Earth. We see evidence of such volcanism on all of the large inner solar system worlds — Mercury, Venus, Earth, the Moon, and Mars. For these bodies, volcanism is the consequence of a cooling interior, creating a supply of magma that, one way or the other, makes it to the surface. By comparing the volcanic landforms, processes, and histories of these five bodies, we can get a solid understanding of the volcanic characteristics of rocky planets in general, both within our own solar system and beyond.

Earth, Venus, and Mars

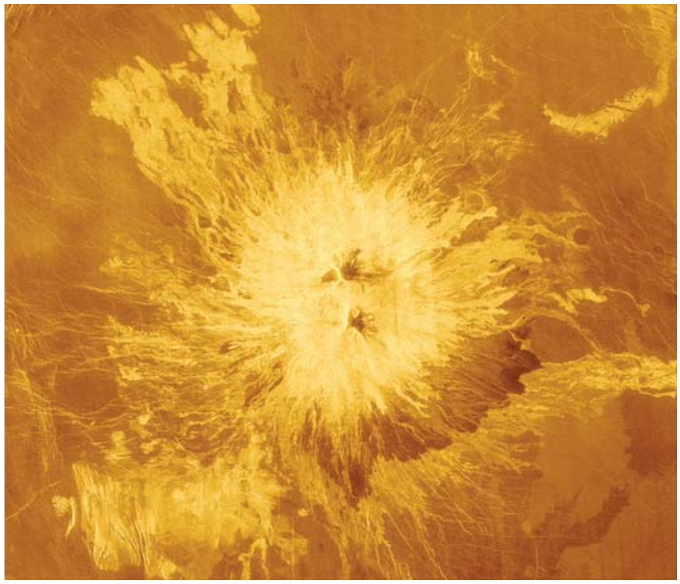
Our planet is a volcanic powerhouse, with more than a dozen effusive and explosive volcanoes active at any given time. Some of the most pronounced manifestations of volcanism on Earth are the giant shield volcanoes that make up ocean islands like Hawai'i, and composite volcanoes such as those in the U.S. Pacific Northwest. But although dramatic videos of explosive eruptions like that from Taal in the Philippines in January 2020 are arresting, by volume the vast majority of lava erupts as slow-moving flows on the ocean floor, where tectonic plates are spreading apart.

Venus and Mars lack evidence for plate tectonics, but they both have no shortage of volcanoes. Thousands of cones dot Venus's surface, and lava flows that look relatively recent gush from gigantic rift zones at low latitudes (*S&T:* Sept. 2018, p. 14). In fact, volcanic plains cover more than 70% of the planet. That Venus hosts only about 950 impact craters suggests that these plains are geologically young: Planetary scientists estimate the average surface age of Venus to be only around 750 million years, if not younger. And findings by the European Space Agency's Venus Express mission give even younger ages for some individual flows, with estimates of 100,000 years or even less debated. Some scientists have suggested that Venus might even have active volcanoes today, but this tantalizing prospect remains tentative.

▶ **EARTH** (*Top*) Klyuchevskaya is the tallest and most active volcano on the Kamchatka Peninsula of eastern Russia. It emitted this small plume on January 10, 2018. The volcano has erupted more than 100 times in the past 3,000 years.

▶ **VENUS** (*Middle*) Overlapping lava flows cover the flanks of Sapas Mons and extend for hundreds of kilometers in this radar image. The summit's two flat-topped mesas appear dark.

▶ **MARS** (*Bottom*) This mosaic shows Olympus Mons, the largest known volcano in the solar system. It is more than twice as tall as Mount Everest.



orlds

The Red Planet is similarly endowed with shield volcanoes and vast lava plains. It has two enormous volcanic provinces, Tharsis and Elysium. It's within Tharsis that the biggest shield volcanoes in the solar system are situated — with the largest of them, Olympus Mons, rising to a summit elevation of almost 22 km (14 miles). Expansive lava plains cover much of the northern third of the planet. Some of these plains formed in the last few hundred million years, but even the very oldest terrains in the south likely also have a volcanic origin. Indeed, Mars's volcanic record suggests a protracted history of eruptions, both effusive and explosive, from almost 4 billion years ago through as recently as the last few million years.

Comparing these three worlds, we find some striking similarities. Volcanic activity has played a major role in shaping their surfaces, has persisted for billions of years, and is widespread. Shield volcanoes and other types of edifices are the rule, not the exception. These planets are clearly variations on the same pattern. But as similar as these three surfaces are, they paint a very different picture than those of Mercury and the Moon, in terms of not only types but also distributions and ages of volcanic landforms.

Exploring the Innermost Planet

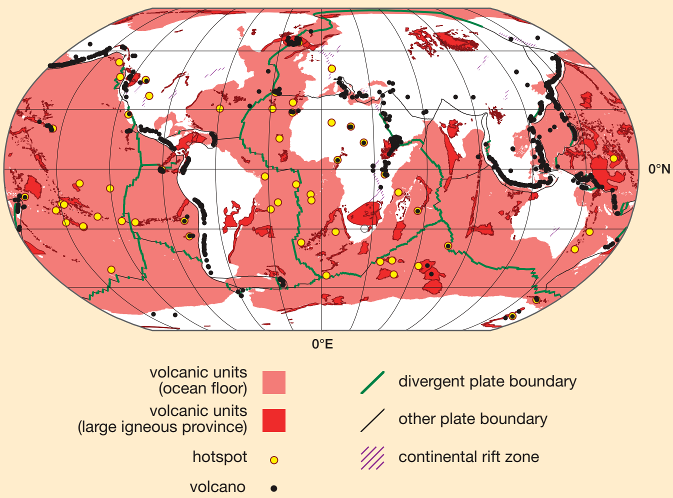
It's hard to explore Mercury. Nestled deep in the Sun's gravity well, and orbiting too close to our star to safely point a telescope at for very long, the innermost planet was the last of the five rocky worlds to be visited with a flyby during the opening act of our exploration of the inner solar system. When NASA's Mariner 10 spacecraft finally flew past Mercury thrice in 1974 and 1975, it returned images of an ancient, impact-scarred, and geologically dormant planet.

Then NASA's Messenger (Mercury Surface, Space Environment, Geochemistry, and Ranging) mission flew past Mercury in 2008 and 2009 before entering orbit in 2011. The craft's observations dramatically improved our understanding of the planet. Chief among Messenger's discoveries was

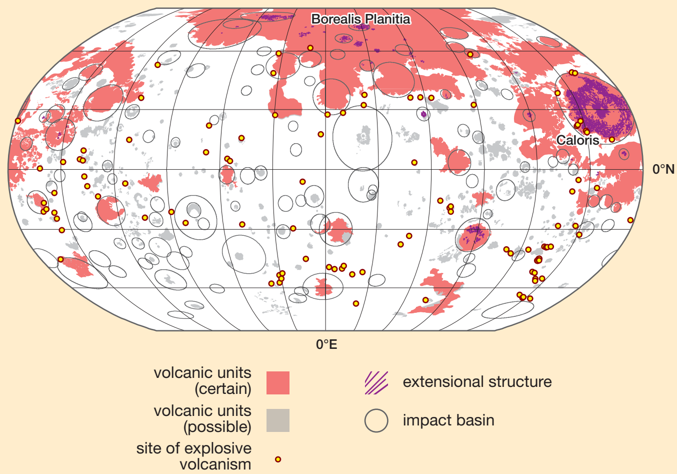
EARTH: JOSHUA STEVENS AND JEFF SCHMALTZ / NASA EARTH OBSERVATORY; VENUS: NASA / JPL; MARS: NASA / JPL / USGS

▼ **GLOBAL MARKS OF VOLCANISM** Each of the inner solar system worlds has its own collection of major volcanic units and landforms. On Mercury and the Moon, these mostly take the form of lava plains created by effusive (not explosive) volcanism. Mars, Venus, and Earth have tall volcanic peaks the smaller worlds lack. *Extensional structures* are things like rifts and troughs. Coronae are circular features potentially created by upwelling magma.

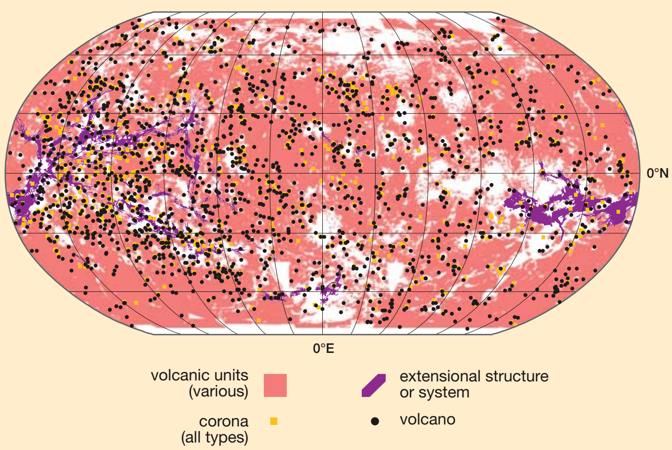
EARTH



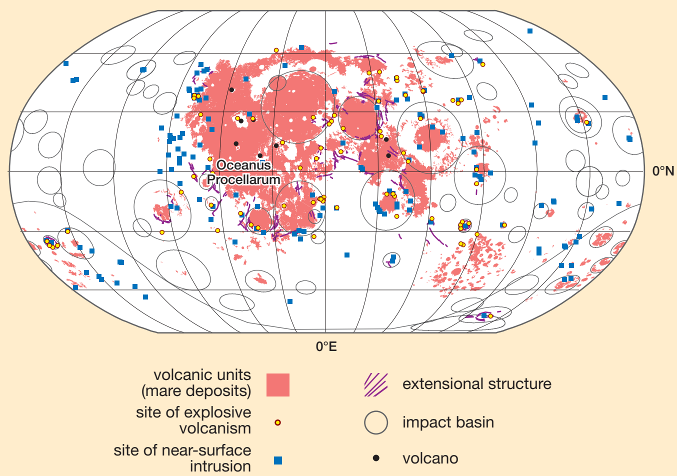
MERCURY



VENUS

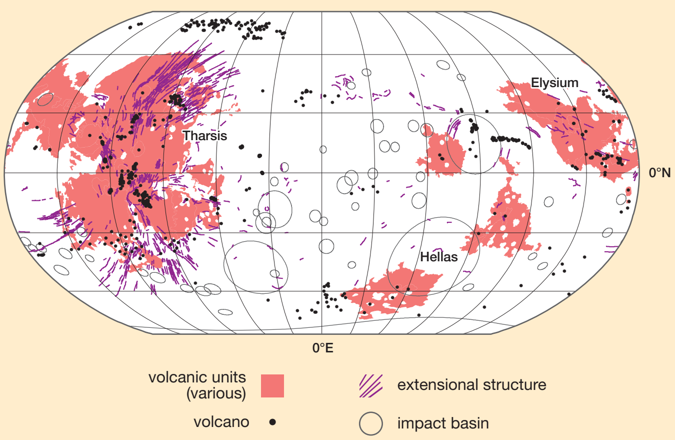


THE MOON

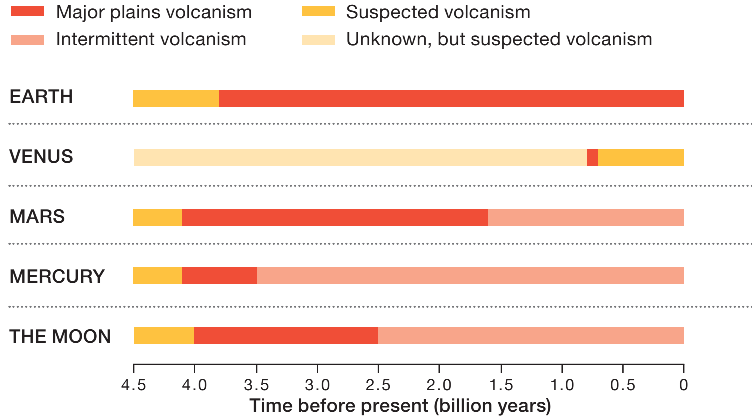


MAPS: THE AUTHOR (5); INFOGRAPHIC: TERRI DUBÉ / S&T; SOURCE: THE AUTHOR

MARS



COOL DOWN Several worlds have largely or entirely shut off their volcanism. The volume of their outer silicate layers may control the timeline.



that the majority of smooth, low-lying plains — distributed widely across the planet, occupying around a quarter of the surface, and often situated within impact basins — consist of lavas that poured across the landscape as quickly moving flows before solidifying.

Messenger also returned images of irregularly shaped pits that look like sites of explosive volcanism, where gas-rich magmas erupted violently instead of as gentle flows. Most such sites sit in impact craters and basins, or along major tectonic structures. But notable by their absence are the large volcanoes that are so widespread on Earth and Venus, and that form the biggest mountains on Mars.

Messenger told us something else intriguing, too: All of the planet's major volcanic units were in place by around 3.5 billion years ago. Although explosive activity and smaller lava flows took place thereafter (some within the last billion years or so), most of Mercury's volcanic history was complete within the first quarter of solar system history.

Messenger revealed that Mercury bears more than a passing resemblance to our Moon, particularly in terms of volcanic characteristics. The Moon also lacks giant volcanic constructs – it has some short peaks and domes, but the few low swells that might be shield volcanoes are so broad they're all but undetectable without high-resolution topography. Like Mercury, the dominant volcanic features of the Moon are the vast basaltic lava plains, the lunar maria. Most of the maria lie in earlier impact basins, just like Mercury's flood plains.

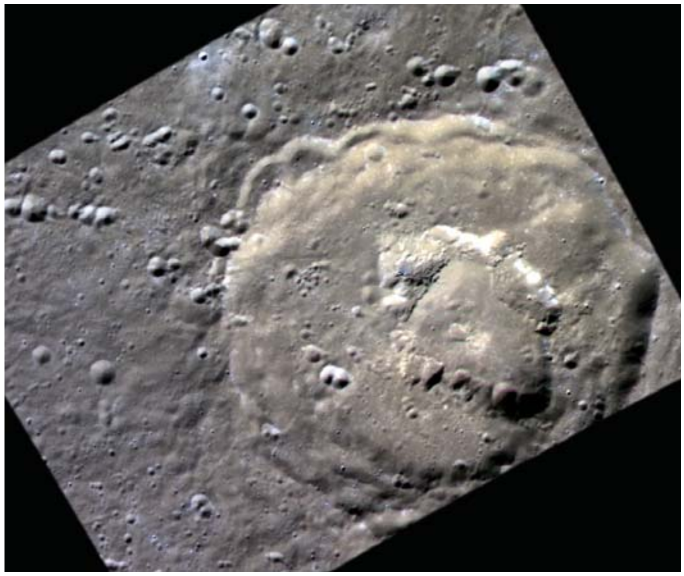
Explosive eruptions also took place on the Moon — but, as for Mercury, most examples are within and around the edges of impact features. And, like Mercury, the majority by volume of the lunar maria had formed by around 3 billion years ago. Younger flows are found mainly in a region called Oceanus Procellarum, where heat-producing radioactive elements are concentrated. Some lavas may be as geologically recent as within the last 100 million years, but these flows are tiny compared to their older counterparts.

VOLCANIC PIT ON MERCURY: NASA / JHU APL / CARNEGIE INSTITUTION OF WASHINGTON; LUNAR VOLCANISM: NASA / GSFC / ARIZONA STATE UNIVERSITY

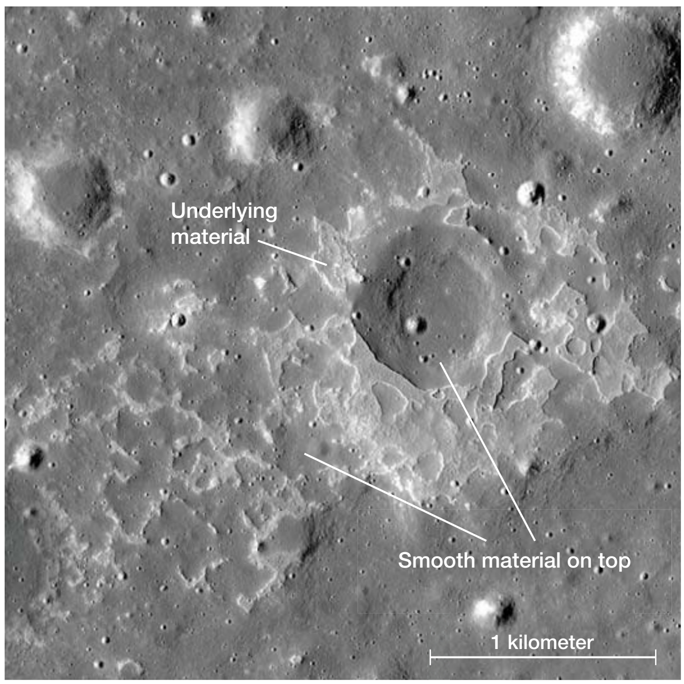
Total planetary volume (10 billion km^3)	Crust and mantle volume (10 billion km^3)	Planetary shrinkage due to interior cooling (km)
108.32	90.67	?
92.85	78.76	?
16.32	13.67	0.2-3.8
6.08	2.60	4.7-7.1
2.20	2.18	at least 0.07

Shrinking Planets

It turns out, then, that Mercury and the Moon are volcanic cousins, if not quite siblings. But when we compare their volcanic characteristics with those of Earth, Venus, and Mars, we can see just how different they are from their larger planetary kin.



▲ **PAST EXPLOSION** The orange tint and irregularly shaped depressions in this enhanced-color image of Mercury's 69-km-wide Navoi Crater suggest explosive volcanism once happened here. Sunlight from bottom.



▲ **LUNAR VOLCANISM** Smooth flows overlie older, lighter surface material in this volcanic deposit near the crater Maskelyne (sunlight is coming from the right). Regions like this one, called *irregular mare patches*, appear to be places where small amounts of basaltic lava erupted to the surface roughly 100 million years ago, long after major volcanic activity ended on the Moon.

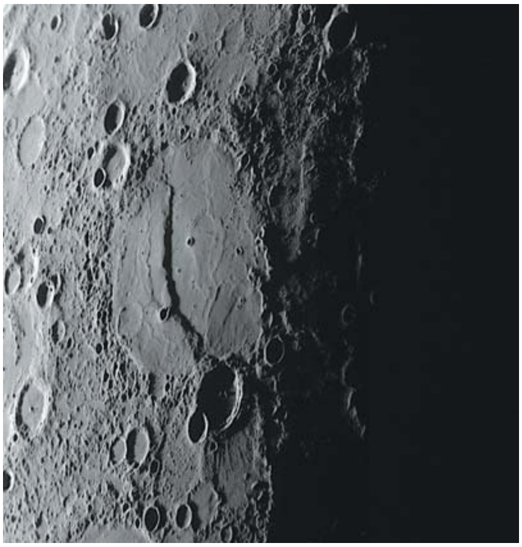
So what might explain these differences? One possibility is a similar phenomenon to why it's easier to take a ring off your finger when your hand is cold than when it's warm: Solid objects tend to shrink as they cool down. In planetary terms, we call this process *global contraction*.

Global contraction is, simply put, a natural consequence of aging. Planets start off hot, due to a combination of the accretion process itself, tidal heating, and the decay of radioactive elements. But over time, that heat is lost, through convection, advection, and conduction — the latter through the solid, outer layer, called the lithosphere. And because the metal and rock components of planetary bodies get smaller as they cool, so too does the overall volume: The body physically shrinks with time. (Icy moons actually get bigger as they cool, but that's another topic — see the August issue, page 32.)

This shrinking makes the planet shrivel like a prune. To accommodate the reduction in volume, the ground breaks, creating long, steep cliffs that develop all over the surface. These scarps are thrust faults, where one block of the crust slides up over another. The discovery of such a set of scarps across Mercury in the 1970s led the Mariner 10 team to suggest that the planet had already cooled and shrunk. Subsequent Messenger data indicated the planet has shrunk up to 7 km in radius (0.3%) over its history. A set of smaller scarps on the Moon tell us a similar story for that body.

The scarps form because the lithosphere is being horizontally compressed. Horizontal compression also makes it difficult for magma to rise to the surface, because the cracks and conduits it would otherwise use to ascend are squeezed shut. And so to erupt, the magma must find places where the lithosphere is weak. Few things weaken a lithosphere more than the terrific forces involved during impact cratering — explaining why most smooth plains on Mercury and the Moon lie within pre-existing impact craters and basins. This is the same reason why most sites of explosive volcanism on these two worlds happened within impact craters or along major faults. And with Messenger data, scientists were able to see that the big thrust faults started to grow on Mercury at around the same time as major volcanic action ended — exactly what's expected when a planet starts to cool, contract, and close off pathways for magma to reach the surface.

There's another notable consequence of global contraction: There is almost no stretching of the lithosphere, only compression. (Think again of that shriveling prune: There's no part of it that stretches to be *wider*.) And so, major extensional tectonic features — troughs, valleys, and rift zones — are virtually absent on Mercury and the Moon. The few that exist are small and localized. This tectonic trait stands in stark contrast to the spreading centers between plates on Earth, or the giant troughs of Mars and immense rift zones of Venus, where major crustal extension can take place even in the absence of plate tectonics. On those planets, magma buildup beneath the surface can force the overlying crust to crack.



SHRINKAGE Lava flows filled this crater on Mercury, creating a smooth surface and submerging a smaller crater that lay inside the large one. Later, the long scarp formed, cracking the smooth plain as the planet shrank. The cliff is about 1 km high.

NASA / JHU APL / CARNEGIE INSTITUTION OF WASHINGTON

It's clear, then, that global contraction provides a ready explanation for not only the volcanic but the tectonic features of Mercury and the Moon. This process hasn't yet affected the three larger inner solar system worlds in the same way — but it will. So what can we say about the life cycle of a volcanic planet in general?

The Slow Death of Volcanic Worlds

The heat of planetary formation can sustain active volcanism for many millions of years, aided by the decay of radioactive elements. The oldest crust identified so far on Mercury is about 4.1 billion years old, implying that any earlier material going back to the planet's birth 400 million years before was resurfaced and buried — most likely by enormous outpourings of effusive lava flows. Very little survives of Earth's earliest crust, too, although what little is available suggests volcanic activity occurred as far back as the geological record goes. The oldest rocks on Mars contain chunks of even more ancient volcanic material, the lunar maria were erupting at least four billion years ago, and we can safely presume that Venus had a volcanic past that mirrors that of Earth.

But the ultimate fate of a volcanic world is to cool. And with that cooling, even if it takes place over billions of years, comes global contraction. The rate of *magma* production decreases — already, Earth is likely far less volcanically active than it was in the distant past, because only a third as much heat flows from the planet's interior today as did several billion years ago. But any melt present or formed towards the end of a planet's magma production will have an increasingly hard time reaching the surface as the lithosphere becomes ever more compressed. Eventually, volcanic activity is restricted to where the outer layer is weak — impact craters and basins, and major thrust faults — and the only kind of faulting that occurs is compressive.

This restriction has already taken place on Mercury and the Moon, which are smaller and, with much larger ratios of surface area to volume, have cooled off faster. But it stands to reason that, one day, global contraction will take hold on

Mars, Venus, and our own world as well. Where will the last vestiges of volcanism happen on Earth as the lithosphere squeezes shut? Perhaps at the oceanic spreading centers, or major continental rifts like that in East Africa. We won't be around to see it, but one day, even if melting continues in the interior, all of Earth's volcanic activity will come to an end — that is, if the Sun doesn't enter its red giant phase and consume the planet first.

Volcanic Exoplanets

The reason all this matters isn't just to understand why the worlds of the inner solar system look the way they do. By studying our volcanic neighbors, we'll be better placed to say something about where we might find evidence for volcanic activity in other planetary systems.

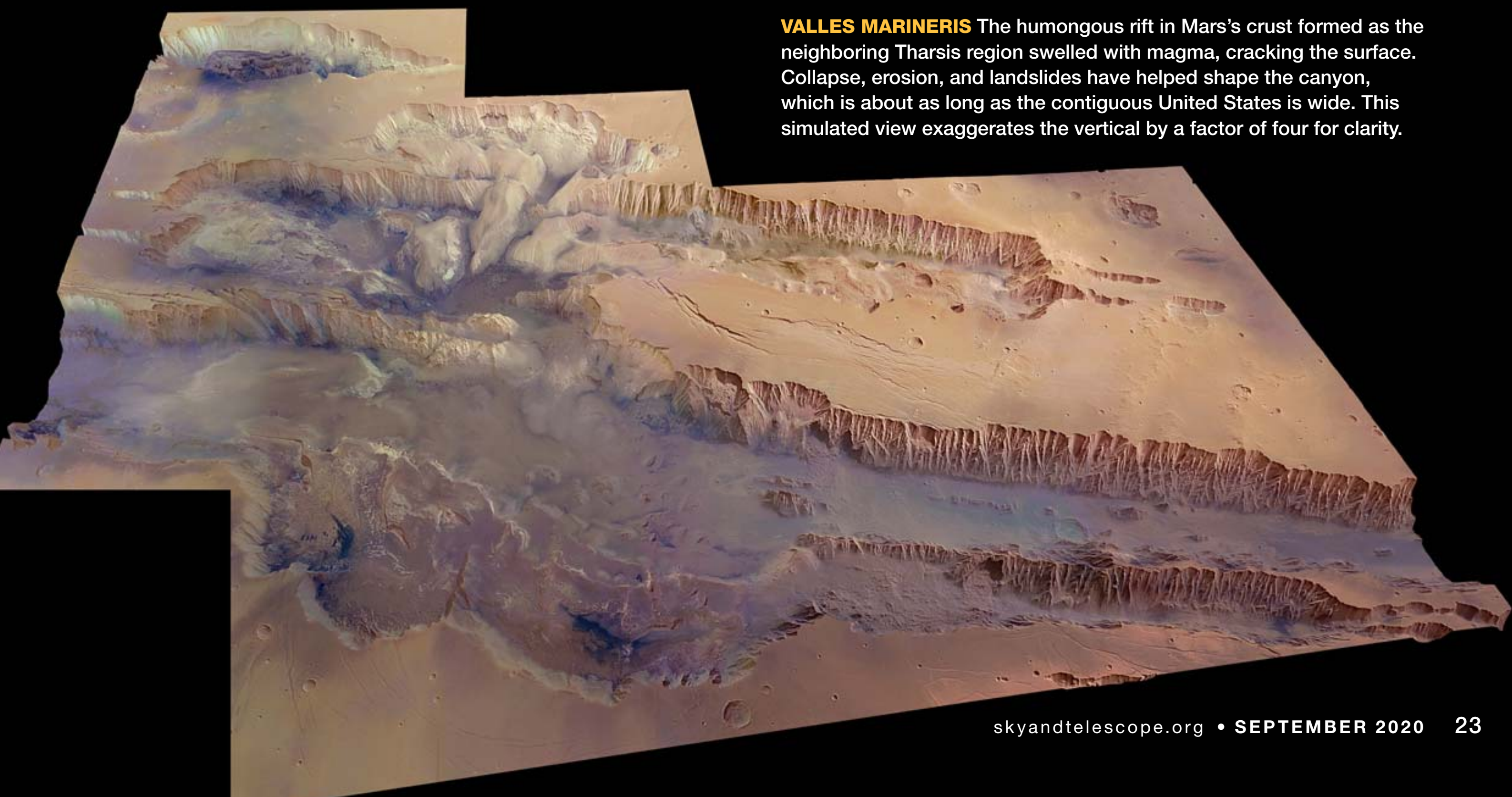
For example, multi-billion-year volcanic activity in the solar system seems to require a size somewhere between Mercury and Mars. If this is true for other planetary systems, then we should expect to find ongoing, radioactive decay–powered volcanism on small worlds only if they orbit young stars. Around older stars, we should focus on larger, Earth- and Venus-size planets.

Physical size isn't everything, though: Mercury is almost three times bigger than the Moon, but both worlds share a similar volcanic history. Yet the volume of Mercury's mantle, where most heat-producing elements reside, is about the same as that of the Moon. So mantle size, rather than planetary size, might be the better indicator of volcanic longevity.

We're still some way from definitively finding extrasolar volcanism. At present, we detect most exoplanets with the radial velocity and transit photometry methods. With the first approach, astronomers scrutinize subtle changes in a star's emitted light for evidence of an orbiting companion, whereas the second method involves looking for dips in a star's brightness as a planet passes in front of it. But only transit photometry affords scientists the chance to measure properties of an exoplanet's atmosphere, where we can look for chemical changes indicative of volcanic activity. In the future, telescopes may be capable of resolving actual topography — like that associated with the giant shield volcanoes of Mars — or even image those surfaces directly in search of plumes of heat that would attest to active eruptions. But we'll likely have to wait decades for that.

For now, we have plenty more work to do here. Were ancient lavas on the inner solar system worlds made of exotic materials, as suggested by billions-year-old rocks on Earth and compositional data returned by Messenger for Mercury? What geological history lies buried beneath those young lava plains on Venus? How exactly did Mars's oldest crust form? The most effective way to answer these and other questions is by comparing and contrasting the volcanic characteristics of the inner solar system worlds. By doing so, we will continue to gain new insights into the rules that govern volcanism in general — and, perhaps, a better understanding of the volcanic past, and eventual future, of our own home.

PAUL BYRNE is an associate professor of planetary science at North Carolina State University. Obsessed with space since before he could spell "space," he's endlessly driven to understand why planets look the way they do.



VALLES MARINERIS The humongous rift in Mars's crust formed as the neighboring Tharsis region swelled with magma, cracking the surface. Collapse, erosion, and landslides have helped shape the canyon, which is about as long as the contiguous United States is wide. This simulated view exaggerates the vertical by a factor of four for clarity.

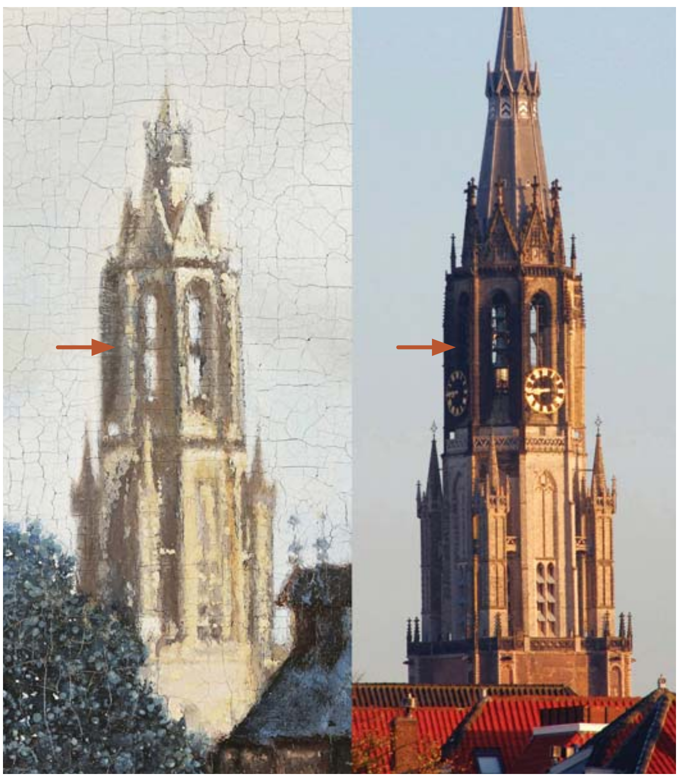
by Donald W. Olson, Russell L. Doescher, Charles A. Condos, Michael A. Sánchez, and Tim Jenison

Johannes Vermeer (1632–1675) and Rembrandt van Rijn (1606–1669) rank as two of the most celebrated and significant artists from the period known as the Dutch Golden Age. Both are especially renowned for technical mastery in rendering the effects of light and shadow. Although Rembrandt produced hundreds of paintings, etchings, and drawings, art historians have identified only about three dozen paintings by Vermeer's hand. Vermeer's most widely recognized work is the enigmatic and enchanting canvas titled *Girl with a Pearl Earring*, which inspired a best-selling novel in 1999 and a 2003 motion picture starring Colin Firth and Scarlet Johansson.

Authorities in the past, however, considered Vermeer's *View of Delft* as his greatest masterpiece. The dark town wall and entrance gates make a dramatic contrast with brilliant sunlight that illuminates Delft's tiled roofs and the tower of the Nieuwe Kerk (New Church).

In 1696, *View of Delft* fetched the highest price at an auction that included 21 of Vermeer's works. The Dutch

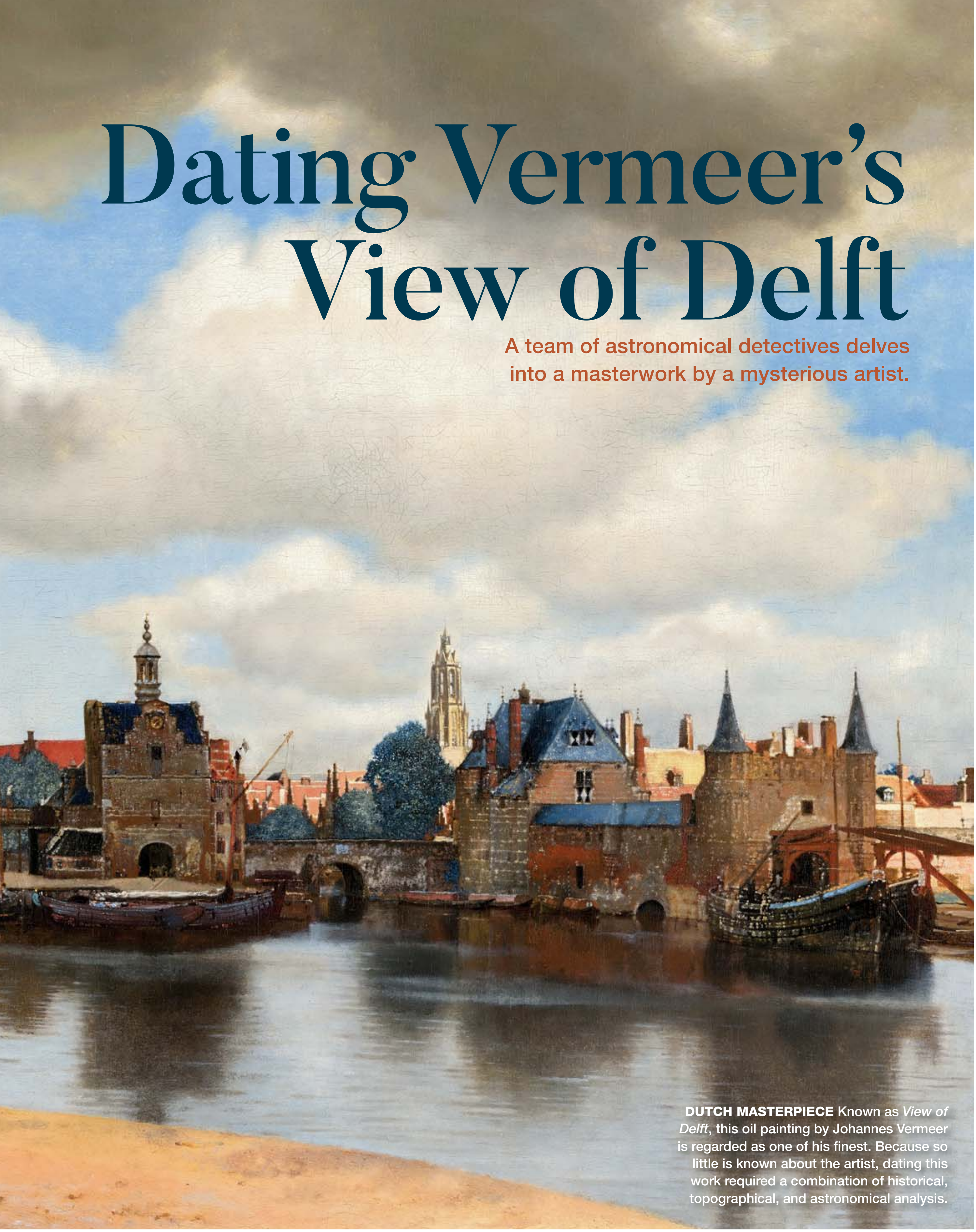
▼ **A BRIEF MOMENT OF LIGHTING** Vermeer's depiction of light and shadow on the stone octagon of the Nieuwe Kerk tower matches the photograph (righthand image, below) taken when the Sun's azimuth was near 110° on October 16, 2019. The narrow, illuminated vertical column is an especially sensitive indicator of the Sun's position, as it appears for only a few minutes as the Sun moves across the sky. The tall vertical openings of the octagon are now partially blocked by the bells of the carillon installed in 1660 and the modern clock faces. At the top, the short wooden spire of the 17th century burned after a lightning strike in 1872 and was replaced by the taller spire seen today.



COMPARISON: PAINTING: MAURITSHUIS, THE HAGUE;
PHOTO: RUSSELL DOESCHER; VIEW OF DELFT: MAURITSHUIS, THE HAGUE

Dating Vermeer's View of Delft

A team of astronomical detectives delves into a masterwork by a mysterious artist.



DUTCH MASTERPIECE Known as *View of Delft*, this oil painting by Johannes Vermeer is regarded as one of his finest. Because so little is known about the artist, dating this work required a combination of historical, topographical, and astronomical analysis.

Royal Cabinet of Paintings acquired *View of Delft* for the Mauritshuis museum in The Hague at an auction in 1822, when the catalog described it as "the most important and most celebrated picture by this master." Vincent van Gogh visited the museum and remarked, in an 1885 letter to his brother, that "the town view in The Hague is incredible." In 1921 the French novelist Marcel Proust went so far as to say: "Ever since I saw the *View of Delft* in the museum in The Hague, I have known that I had seen the most beautiful painting in the world." As recently as 1995 Arthur Wheelock, Jr., a Vermeer expert at the National Gallery in Washington, DC, described *View of Delft* as "extraordinary" and rated it "Vermeer's most famous painting."

Art historians have long noted that almost no biographical information about Vermeer's life survives and that there is extraordinarily little evidence for dating his works. We observed that in *View of Delft*, shadows extend from right to left and wondered if astronomical analysis could help determine the time of day and the date for this remarkable Vermeer masterpiece.

Fixing the Season and Time of Day

In an essay posted on his Vermeer website, art historian Kees Kaldenbach used the appearance of the trees and boats to claim a precise dating to the "first half of the month of May," but he eventually amended this result to a date "some weeks later." The author Ton den Boon, in his 2009 book *Johannes Vermeer: The Delft Master of Light*, agreed that the painting depicted "late spring or early summer," and other commentators have made similar assertions.

Unlike the consensus regarding the season, the existing literature offers a wide variety of suggestions for the time of day depicted in *View of Delft*. In his pioneering 1833 *Catalogue Raisonné*, John Smith wrote that this Vermeer canvas showed "a view of the town of Delft, at sunset." Art historian Alan Chong, in his 1992 monograph, *Johannes Vermeer*, claimed that "most light comes from the right, the west, which could be any time in the afternoon." Dutch scholar P. T. A. Swillens, in his 1950 book *Johannes Vermeer: Painter of Delft, 1632-1675*, instead judged that the "artist espied his subject when the sun stood high in the heavens at midday." Vermeer expert Walter Liedtke, in his 2000 book A *View of Delft*, agreed that "the sun is high behind the viewer, which it usually is in the middle hours of the day."

We disagree with those assessments regarding compass direction and time of day and instead reached conclusions similar to those of author Anthony Bailey in *Vermeer: A View of Delft* from 2001. By studying maps of Delft, Bailey showed that Vermeer was looking generally to the north and concluded that the corresponding time must be "morning, with the sun striking the buildings from the south east."

We aimed to improve the precision of Bailey's conclusion regarding the Sun's position.

Nieuwe Kerk's Octagon

Our method was to analyze the distinctive pattern of light and shadow on the octagonal shape of the Nieuwe Kerk tower. According to maps and Google Earth's ruler tool, the main axis of the church points toward an azimuth of 58° (that is, 32° north of east). With the orientation of one face known, simple geometry then determines the orientation of all eight faces of the octagon. As a preliminary result, we estimated that the azimuth of the Sun had to be somewhat greater than 103° (or slightly more than 13° south of east) to illuminate the octagon's faces as seen in *View of Delft*.

Our analysis assumes that Vermeer accurately depicted the Nieuwe Kerk. The existing literature asserts just the opposite, however, with most authors arguing that the Nieuwe Kerk in the painting is significantly altered and distorted.

The primary source for this claim is an article co-authored for the journal *Artibus et Historiae* in 1982 by Arthur Wheelock, Jr., and Kees Kaldenbach. They offered very specific details: "Compared to the total width of the *View of Delft*. . . the tower (c. 61-62mm) occupies about 1/19th part of the width. Compared to present-day photographs taken from near Vermeer's point of view, Vermeer's tower is two times too wide."

Many subsequent writers repeated uncritically this conclusion about the inaccuracy of Vermeer's painting. For example, in his 2017 book *Vermeer in Detail*, Gary Schwartz stated: "For all its apparent truth to life, the *View of Delft* takes some interesting liberties with the situation depicted . . .

▼ **FAMOUS FACE** Thanks to a 1999 novel and the popular 2003 movie of the same name, *Girl with a Pearl Earring* is one of Vermeer's best-known works. Although radically different in subject matter, *Girl* shares the same masterful understanding of light and color exhibited in *View of Delft*.

MAURITSHUIS, THE HAGUE

the famous tower of the Nieuwe Kerk is aggrandized, with a width twice as large as it would have appeared."

If these assertions were true, then our calculations would be suspect. But we can show that Wheelock and Kaldenbach made a serious mistake of measurement, calculation, or transcription and that their numbers for the tower's width are greatly in error, by about a factor of two.

Seeking Ground Truth

Two of us (Olson and Doescher) from Texas State University traveled to Delft and The Hague in the autumn of 2019, and another of us (Jenison) made several trips to the Netherlands in the past ten years. We were able to make accurate measurements at the Mauritshuis museum. On the framed canvas, the width of the Nieuwe Kerk tower at the octagon's upper level with the tall vertical opening is actually 23 millimeters, corresponding to $1/50$ of the painting's total 1,157-mm horizontal width. The lower level of the tower is 32 mm wide on the painting, that is, $1/36$ of the total width.

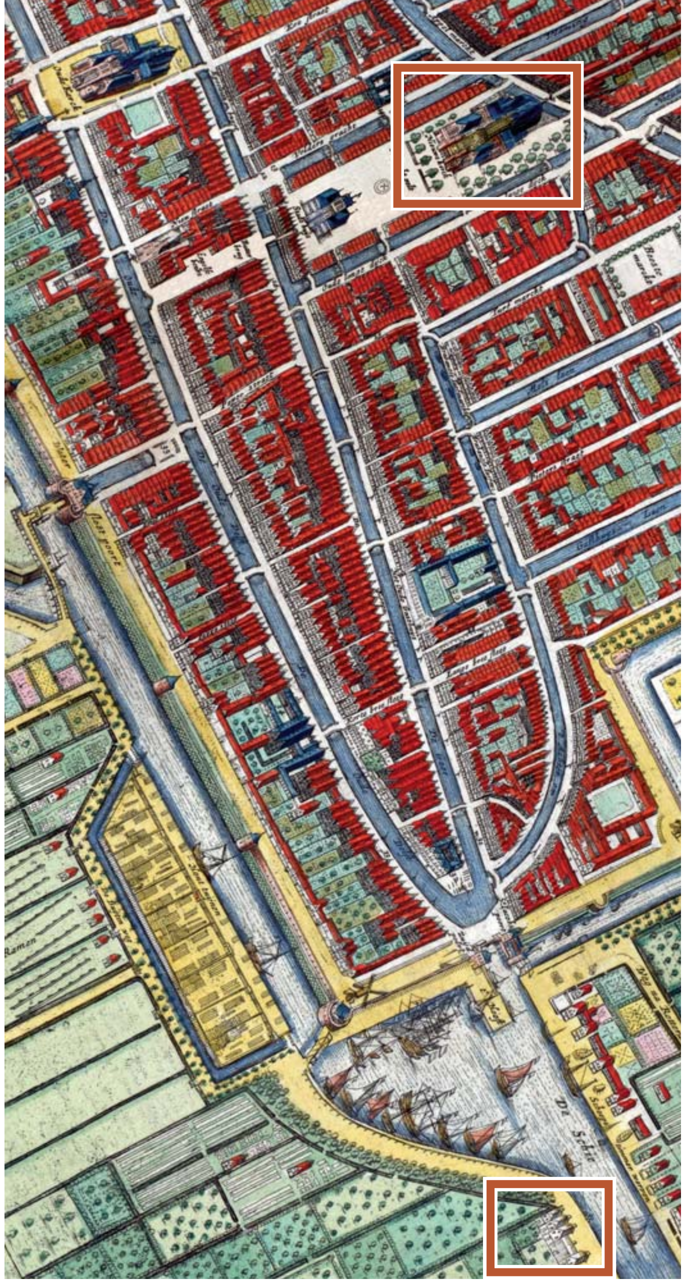
In Delft, our topographical survey established that the painting's field of view is 42° wide. At the Nieuwe Kerk we used measuring tapes to determine the tower's width at various levels. We calculated that the projected angular width of the tower as seen from Vermeer's location would be about 0.85° and 1.2° at the upper and lower levels, respectively, in good agreement with the ratios that we measured on the painting.

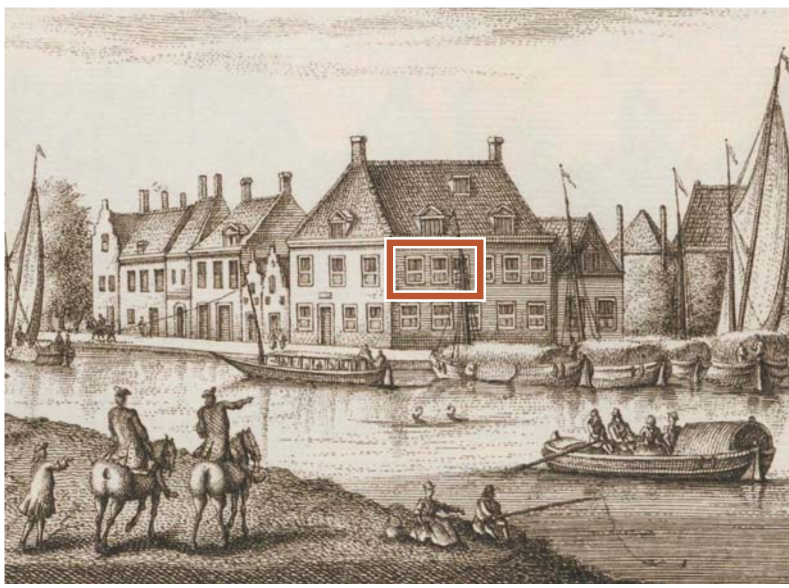
High-resolution digital images of *View of Delft* are readily available online. Without making a trip to The Hague, readers can use image editing software to verify that the tower's width ranges between $1/50$ and $1/36$ of the painting's total width.

Despite the many contrary statements in the existing literature, we can be certain that Vermeer accurately depicted the width and proportions of the Nieuwe Kerk tower. This gave us confidence that our azimuth calculations for the Sun's position were indeed valid.

As shown on map detail at right, Vermeer's location for *View of Delft* was just south of a triangular harbor known as the Kolk (the Pond). By aligning architectural features on a combination of 17th-century maps and prints, 19th-century maps, and Google Earth imagery, we were able to identify the artist's viewpoint as a window on the upper floor of an inn.

Unfortunately, the inn burned down in 1879, but from nearby locations we were able to take photographs over sev-





▶ **VERMEER'S DELFT** (*Top*) This detail from the 1649 Delft map by Johannes Blaeu has been rotated so that north is up. Vermeer's viewpoint (indicated near the bottom) was just south of the triangular harbor known as the Kolk. His line of sight was generally north, looking over the town's wall, entrance gates, and roofs, toward the tower of the Nieuwe Kerk (indicated near the top of the map).

▶ **VERMEER'S VIEWPOINT** (*Bottom*) The artist's location for *View of Delft* was one of the windows (indicated) on the upper floor of an inn, seen in this print from 1736. Wim Weve, the leading authority on early Delft architecture, established that this inn existed by 1632 and burned down in 1879.

MAP OF DELFT: LIBRARY OF CONGRESS; VERMEER'S LOCATION: COLLECTION OF DONALD OLSON eral weeks during the autumn of 2019. The shadows on the Nieuwe Kerk in our photos matched those in Vermeer's painting only when the Sun's azimuth was near 110°.

◀ **CARILLON** Vermeer's *View of Delft* shows an empty bell tower at the octagon level of the Nieuwe Kerk and therefore dates from before the installation of the carillon and clock faces seen in this detail from a 1667 print by Coenraet Decker, with the view looking northeast from Delft's marketplace. François Hemony began installing the carillon in the tower during the spring of 1660. The column of four large bells on the right side of this view would have been visible from Vermeer's location south of the church.

A Curious Clock and Missing Bells

A close look at *View of Delft* reveals another remarkable clue. The façade of the building known as the Schiedam Gate includes a clock! However, a blob of paint on the lower left of the clock face makes it difficult to read the exact time. We surveyed the existing literature and found that previous Vermeer scholars have interpreted the indicated time in a variety of ways: "a time between seven and half past seven," "just past 7 o'clock," "ten past seven," "exactly 7:12," and "about 7:15 to 7:30 A.M."

Some of these authors, especially those offering precise times, appear to make the incorrect assumption that the Schiedam Gate clock possessed both an hour and a minute hand. However, minute hands were not employed on tower clocks until the late 19th century. Tower clocks in the 17th century always had only a single hour hand, according to independent studies by G. Roosegaarde Bisschop, Laura Meilink-Hoedemaker, and Wim Weve, three experts on Dutch architecture. Many prints of Delft from the 17th and 18th centuries include the Schiedam Gate and its clock, always with a single, long hour hand. The front half of the hand points to the time, while the back half acts as a counterweight.

▼ **NAME THE HOUR** This detail, from just left of center in *View of Delft*, shows the Schiedam Gate clock. A globule of paint at the lower left of the clock face makes the displayed time difficult to read. Tower clocks in the 17th century had only a single long hour hand, with the front half pointing to the time and the back half acting as a counterweight. The hand's straight line, extending here from upper right to lower left, appears to indicate a time near 8:00 a.m.

In our analysis of Vermeer's painting we noted that the clock's hand extends on the clock face from upper right to lower left, suggesting that the time depicted is near 8:00 a.m. The alternate interpretation, of 2:00 p.m., is ruled out because the sunlight is coming from the south-east, indicating a morning clock time.

Today, four sides of the Nieuwe Kerk octagon feature clock faces, and three sides host the bells of a carillon. These bells offer another important clue. According to essays about the Delft carillon by Laura Meilink-Hoedemaker on her website, and by Adelheid Rech on the Essential Vermeer website, the Dutch foundry of François Hemony cast the carillon bells in 1659 and 1660. Hemony installed 20 bells beginning in April and May 1660, followed by 10 bells in July 1660, and the last three bells in August and September 1660.

As art historians have noted, Vermeer's painting shows no bells in the octagon. The canvas therefore must depict the situation before the installation of the carillon in 1660.

An April or September Sun?

We calculated the Sun's position in the sky of Delft at 8:00 a.m. on each day for 1659, with dates in the Gregorian calendar system, which South Holland adopted in 1583. Because modern time zones did not exist in the 17th century, we calculated the position of the solar disk on each day at 7:43 UT, equivalent to 8:00 a.m. local mean time in Delft. The requirement that the Sun's azimuth must be near 110° to produce the shadows depicted on the Nieuwe Kerk tower was met on only two dates: April 6th and September 3rd. We also did the same calculations for 8:00 a.m. apparent solar time (the time on sundials, which were possibly used to set the mechanical clocks), with the corresponding dates shifting slightly to April 8th and September 4th. These April dates can be ruled out as being too early in the year, because the painting depicts abundant leaves on the trees, something that does not occur until late April or May at this latitude. That means September 3rd or 4th are the likeliest dates.

This September result conflicts with the previous consensus that *View of Delft* depicts the scene in the late spring or early summer, not far from the summer solstice. However, the Sun then rises in the northeast, which means the octagon face painted by Vermeer would be backlit and completely in shadow — not a match for the painting.

Standing at the Artist's Side

If Vermeer intended to portray a morning scene consistent with the time shown by the clock in the painting, then the combined evidence — the hour hand of the Schiedam Gate clock, the empty bell tower, and the Sun's position in the sky — indicates that the painting dates from 1659 or an earlier year and matches the view that the artist could have observed from his window at the inn at 8:00 a.m. on a date near September 3.

Vermeer is known to have worked slowly and completing all the details on the large canvas of his masterpiece may have taken weeks, months, or even years. His remarkably accurate depiction of the distinctive and fleeting pattern of light and shadows on the Nieuwe Kerk suggests that at least this detail was inspired by direct observation of the sunlit tower rising above the wall and roofs of Delft.

DON OLSON and **RUSSELL DOESCHER** both recently retired from teaching physics and astronomy at Texas State University, where **CHARLES CONDOS** and **MICHAEL SÁNCHEZ** received B.S. degrees in physics. **TIM JENISON**'s analysis of optics and 17th-century art was featured in the 2013 film *Tim's Vermeer*. The authors received research assistance from Daniel Barringer at Texas State University, Hans Mooij of the Technische Universiteit Delft, and Margaret Vaverek of Texas State University's Alkek Library.

FURTHER READING:

- Google Arts & Culture "Meet Vermeer" website: **artsandculture.google.com/project/vermeer**
- A zoomable image is presented here: **https://is.gd/ViewofDelftzoom**
- Mauritshuis museum's downloadable high-resolution image: **https://is.gd/MauritshuisViewofDelft**
- "Essential Vermeer" website: **essentialvermeer.com**

THE VIEW TODAY This photograph shows the scene depicted in *View of Delft* as it appeared on the morning of October 10, 2019, from a window 90 feet above the water level. The inn with Vermeer's viewpoint stood closer to the shore below.

DON OLSON

Visiting Delft

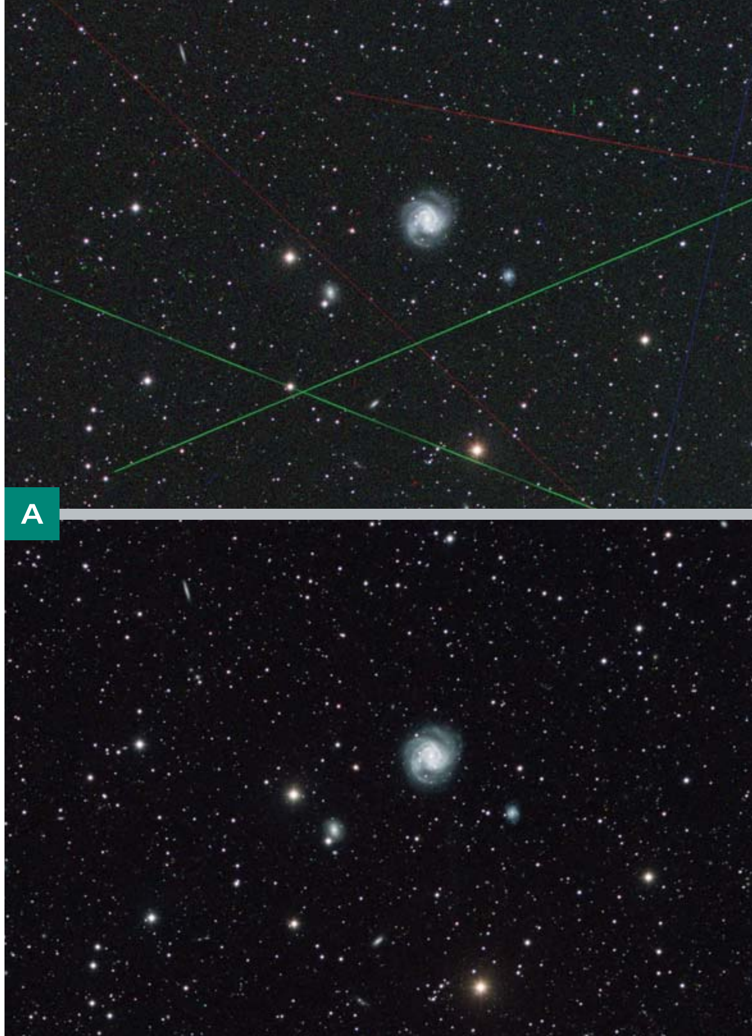
Readers who wish to see Delft and the Nieuwe Kerk illuminated as they are shown in Vermeer's painting should position themselves on the south side of the Kolk at the appropriate time. But what modern dates and times are best? Local mean time, as used in the past at the longitude of Delft (4°22′ East), was 17 minutes ahead of UT. The Netherlands today uses the European time zone and daylight-saving time, with clocks set 2 hours ahead of UT in summer and early fall. Therefore, the correct time to look is around 9:40 a.m. during the first half of September, 9:15 a.m. in the second half of September, and 8:50 a.m. in the first half of October.

The Pros and Cons of Image Stacking

This method is all about improving signal and reducing noise, though you need to know when to apply it.

For roughly a century, photographing deep-sky objects was a relatively straightforward endeavor. You'd load your camera with film, aim your telescope at a chosen target, open your shutter, and keep a guide star on the cross-hairs of a guiding eyepiece. When the exposure was deemed long enough, you'd close the shutter and move on to another target. Later you'd develop your film, print your favorite shot, and that was it. Photographing the Sun, Moon, and planets was a similar exercise, though the exposures were considerably shorter.

But with the advent of desktop computers and digital detectors in the late 20th century, new techniques arrived that greatly expanded astrophotographers' abilities to extract more and fainter detail from their deep-sky images. One technique that has become ubiquitous in today's processing arsenal is image stacking.



A

The Power of Image Stacking

The term "image stacking" is self-explanatory: Combine multiple images of a single object to get a better result. Rather than take a single, long exposure of your chosen target, you capture many short ones and then combine the results with post-processing software. Stacking originated in the darkrooms of professional astronomers, though it required a complex and difficult technique, which limited its migration into the amateur community. That changed when home computers and astronomical image-processing software became widely available.

The sensitivity of CCD (and now CMOS) cameras, combined with the impressive processing power of home computers, means that an astrophotographer today can combine many short exposures to achieve results similar to a single, long exposure. This was a game-changer. For one, we no longer needed lengthy, uninterrupted intervals of painstaking guiding that could be ruined if a tripod was bumped or an airplane crossed the field of view. If you shoot, say, a dozen 5-minute exposures with the intention of stacking them into the equivalent of a 1-hour exposure, you can simply discard any spoiled frames without significantly affecting the end result.

There are multiple benefits to image stacking besides mitigating the damage that a passing airplane or satellite might cause. Stacking also permits you to capture great photos by working within the capabilities of your equipment.

Imagers often limit the length of their individual exposures to the time that their telescope mount can accurately track without requiring corrections. This often means a series of 3- to 5-minute exposures, depending on the tracking accuracy of their mounts. Many commercial mounts use

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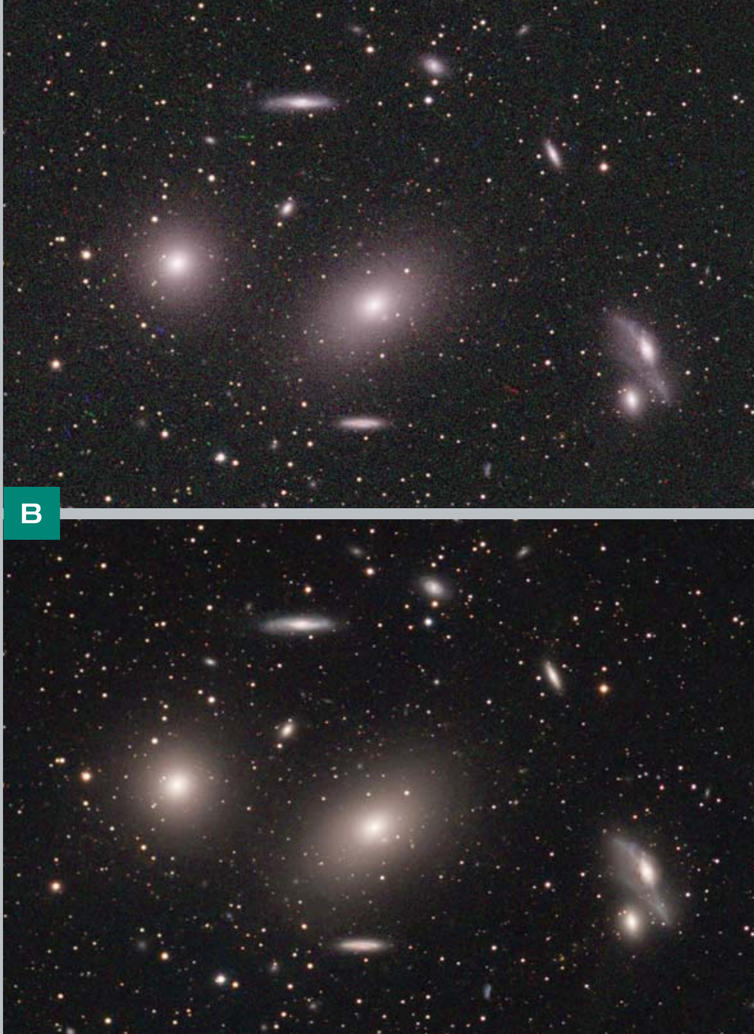
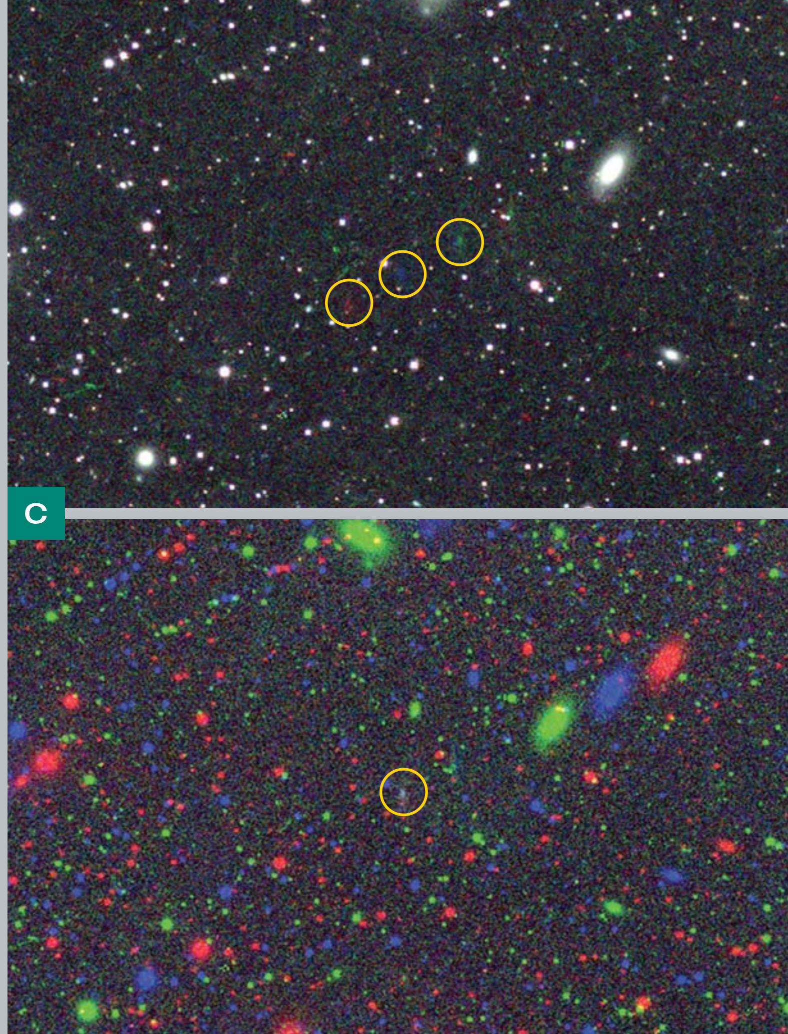




A SINGLE VS STACKED Combining multiple exposures of a given target suppresses noise and other unwanted signals, including bright satellite trails in deep-sky astrophotos. These examples of M61 seen above left demonstrate the power of stacking. The top image combines a single 20-minute exposure recorded through each RGB filter, while the bottom image is a stack of twelve 20-minute images shot through each color filter.

B OVERPOWERING NOISE The first goal of stacking is to improve the signal-to-noise ratio of the resulting image. This comparison of the area surrounding M86, in Virgo, shows the difference between 20 minutes of exposures through each RGB filter recorded with a 4.2-inch f/5 refractor *(top)*, with the same field using four hours of exposure per color filter *(bottom)*.

C NEARLY OVERLOOKED Stacking can also minimize or erase faint comets from your images, if you don't know they're present in the first place. The faint and distant Comet Schwartz C/2014 B1 is barely perceptible in the individual red, green, and blue images *(top)* but becomes more apparent when stacked images are registered on the comet itself *(bottom)*.

worm-gear drives that inherently have *periodic error*. This causes the drive to alternately slightly speed up and slow down during each revolution of the worm gear, producing elongated stars in the image. Not all mounts are created equal, so the periodic error can be different for each mount even of the same model. By limiting exposures to a shorter duration than the cycle of this periodic error, you can often capture perfect star images without the need for guiding. Stacking allows you to make full use of these short exposures. But how does it accomplish this?

More Signal, Less Noise

Stacking several shots improves the *signal-to-noise ratio* (SNR) compared with that in a single short exposure. This is important because every digital exposure records both signal *and* noise, and we want to collect as much signal as we can while reducing the amount of noise. Noise accumulates more slowly during an exposure than the signal does, which is why a long exposure is better than a short one. That's why combining multiple exposures lets you vastly improve the resulting SNR compared with that of the individual sub-exposures, greatly improving the overall quality of the image. Noise isn't actually reduced by stacking; it's simply being overpowered by a much greater increase in the signal.

Stacking short exposures also permits imagers to capture targets under light-polluted skies — something that was nearly impossible to do with film. But you'll need much more accumulated exposure under bright skies to record the same result you could under a pristine dark sky. This is because much of your exposure records light pollution — an undesirable "signal," but signal nonetheless.

However, stacking is just as beneficial when shooting under dark conditions. The same principle applies: Increase the desired signal while reducing the overall contribution of noise. Perhaps the biggest difference is that under a dark sky you can shoot longer individual exposures to stack later.

How to Stack

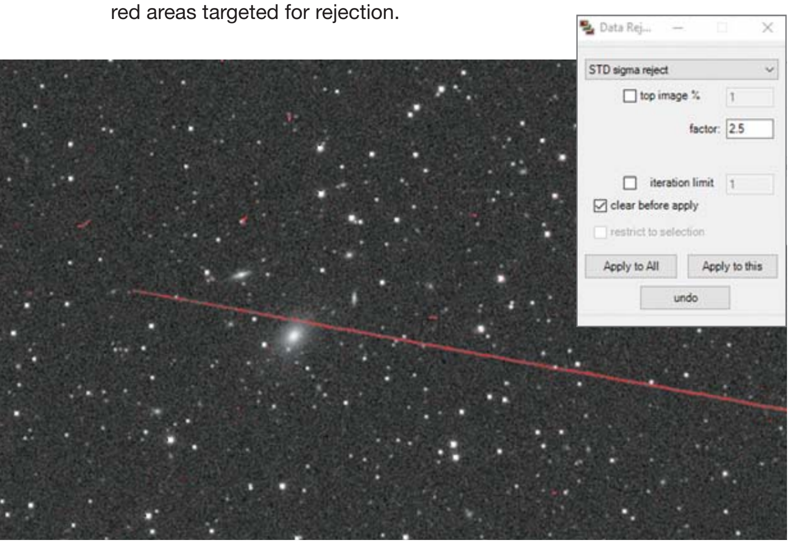
Stacking is now so common in astrophotography that virtually all astronomical image-processing software includes several ways to combine images.

Before stacking your shots, you first need to calibrate and align them with one another. Although your mount may have provided very good tracking, your pointing may slowly creep over the course of an hour — not enough to produce elongated stars in individual sub-exposures, but enough that if you simply stacked the frames without aligning, the result would be a trailed image. Some imagers use an additional technique called *dithering*, which offsets the telescope's pointing by a few pixels in a random direction between exposures. This helps to ensure that small imperfections in detectors (including hot or dead pixels) do not appear in the same spot on every exposure after aligning the series and can be removed using a method I'll describe further on.

After you've aligned your individual images, you can stack them using one of the common methods, including *sum*, *average*, *median*, or *sigma rejection* (an outlier-rejection method).

Stacking using the sum method performs basic math — it takes your images and adds the values for a given pixel location together. This routine ensures no photons are wasted

▼ **OUTLIER REJECTION** The most powerful stacking routine for removing unwanted signal is known as sigma rejection. Most advanced astronomical image-processing software includes some variant of this algorithm, which examines each pixel in each aligned image and rejects signal that falls outside of the measured average. The screen below shows the STD sigma reject routine in *CCDStack2*, which highlights in red areas targeted for rejection.



▲ **MOVING TARGETS** Stacking isn't always the best strategy, particularly if you're interested in recording moving objects. These two minor planets were seen passing through a field in southern Virgo on the evening of March 24th as the author was recording images through red and blue color filters. The interlopers were only noticed by blinking the unstacked individual images.

and works well for bringing out extremely weak signals. There are a few downsides to summing your exposures, however. Summing includes many signals you'd likely prefer to remove, such as airplane and satellite trails, and random artifacts caused by high-energy cosmic rays that leave bright spots or lines in an image. The pixel values of a summed image quickly exceed the bit depth of your camera, departing from 12-, 14-, or 16-bit depth, so save your image in a file format (such as IEEE floating-point FIT data) that can accommodate large pixel values.

Another common stacking technique is averaging the data (sometimes referred to as *mean combine*). This method takes the average value for a given pixel in the stack, resulting in a smoother image than a summed result. The benefit to averaging is it produces a high SNR that is kept within the bit-depth range of your original data. But the downside is that averaging does not remove unwanted signals.

Median combine works by assessing the range of values for a given pixel location in the stack and assigning a final value that is at the midpoint of the range. This method is good for removing noise in your images but produces a lower SNR than an image stacked using the average algorithm. Median combining does not remove pixels with outlier values (satellites, airplanes), but these values do not affect the resulting value at the midpoint of the range the way they do with averaging.

There are stacking methods called minimum and maximum, which reject the highest- and lowest-value pixels from an image series and stack similarly to a median combine. Some programs offer this tool as a single min/max setting, while others allow you to only reject the minimum, or the maximum. This can work well for removing bright, unwanted signals, including some streaks from satellites and airplanes.

The last option for stacking can be the most powerful, particularly today when the number of satellites orbiting the Earth is rapidly increasing (see our March issue, pg. 14). This technique, known variously as sigma rejection, sigma clip, or some other variant that includes sigma in the title, is perhaps the best for removing outlier signals while producing a high SNR in the final image stack. Sigma rejection basically works by examining your images and calculating

◀ **LUCKY IMAGING** Planetary images benefit greatly from stacking. The top picture of Mars is a single video frame recorded with a monochrome camera and a red filter. The stacked result (middle) combines 1,600 frames, greatly overpowering the noise compared with a single frame. The bottom photo includes stacked video sequences shot through green and blue filters and combined and sharpened to produce the color result.

the average signal for a given pixel, then rejecting everything that deviates substantially from that calculated average.

Sigma-rejection algorithms work extremely well at removing satellite trails, airplane streaks, and even slight guiding errors if only one or two images suffer from less-than-perfect guiding. It produces a smooth, low-noise result slightly lower than simple averaging. The downside is that sigma rejection requires a lot of frames to work best — often 10 or more. When combined with dithered guiding, the method also excels at removing cosmetic defects from your image, including hot and cold pixels, and even bad columns on a CCD detector.

Planetary Stacking

Stacking isn't only useful in deep-sky images. Every high-resolution picture of sunspots, lunar craters, and the major planets you see today was likely produced by stacking. Planetary imagers perform a slightly different type of stacking known as *lucky imaging*.

This technique uses a high-speed video camera to record dozens and sometimes hundreds of frames per second to improve the chances of capturing sharp frames during brief periods of steady seeing conditions. These videos are then loaded into a planetary stacking program where each frame is evaluated for sharpness and contrast. Then the sharpest frames are averaged, creating a single, high-dynamic-range image with an excellent SNR. Such an image can then be sharpened to show features approaching the theoretical resolving limit of the telescope used to acquire the data.

Image stacking revolutionized planetary imaging, perhaps even more than it did deep-sky photography. Some intrepid imagers have even experimented with lucky imaging of some of the brighter deep-sky objects, such as the Homunculus nebula surrounding Eta Carinae (*S&T:* Mar. 2009, p. 74). Lucky imaging produces by far the highest-resolution images with amateur equipment.

When Not to Stack

Stacking has many important benefits, but there are times when it isn't the best solution to a problem.

Most stacking algorithms minimize, and in many cases completely remove, moving objects from your images. This means that minor planets (asteroids) and faint comets can be unintentionally erased from a series of images when combined using sigma-rejection methods. So, if you're hunting for undiscovered objects within the solar system, you'll be best served by animating a series of images to look for moving targets. Stacking a series of images using the sum method works well for minor planets, but the result requires aggressive stretching to show their faint streaks during an exposure series.

Stacking is also tricky when you are targeting a moving object, such as a comet. For these objects you'll need to register your images on the comet before stacking (see *S&T:* July 2020, p. 36). Since astrometry is concerned with accurately measuring the positions and motions of objects, stacking isn't advised. Photometry benefits from the increased SNR produced by the method, though you should only use average stacking to avoid distorting the data.

There are times when it isn't advisable to stack planet images or even lunar photos. Several impacts have been recorded on Jupiter that just happened to be noticed by the photographers while they were recording their videos. These important events would have gone undetected if the video frames were stacked as intended! Likewise, several amateurs recorded a meteor impact on the Moon as totality began during the January 21, 2019, lunar eclipse. Stacking these images and video frames erases the impact flash from the result, demonstrating that it pays to carefully examine your videos for transient events before stacking.

With the exceptions noted above, there's no denying that stacking can lead to impressive improvements in your astronomical images. With the ready availability of sensitive cameras, excellent imaging telescopes, and powerful computer software, your results will be limited only by your imagination. Stacking is a powerful technique that has become a standard method in both professional and amateur astrophotography. Just remember to check your unstacked images so that you don't miss out on a discovery just waiting to be revealed.

■ Associate Editor **SEAN WALKER** has been stacking astrophotos for more than 20 years.

LUCKY CATCH
Although stacking vastly improves the quality of planetary images, it can erase momentary events, such as impacts. Fortunately, imager Anthony Wesley was paying attention while recording videos of Jupiter on June 3, 2010, when an asteroid collided with the planet.

The Hunt for the

First Exomoons

A handful of scientists are attempting to discover the first moons outside our solar system — a finding that would be transformative, yet remains elusive.

David Kipping was almost shaking with excitement. He was staring at a plot on his computer screen with a peculiar dip that kept reappearing no matter how he processed the data. It looked like the first glimpse of a moon beyond the solar system.

He left his desk and went for a walk. "I had to sit on a bench and take deep breaths to try and center myself a bit because I was just, like, crazily excited about it — thinking 'This is gonna be amazing, this is gonna change my life,'" he says.

But Kipping, then a postdoc at Harvard University, also knew that his excitement might be clouding his judgment. Once he had talked himself into being more objective, he returned to his office. And after a few days, another astronomer helped him discover that the exomoon was nothing more than an artifact produced when the telescope vibrated a little. He was devastated.

Unfortunately, it wasn't the only heartache of Kipping's career — several exomoons have appeared on his computer screen before vanishing into thin air.

That appears to be a common trademark of alien satellites. Even the few candidates that have managed to make it onto the pages of prominent journals have remained evasive. Signs of a volcanically active exomoon might be easily explained away. The same is true for one possibly floating freely through space with its planet, as well as the satellite that might have carved a gap in the rings around a Saturn-like exoplanet. Even the best candidate, a Neptune-size world that garnered much attention in 2018, has now slipped through astronomers' fingers.

And yet Kipping and a few others trudge onward, aware that the first discovery, though teasingly difficult, would be transformative — even Nobel prize–worthy.

But first, they have to find one.

Attempting the Impossible

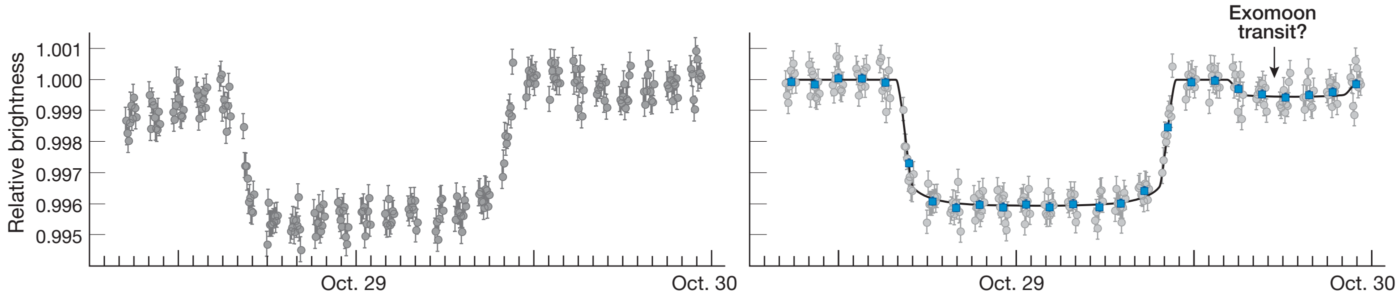
If our solar system is any guide, moons should exist in abundance throughout the galaxy — perhaps reaching numbers as high as tens of billions. To discover them, Kipping started digging in 2011 through publicly available data from Kepler, NASA's prolific exoplanet-finding spacecraft. But the search has not been easy.

Kepler launched in 2009 and watched 150,000 stars near the constellation Cygnus for four years in an effort to spot transits: instances when a planet passes in front of its host star and blots out a small fraction of starlight. That manifests as a recurring dip in a star's *light curve*, its brightness plotted over time. The mission was a wild success, and the telescope glimpsed roughly 2,500 confirmed distant planets.

If any of those happen to host moons, their presence should have a similar effect. If the exomoon passed in front of the star before or after the planet, for example, there would be a second, tinier dip in the star's light curve. Alternatively, a massive moon could exert a gravitational tug strong enough to

If our solar system is any guide, moons should exist in abundance throughout the galaxy – perhaps reaching numbers as high as tens of billions.

ILLUSTRATIONS: LEAH TISCIONE / *S&T*



▲ **AN EXOMOON?** Hubble Space Telescope observations of the star Kepler-1625 show a clear dip when a planet passed in front of the star in 2017 *(left, central dip)*. Depending on how they remove instrumental effects from the data, astronomers see (or don't see) signs of a second, much smaller dip after the planet Kepler-1625b transited. The right-hand graph is one version of the correction, with averaged data in blue.

A. TEACHEY ET AL. / *ASTRONOMICAL JOURNAL* 2020

perturb the planet's orbit, causing the planetary transits to diverge from a steady, clocklike recurrence. Transits might occur earlier or later than expected, or change in duration.

The issue is that these effects are minuscule. Some of the largest moons in our solar system are roughly the size of Pluto and Mercury — too small to easily detect around other stars. Exomoon transits also wouldn't occur in reliable patterns. "A moon can actually play hide-and-seek and hide behind the planet or be tilted enough to miss sometimes," Kipping says.

In addition, there might be a dearth of exomoons — at least around planets close to their stars. After Kipping looked at roughly 60 exoplanets only to find zero exomoons, he decided to adopt a slightly different strategy, in which he and graduate student Alex Teachey (both now at Columbia University) combined different light curves together from 284 systems to look for an ensemble effect.

The study took three years, and by 2017 the team was convinced that Kepler planets residing from 0.1 to 1 astronomical unit did not host moons — at least not ones larger than the Galilean satellites of Jupiter.

"We were really surprised not to find anything," Kipping says. Then Stephen Kane (University of California, Riverside) explained why. He found that it's nearly impossible for planets so close to their stars to host moons, because there is no safe orbit for a moon to reside in. Too far from the planet, and it gets stripped away by the star's gravity. Too close, and it gets ripped to shreds by the planet's gravity.

Given that Kepler was mostly able to detect planets close to their host stars, this explains why Kipping and Teachey haven't been able to find any moons within the Kepler data so far.

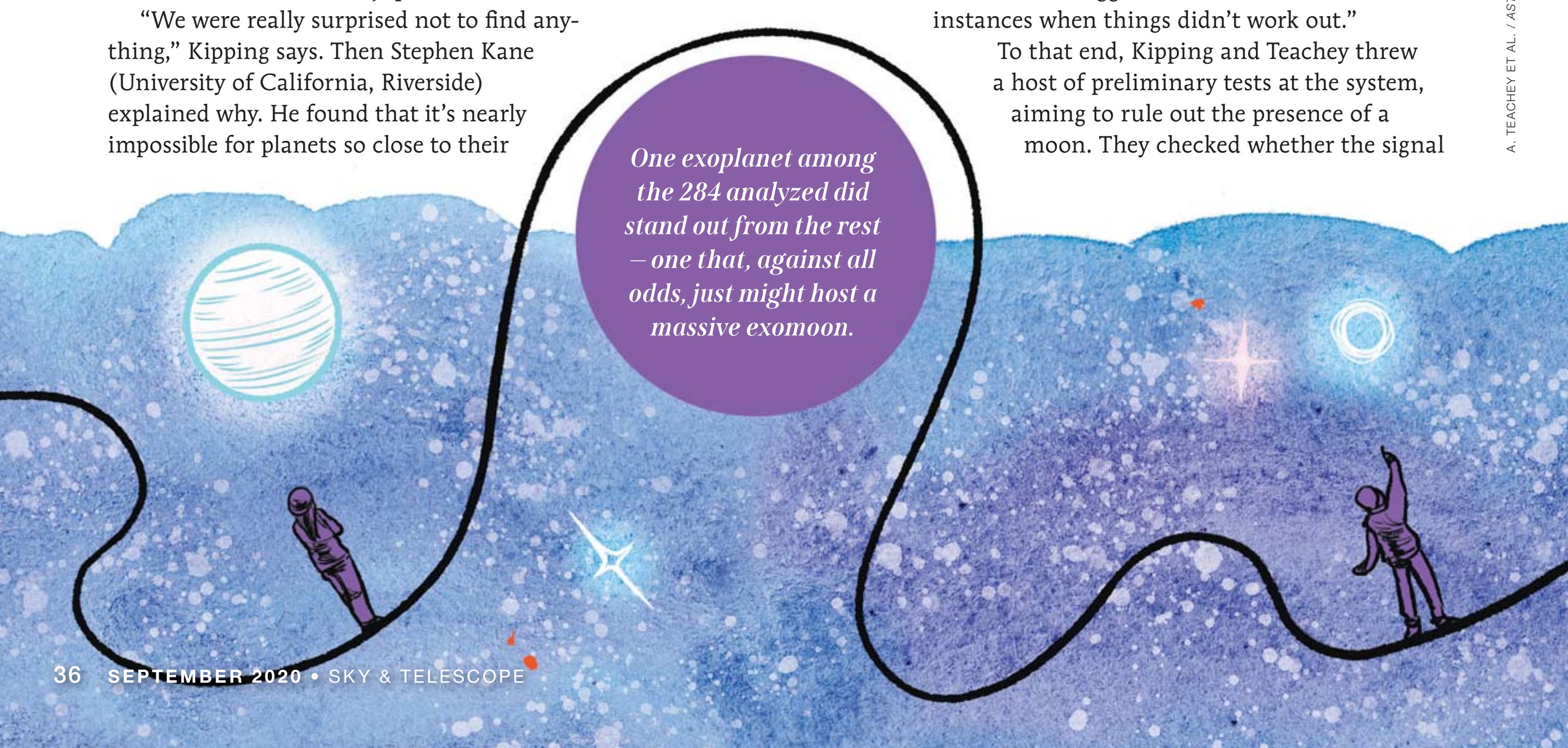
That said, one exoplanet among the 284 analyzed did stand out from the rest — one that, against all odds, just might host a massive exomoon.

At Last, an Exomoon Candidate

That object, known as Kepler-1625b I, orbits a planet about the size of Jupiter around a star roughly 8,000 light-years away. Because the satellite is likely the size of Neptune, the team nicknamed it "Neptmoon."

But Kipping knew to be cautious — especially after so many false positives throughout his career. "You can really get wrapped up in your own little world sometimes when you're staring at these data sets," he says. "So it's important to think about the bigger context and to remember instances when things didn't work out."

To that end, Kipping and Teachey threw a host of preliminary tests at the system, aiming to rule out the presence of a moon. They checked whether the signal


One exoplanet among the 284 analyzed did stand out from the rest — one that, against all odds, just might host a massive exomoon.

could be stellar activity or another planet. But the candidate withstood every test.

"We really felt like we had turned over every stone that we could possibly think of," Teachey says. "We wanted to be at least as hard-nosed about this as anyone else. Because it really does us no good to put out a sensationalist conclusion that's not going to hold up to scrutiny."

The team decided the best way to bolster the discovery was to train the Hubble Space Telescope on the star for 40 hours in October 2017. And sure enough, Hubble, whose sensitivity is four times greater than Kepler's, spotted a secondary dip in light after the planet crossed the star. Moreover, the planet also started its transit 77.8 minutes ahead of schedule — a sign that something was tugging gravitationally on the planet.

Both signals were consistent with an exomoon, but Kipping and Teachey remained circumspect. As did other astronomers.

"The data wasn't a slam dunk," says Laura Kreidberg (Center for Astrophysics, Harvard & Smithsonian). "It was kind of right on the edge of significance. And so that tripped some wires of like, 'Okay, let's put on our skeptical-scientist hat and make sure this thing is real.'"

Kreidberg reviewed the data using her own analysis and confirmed the planet's early transit, but she didn't detect the moon's secondary dip. The results left her unconvinced that the moon exists.

Meanwhile, René Heller (Max Planck Institute for Solar System Research, Germany) and his colleagues confirmed both the early transit and the secondary dip. But the researchers argue that it could be due to a second unseen planet rather than an exomoon.

Today, Heller remains uncertain. "I have my doubts, but I wouldn't be surprised if it turns out that it really is a moon," he says.

There is only one way to settle the issue: more data. To transform the candidate into a discovery, the team needed to make a prediction based on their model, and then verify that prediction.

It should have been easily done. After the team analyzed the results from Hubble, they predicted that the next time the planet transited its host star, the moon would be on the opposite side of its orbit, with a transit preceding that of the planet itself. So they put in a second Hubble proposal, but the committee denied it.

"That would have been, like, a complete slam dunk," Kipping says. "At that point, it would have been a discovery."

Unfortunately, it was the team's only opportunity. The more you project these planetary system models into the future, the greater the uncertainty. "So if we are going to look for it again, we kind of have to get back to scratch and do a completely blind search," Kipping says. "It's not even guaranteed to transit."

Instead, the existence of Kepler-1625b I will remain an open question.

"It's a very frustrating situation," Kipping says. "I really tore my hair out many a night thinking about that — how if we'd gotten that observation, at least then we would have known, even if we hadn't seen the moon. I could have been able to sleep at night thinking, 'Okay, we can move on.'"

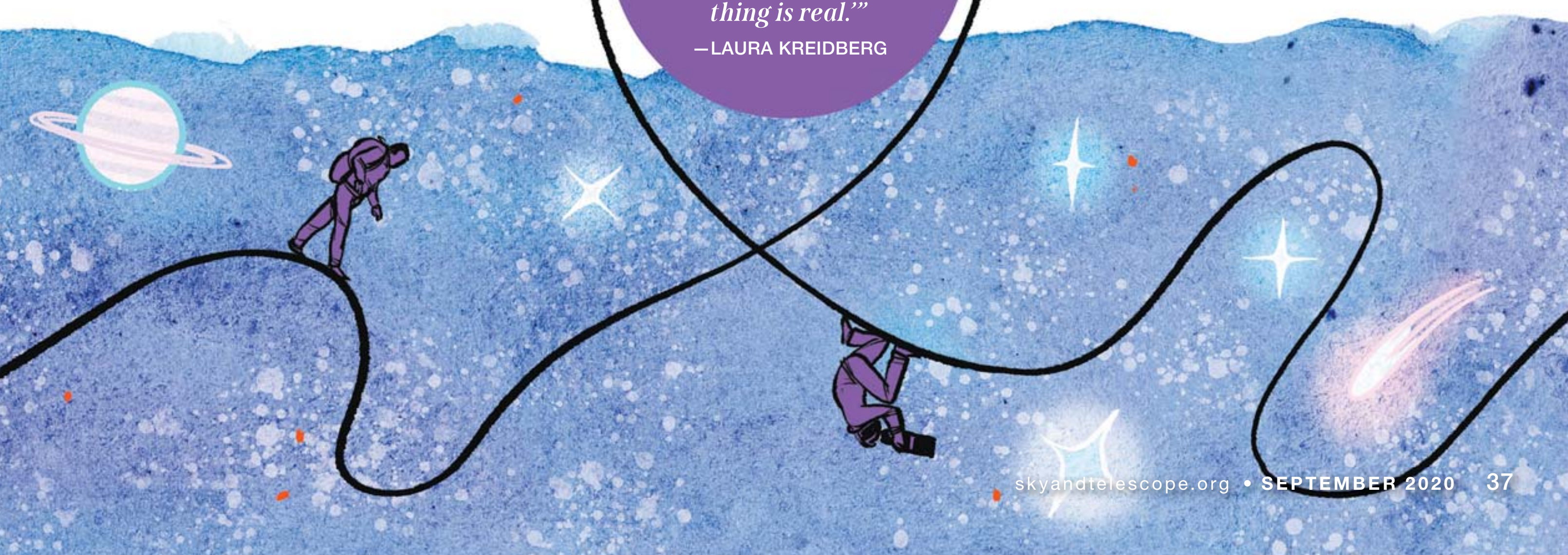
Harboring Secrets

Other claims have been even more difficult to verify.

In 2013, David Bennett (then University of Notre Dame) and his colleagues discovered what looked like a planet floating freely through the galaxy. Though typically invisible, the exoplanet briefly revealed itself when it happened to pass in front of a background star — a chance alignment that caused the foreground planet to act as a magnifying glass to focus and brighten the distant star's light. A small anomaly in the spike of light appeared to come from a moon in tow behind the planet. But because the discovery was based on a one-time event, it's impossible to confirm.

Then in 2015, Matthew Kenworthy (Leiden Observatory, The Netherlands) and Eric Mamajek (then University of Rochester) claimed that an exomoon might have carved a gap in the ring system surrounding a distant Saturn-like exoplanet. But observers have yet to see the

"That tripped some wires of like, 'Okay, let's put on our skeptical-scientist hat and make sure this thing is real.'"
—LAURA KREIDBERG



rings eclipse the star, called J1407, a second time. Kenworthy now wonders if the ringed world is also a free-floating one that made a one-time transit.

Similarly, researchers have invoked exomoons to describe a number of odd observations. Last year, astronomers suggested that debris gradually vaporized from an exomoon could explain the strange behavior of Boyajian's star, which dips in brightness over days or weeks (*S&T:* June 2017, p. 16). Soon after, a different team postulated that an exomoon could explain the unusually high layer of sodium present in the atmosphere of WASP-49b — so long as the satellite was volcanically active.

Every candidate has encouraged scientists to think outside the box. Even Kepler-1625b I, should it exist, would be quite unusual. Weighing in at the mass of Neptune, it would be larger than any of the moons in our solar system — so large it defies easy explanation.

In our solar system, moons form in one of three ways. They can coalesce from rings of gas and dust left over from a planet's formation. They can form from debris knocked into orbit around a planet after a giant impact. Or they can be gravitationally captured. But Kepler-1625b I failed to fit neatly into any of those origin stories — at least at first.

Then Heller found that if a pair of planets swung too close to the exoplanet Kepler-1625b, one of the objects might have been gravitationally captured by Kepler-1625b while the other was flung out of the system entirely. Although this situation might be exceedingly rare, astronomers would find the resulting moons first due to their mammoth size.

Such speculations show that the ultimate detection of an exomoon would be worthwhile, because it would provide an important window into a planetary system's formation and evolution.

Consider the four largest moons of Jupiter. Io, Europa, Ganymede, and Callisto orbit in the same plane, and for every lap Ganymede completes around Jupiter, Europa makes two orbits and Io completes four. The worlds likely formed in a disk of dust and gas around Jupiter and evolved together. In addition, the density of the moons drops with their distance from Jupiter. Io is extremely dense and therefore contains more rock than ice, whereas the farthest, Callisto, is less dense and therefore contains far more ice. That suggests that close-in moons were not able to incorporate water because Jupiter's proximity made it too hot for water to freeze. So while that disk of material is long gone, the moons serve as records of its temperature and composition.

"Finding any exomoons would be amazing, because you have another chapter of the story," says Jessie Christiansen (NASA Exoplanet Science Institute).

But perhaps the most tantalizing reason to continue the exomoon hunt is that some could be a haven for life.

First, they might reside in a star's *habitable zone*, the region where liquid water can exist on a rocky world's surface. But even if they orbit in the icy outer edges of a planetary system, they could still potentially support liquid water. Extra warmth could come from the reflected light and emitted heat of a host planet and even its gravitational pull. Just as the Moon raises tides on Earth, the gravitational tug of a planet could send energy rippling through a nearby moon.

"It really expands the habitable real estate in the galaxy," Christiansen says.

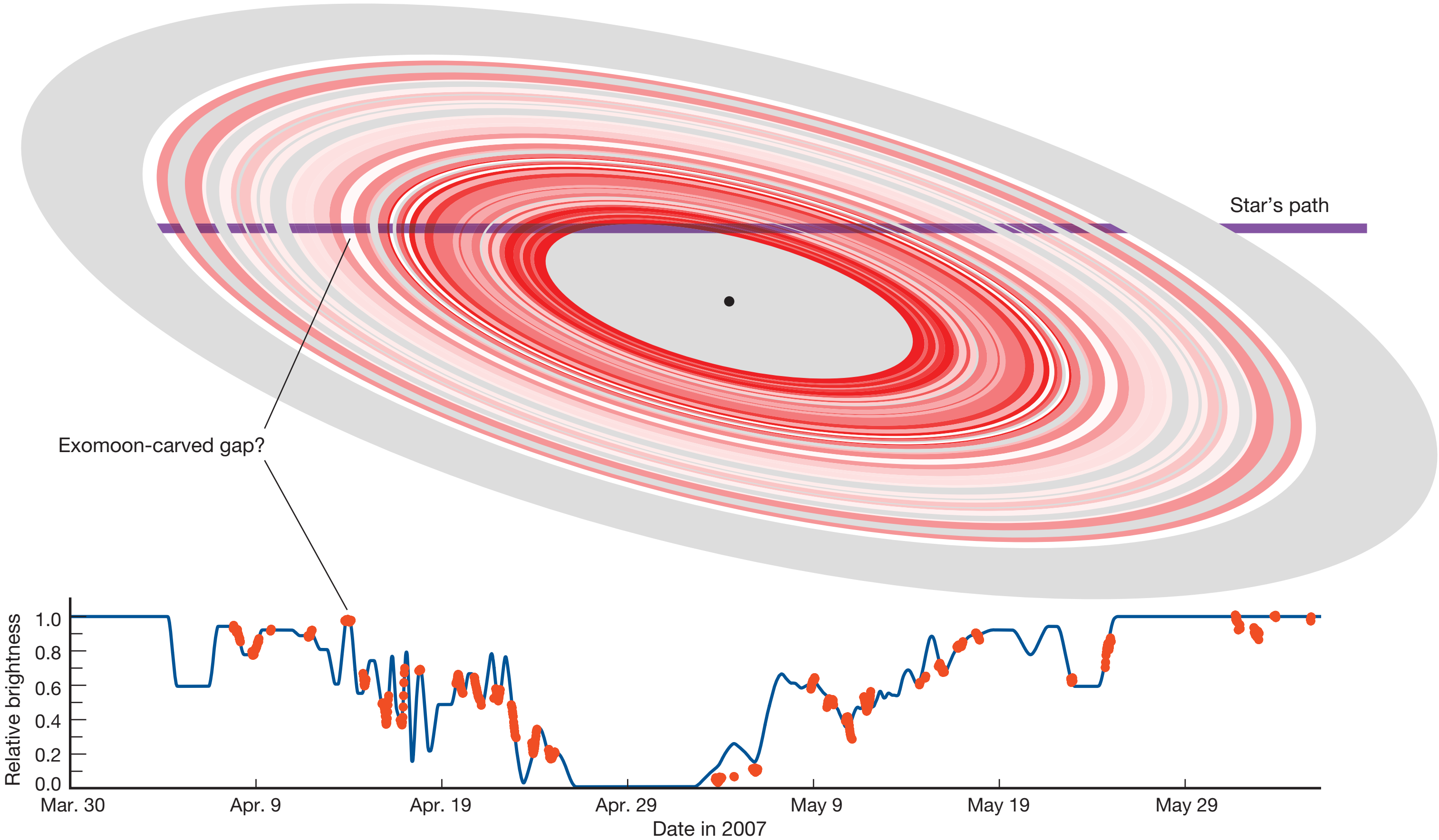
But proximity is a double-edged sword. If those tides are too strong, the moon might be overrun with volcanic eruptions (like Io). Still, just the right amount of tidal heating could keep moons comfortably toasty — even if they reside in the frigid outer depths of the planetary system. Indeed some moons in our own solar system, including Europa and Enceladus, have been flagged as possible oases due to this effect.

And it gets better: "A planet could be ejected out of its star system, floating through the galaxy, and have a habitable moon," says theorist Rory Barnes (University of Washington). "So from a subsurface habitability standpoint, the entire universe is habitable."

Researchers have invoked exomoons to describe a number of odd observations.

The Race Edges Forward

With such enormous potential, it's no wonder Kipping and Teachey are dedi-



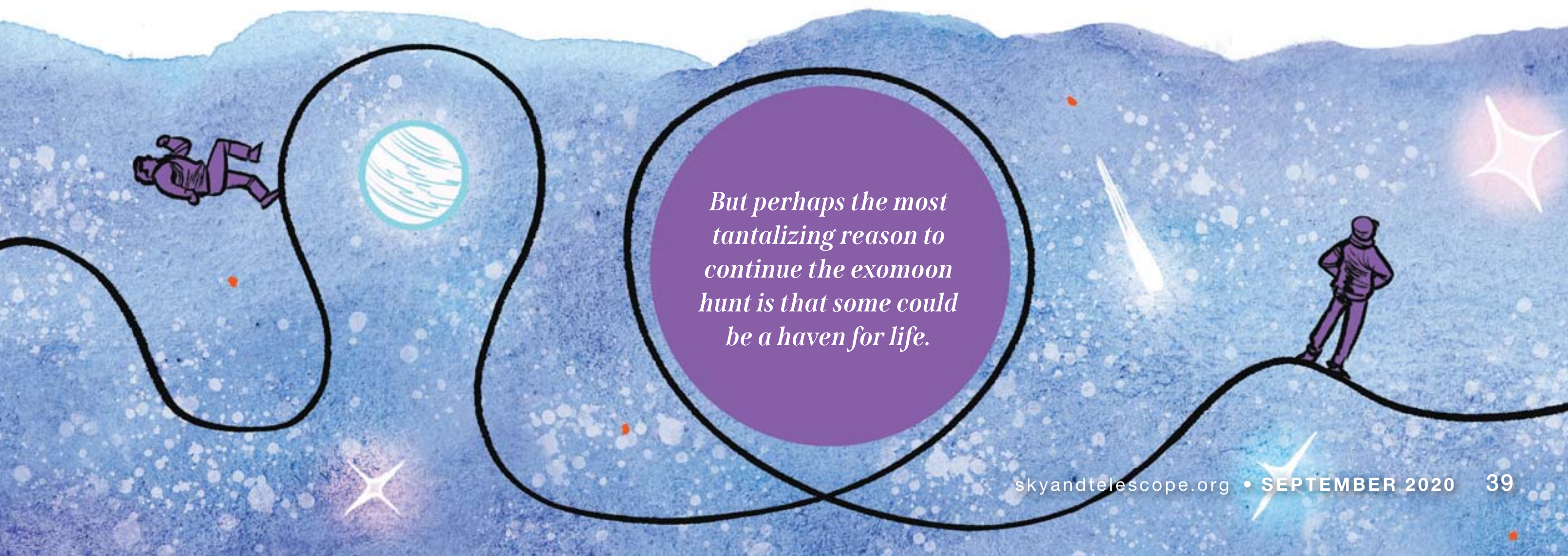
▲ **AN EXOMOON-CARVED GAP?** In 2007 something eclipsed the star J1407, creating a bizarre pattern (graph; red points are data, blue line is the pattern extrapolated). Astronomers used the pattern to infer that a complex ring system had passed in front of the star (top image). The intensity of the ring color corresponds to starlight transmission: More intense ring color means less light made it through. The gray sections are where astronomers have no data. One large gap might be made by a moon embedded in the rings.

M. KENWORTHY AND E. MAMAJEK / *ASTROPHYSICAL JOURNAL* 2015

cated to finding the first exomoon. And while they're happy to have the field mostly to themselves, Teachey wants to see more scientists become involved. "You see progress when you have more people, more money, more resources, going to the work," he says. "That's really only going to happen if we get more people excited and engaged in this work directly."

Perhaps that day will come. For now, they're laying the groundwork so that detections will soon be viable — enough to gather a statistical sample. "All kinds of new doors [will] open to us once we have that sample, but they're not just gonna fall out of the sky for us," Teachey says. "Somebody's got to actually go looking for these."

But precisely how long that might take is an open question. Kipping is convinced that he could deliver an unambiguous signal within a year if he were granted the telescope time to do a blind search. "That's a high-risk exercise," he says. "Some might call it a fishing expedition. And it's not obvious to me there's an appetite for that."



Some Exomoon Candidates

System	Distance	Planet Type	Reason astronomers suspect an exomoon	Status
J1407	450 light-years	super-Jupiter	gap in complex eclipse pattern from potential planetary rings	no second eclipse seen, might be free-floating
Kepler-1625	8,000 light-years	Jupiter-size	change in planet's transit time, potential transit by moon detected	unconfirmed
MOA-2011-BLG-262	2,000 light-years?	Jupiter-size	anomaly in microlensing signal	one-time event, unable to confirm
WASP-49	640 light-years	hot Jupiter	high-altitude sodium may be plasma from a volcanically active moon orbiting the planet	inference only

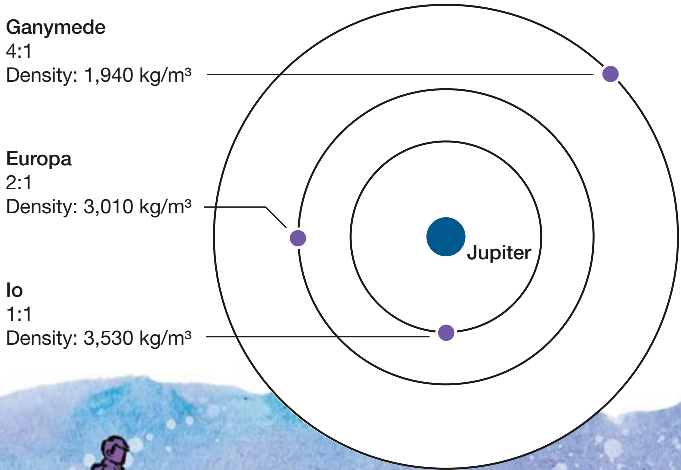
Without that appetite, the hunt might take a while. There have been two follow-up missions to Kepler: a mission known as K2, which continued to use the Kepler telescope but pointed at many patches of sky, and the Transiting Exoplanet Survey Satellite (TESS), which is currently looking for exoplanets around nearby stars. But neither will likely help in the hunt for exomoons. Unlike Kepler's initial mission, they have only looked at stars for short periods of time, meaning that most planets found in the data hug their host stars — in the wasteland where exomoons can't typically reside.

So Teachey is now working through the Kepler data again. In the past, the searches were rather limited, but he now intends to scour each and every light curve. To do so, he has trained a *convolutional neural network* — the same type of algorithm used for facial recognition on Google Photos and Facebook (*S&T:* Dec. 2017, p. 20) — to look at a light curve and recognize an exomoon's signal. Thus far, the results have been wildly accurate, at least on the artificial light curves.

He has now fed 1.2 million real transits to the algorithm, and it's spitting out attractive targets. Although it's too early to say whether they are of the caliber of Kepler-1625b I, both Teachey and Kipping are hopeful that the new technique could be a game-changer — perhaps providing our first glimpse at a moon beyond our solar system.

"If there are no Galilean-size moons out there, I would be gobsmacked," Kipping says. "It doesn't make any sense from a physical perspective that planets would not have moons like the moons we find in our backyard."

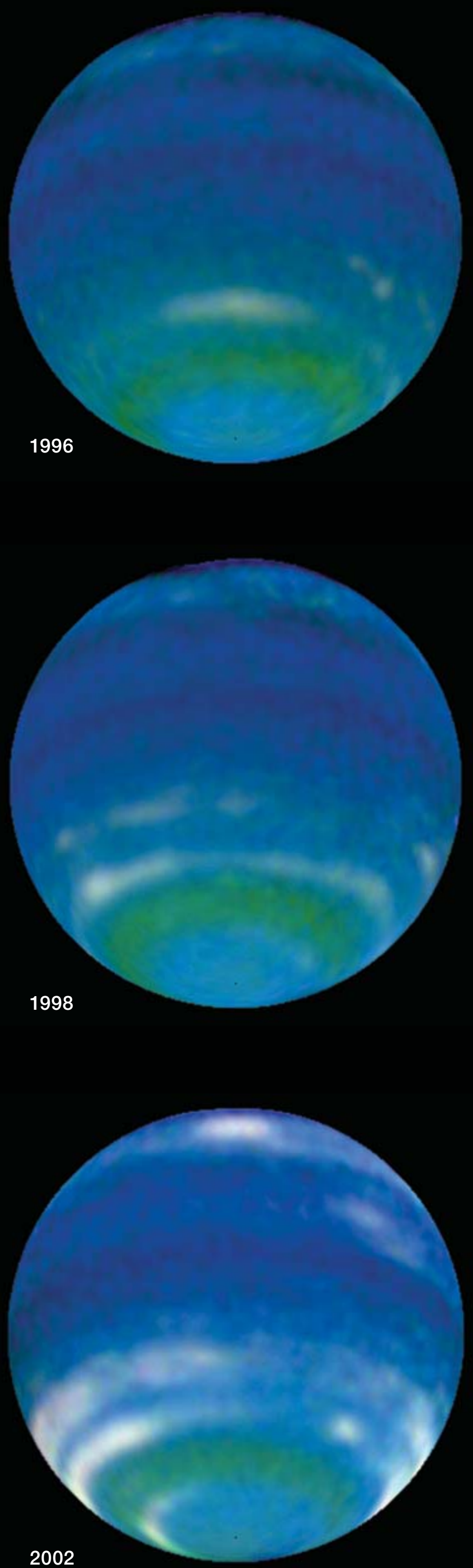
▼ **JUPITER'S MOONS** The three inner Galilean moons orbit in a 1:2:4 resonance with one another: Io circles Jupiter twice for every circuit Europa completes and four times for every Ganymede revolution. The moons' densities also fall with growing distance from the planet, indicating ice was scarce close to Jupiter during the moons' formation.



■ *S&T* Contributing Editor **SHANNON HALL** is an award-winning freelance science journalist based in the Rocky Mountains. Last fall, she watched her favorite moon, our Moon, traverse above an icy Arctic Ocean — refusing to rise or set for nearly two weeks.

GREGG DINDERMAN / *S&T*

OBSERVING
September 2020



5 EVENING: The waning gibbous Moon and Mars rise together as a close pair in Pisces. Watch the gap between them shrink as they climb higher. The Moon glides under the planet for viewers in North America, but some parts of the world will see it occult Mars (see pages 46 and 48).

7 EVENING: Algol shines at minimum brightness for roughly two hours centered at 11:30 p.m. PDT.

9 DAWN: The Moon lingers just outside the Hyades with the Pleiades to its upper right.

10 DAWN: Now between the horns of the Bull, the last-quarter Moon is pleasingly framed by Aldebaran, Beta (β), and Zeta (ζ) Tauri.

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

14 DAWN: Some 5° separate the waning crescent Moon from brilliant Venus, while the Beehive Cluster (M44) is at upper left. Catch this sight before the Sun rises.

15 DAWN: At northern latitudes, the zodiacal light is visible in the east beginning about two hours before morning twilight. Find a dark viewing spot and look for a tall pyramid of dim light tilted toward the right, stretching up through Cancer and Gemini into Taurus. Enjoy this sight until the end of the month.

15 DAWN: While you're admiring the zodiacal light, look for the very thin lunar crescent rising with Regulus in its tow, lagging by some 5°.

21 DUSK: As twilight deepens, find the waxing crescent Moon less than 1° from Beta Scorpii. As the pair sinks toward the southwestern horizon, the Moon will eclipse the double star for most of North and Central America (see page 48).

22 AUTUMN BEGINS in the Northern Hemisphere at the equinox, 9:31 a.m. EDT.

24 DUSK: A trio comprising the waxing gibbous Moon, Jupiter, and Saturn arranged in an arc about 11° long adorns the southern horizon.

25 DUSK: The Moon leapfrogs past the planets and is now positioned some 3° lower left of Saturn, the three bodies forming a triangle.
— DIANA HANNIKAINEN

◀ These Hubble images show an increase in cloud cover in Neptune's southern hemisphere that was likely responsible for a curious brightening of the planet between 1996 and 2002. See page 48 for more on Neptune. NASA / ESA / L. SROMOVSKY / P. FRY

SEPTEMBER 2020 OBSERVING
Lunar Almanac
Northern Hemisphere Sky Chart

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

MOON PHASES

SUN	MON	TUE	WED	THU	FRI	SAT
		1	2	3	4	5
6	7	8	9	10	11	12
13	14	15	16	17	18	19
20	21	22	23	24	25	26
27	28	29	30			

FULL MOON
September 2
05:22 UT

LAST QUARTER
September 10
09:26 UT

NEW MOON
September 17
11:00 UT

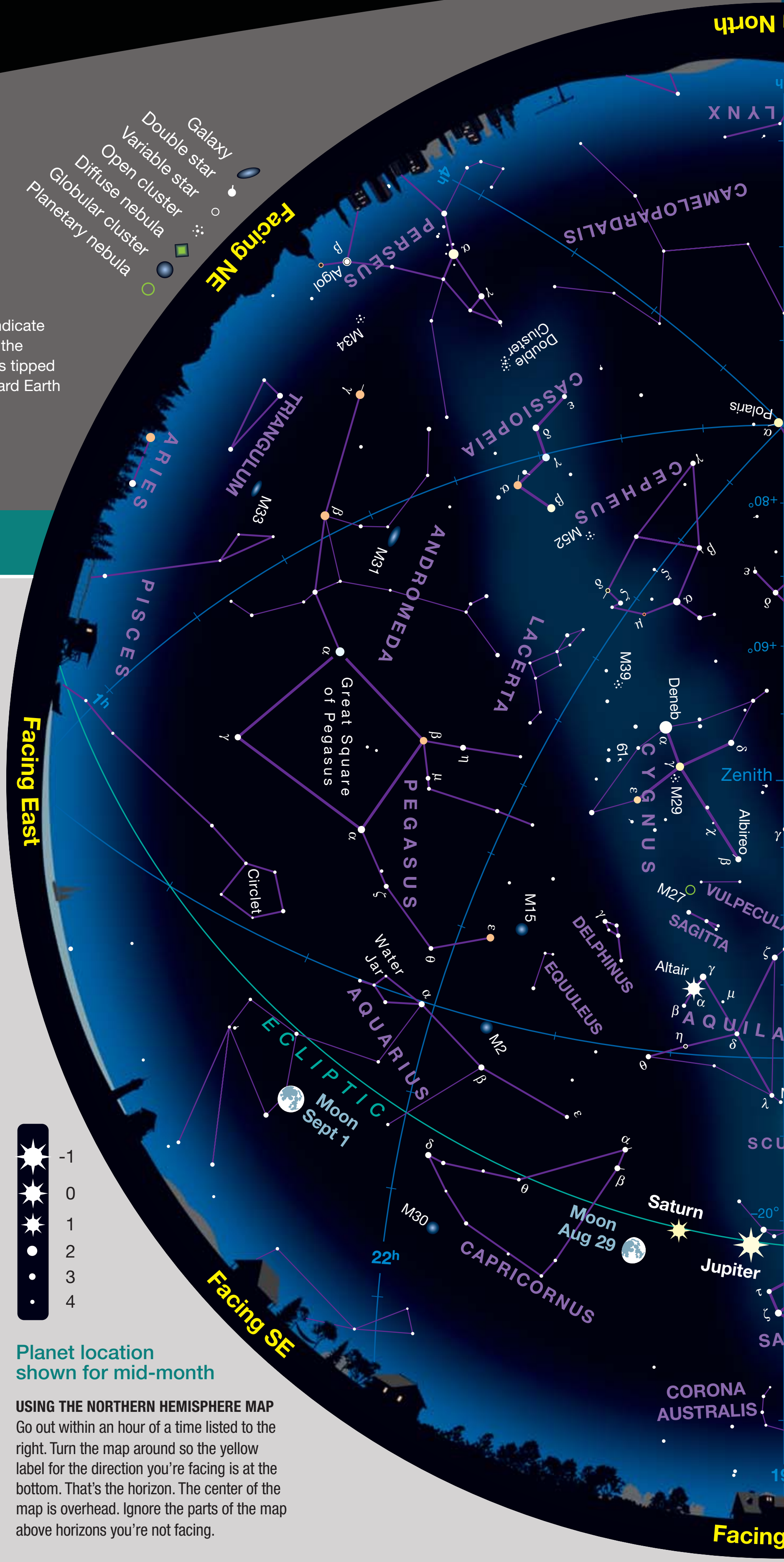
FIRST QUARTER
September 24
01:55 UT

DISTANCES

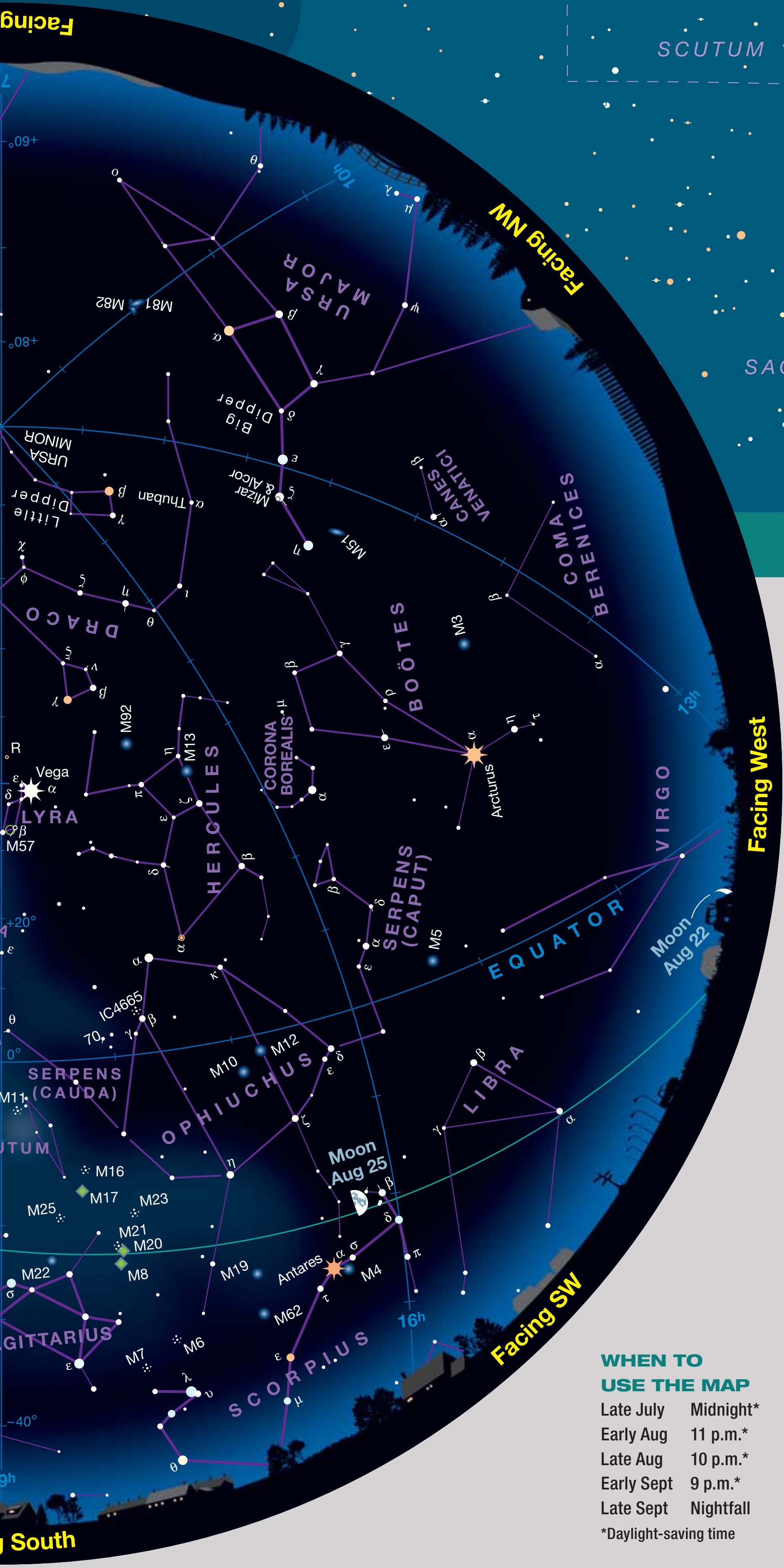
Apogee	September 6, 06h UT
405,607 km	Diameter 29′ 28″
Perigee	September 18, 14h UT
359,082 km	Diameter 33′ 17″

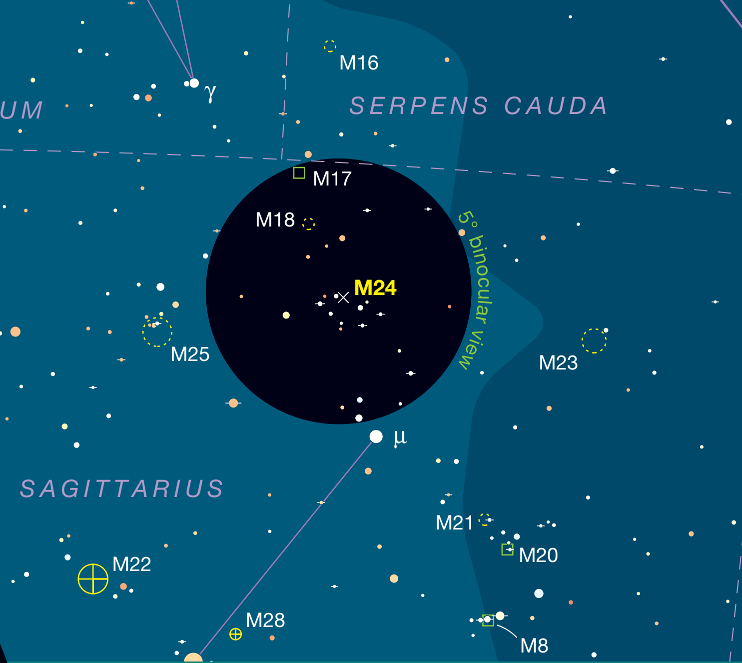
FAVORABLE LIBRATIONS

- Compton Crater — September 1
- Vallis Bouvard — September 14
- Oken Crater — September 21
- Humboldt Crater — September 22



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

A Tunnel in Space

I grew up in Oklahoma, one of the Great Plains states, and mountains have always had a powerful and exotic allure for me. My favorite views in the mountains appear as I start to descend. I'll come around a corner and suddenly, through a gap in the peaks, I'll catch a glimpse of some distant patch of desert or prairie and feel like I've received a privileged view through the heart of creation. This is also how I like to imagine we see **M24** in Sagittarius, the Archer.

M24 looks like an open cluster, but it isn't one. Rather, it's a star cloud — a vast congregation of suns in one of the inner spiral arms of the Milky Way Galaxy. These stars are spread between 10,000 and 16,000 light-years along our line of sight, roughly halfway to the galactic core. Normally we can't see so far into the plane of the galactic disc, but a fortuitous tunnel in the intervening dust clouds affords us this spectacular perspective. The great nebulae in Sagittarius — the Lagoon (M8), Trifid (M20), Eagle (M16), and Swan (M17) — are lights in that wall of dust and new stars, a wall that's nothing more nor less than the next spiral arm core-ward from us. We see through a hole in that arm to the one beyond, where thousands of stars sparkle like a city on a distant plain. The visible boundaries of the star cloud are not drawn by its own gravity, but by the frame of dust clouds that lie between us and it.

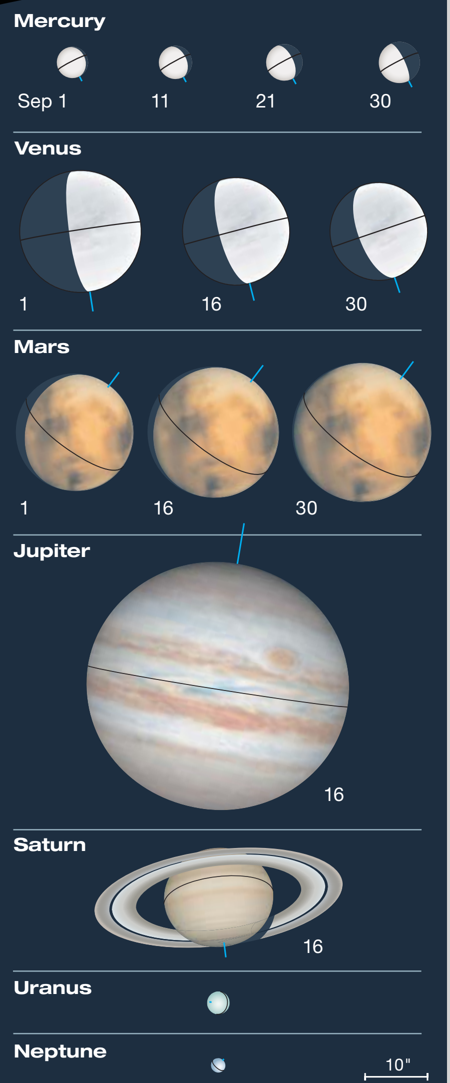
M24 therefore encapsulates everything I love most about stargazing: cosmic distance, chance alignments, galactic structure, and, of course, a beautiful object to contemplate. Go and catch a glimpse of it for yourself.

■ In the night sky as on Earth, **MATT WEDEL** is always on the lookout for new vistas to contemplate.

WHEN TO USE THE MAP

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

*Daylight-saving time



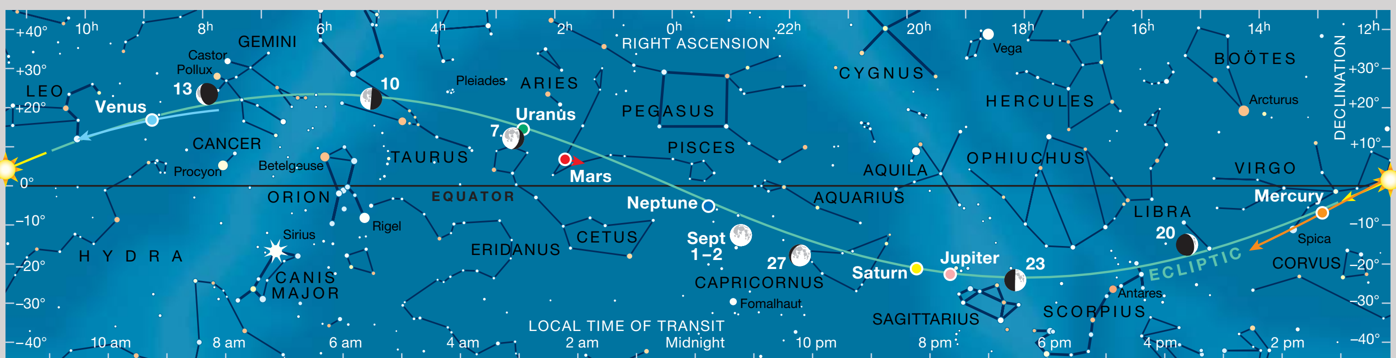
PLANET DISKS have south up, to match the view in many telescopes. Blue ticks indicate the pole currently tilted toward Earth.

PLANET VISIBILITY (40°N, naked-eye, approximate) Mercury: hidden in the Sun's glare all month • **Venus:** serves as the brilliant Morning Star all month • **Mars:** rises in the evening, culminates before dawn • **Jupiter:** transits at dusk, sets after midnight • **Saturn:** roughly 8° east of Jupiter.

September Sun & Planets

	Date	Right Ascension	Declination	Elongation	Magnitude	Diameter	Illumination	Distance
Sun	1	$10^h\ 41.4^m$	+8° 17′	—	−26.8	31′ 42″	—	1.009
	30	$12^h\ 25.8^m$	−2° 47′	—	−26.8	31′ 56″	—	1.001
Mercury	1	$11^h\ 30.9^m$	+4° 08′	13° Ev	−0.6	5.0″	92%	1.340
	11	$12^h\ 28.3^m$	−3° 22′	19° Ev	−0.2	5.3″	84%	1.262
	21	$13^h\ 18.8^m$	−10° 02′	24° Ev	−0.1	5.9″	75%	1.149
	30	$13^h\ 58.0^m$	−14° 54′	26° Ev	0.0	6.6″	63%	1.018
Venus	1	$7^h\ 42.2^m$	+19° 25′	45° Mo	−4.3	19.5″	60%	0.855
	11	$8^h\ 27.7^m$	+17° 56′	44° Mo	−4.2	17.9″	64%	0.930
	21	$9^h\ 13.6^m$	+15° 38′	42° Mo	−4.1	16.6″	68%	1.003
	30	$9^h\ 54.8^m$	+12° 54′	41° Mo	−4.1	15.6″	71%	1.066
Mars	1	$1^h\ 47.4^m$	+6° 32′	131° Mo	−1.8	18.9″	92%	0.496
	16	$1^h\ 48.4^m$	+6° 43′	146° Mo	−2.2	21.0″	96%	0.445
	30	$1^h\ 38.3^m$	+6° 11′	162° Mo	−2.5	22.4″	99%	0.418
Jupiter	1	$19^h\ 15.4^m$	−22° 43′	129° Ev	−2.6	44.3″	99%	4.448
	30	$19^h\ 16.5^m$	−22° 43′	101° Ev	−2.4	40.7″	99%	4.849
Saturn	1	$19^h\ 50.9^m$	−21° 17′	137° Ev	+0.3	18.0″	100%	9.244
	30	$19^h\ 48.2^m$	−21° 26′	108° Ev	+0.5	17.2″	100%	9.645
Uranus	16	$2^h\ 31.0^m$	+14° 22′	133° Mo	+5.7	3.7″	100%	19.083
Neptune	16	$23^h\ 21.8^m$	−5° 19′	176° Ev	+7.8	2.4″	100%	28.926

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



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

Tour the Vega Hour

There's something to see on September evenings no matter which direction you face.

LYRA LUMINARY Overhead during September evenings is zero-magnitude Vega, the fifth-brightest star in the night sky. Vega is a prominent jumping-off point for a tour of the season's constellations.

AKIRA FUJII

What rich heavens there are to observe when Vega shines overhead, as it does from mid-northern latitudes during evening hours this month. To take in the sights we'll look in nine different directions — eight compass directions *and* straight up, where Vega reigns from its perch in Lyra. Use our Northern Hemisphere map to follow along as we take in the sights.

Facing south. The handle of the Sagittarius Teapot hangs on the meridian pretty low, due south. The brightest, broadest section of the Milky Way is above and to the right of the Teapot's spout — a rich region that includes M24, an especially luminous patch. (M24 isn't marked on our map but is located slightly east of a line connecting M17 and M23.) Higher up is the Scutum Star Cloud, which provides the background for the splendid open star cluster, M11. Not far from the lower right of the Teapot you'll find the Stinger of Scorpius, the Scorpion. Its triangle form features the bright pair of Lambda (λ) Scorpii (Shaula) and Upsilon (υ) Scorpii (Lesath). Just above this duo sit the big open clusters M6 and M7.

Facing southwest. The front half of Scorpius and the entire pattern of Libra, the Scales, shine very low in the southwest. The interesting sight here is early-summer star Antares, which is still plainly visible during the Vega hour. Extending far above Antares, and centered about halfway to the zenith, is the vast expanse of Ophiuchus.

Facing west. Fairly high at this hour is brilliant, golden-hued Arcturus. It shines in the kite shape of Boötes, the Herdsman, which is oriented nearly upright. Almost directly above Arcturus is the semicircle of Corona Borealis, the Northern Crown. Last, but not least, as we scan upward, we reach the Keystone asterism of Hercules. The Great Globular Cluster in Hercules, M13, glows at 6th magnitude from what is now the bottom side of the Keystone.

Facing northwest. Though rather low, the Big Dipper is now perfectly displayed upright. Filling even more of the northwest sky is the rest of Ursa Major, the Great Bear, with all four of its paws resting on the horizon. Far above the Great Bear is the Little Bear, Ursa Minor — also known as the Little Dipper. The tail of Draco the Dragon is tucked in between the two Dippers. Ancient pole star Thuban (Alpha Draconis) flickers between Mizar (at the bend in the Big Dipper's handle) and the Guardians of the Pole, Kokab and Pherkad — Gamma (γ) and Beta (β) Ursae Minoris, respectively.

Facing north. Along the northern horizon are Camelopardalis and Lynx, the faintest of the north circumpolar constellations. These dim groups occupy the region below Polaris, the North Star. Polaris, of course, is well known as a handy nocturnal beacon marking true north.

Facing northeast. This direction is as bright and rich as the previous one is empty and faint. The steeple shape of Perseus is near the horizon and the distinctive zigzag of Cassiopeia sits conspicuously above it. Cepheus, the dimmer, sideways-house-shaped constellation, appears to the upper left of Cassiopeia, and Andromeda (with its naked-eye prize, galaxy M31) is to the right of Perseus.

Facing east. Andromeda's main line of stars extends from the northeast to link up with the Great Square of Pegasus, hanging in the east. When Vega is overhead, the Square stands on one of its corners like a giant diamond. Below and to the right of the Pegasus diamond is the attractive Circlet of Pisces.

Facing southeast. The mostly dim but fascinating constellations Aquarius and Capricornus fill this slice of sky. Prominent stars in the southeast are 2nd-magnitude Enif (the nose of Pegasus) and, somewhat higher, 1st-magnitude Altair, in Aquila. Altair brings us full circle back to the bright band of Milky Way we started our tour with.

Looking overhead. Vega and Deneb dominate the zenith. Along with Altair, they comprise the Summer Triangle. But when you look straight up, you're also gazing in the direction our solar system is heading. The exact spot is not far from Vega, situated roughly midway between Beta (β) Lyrae and the extended left foot of Hercules.

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

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

A Fine Planetary Foursome

Venus, Mars, Saturn, and Jupiter offer rewarding views.

In July, the oppositions of Jupiter and Saturn occurred just six days apart. During August, a greatest elongation by Venus crowned the dawn sky. Now we're waiting for October to bring us an opposition of Mars better than any we'll see until 2035.

So, what does September offer? The best combination (arguably in decades) of all four planets at their near-best at the same time.

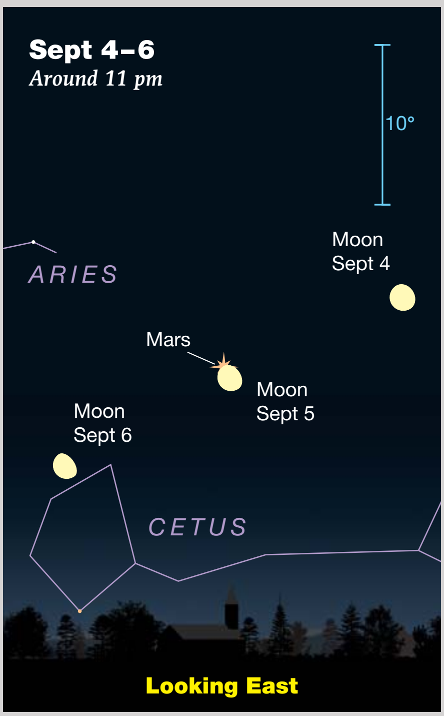
DUSK

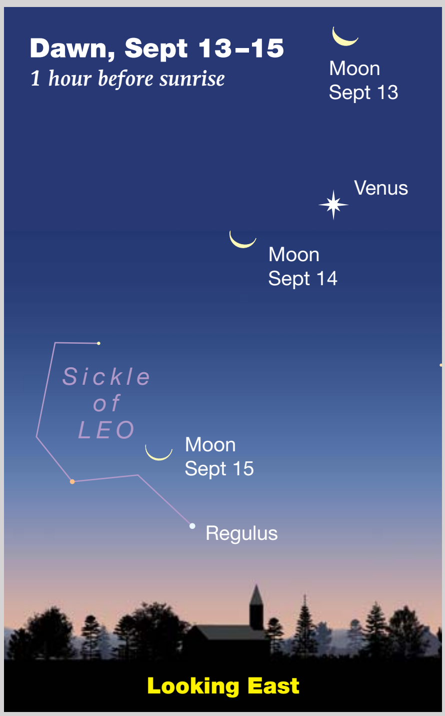
Mercury is the one naked-eye planet that doesn't have a great September. It shines brighter than zero magnitude most of the month and reaches greatest elongation on October 1st, but from mid-northern latitudes it lurks low in the dusk sky and sets less than 50 minutes after the Sun. If you want a challenge, use binoculars or a small telescope to find Spica less than 1° from Mercury on the evening of September 21st.

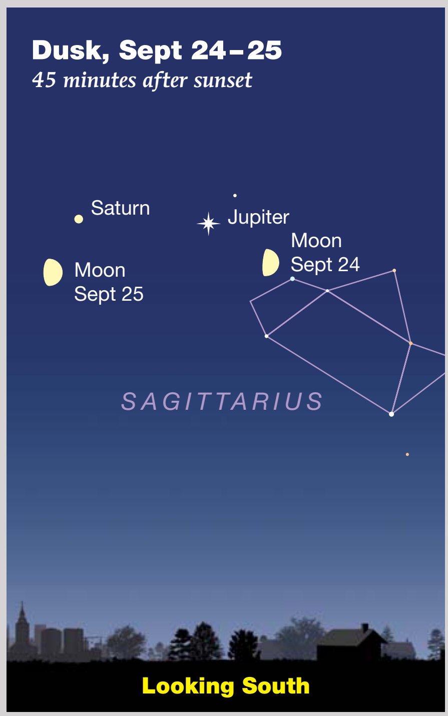
DUSK UNTIL WELL AFTER MIDNIGHT

Jupiter and **Saturn** shine together in eastern Sagittarius. They're highest in the south a few hours after sunset as September begins, and culminate during evening twilight as the month ends. The angular distance between the two worlds has increased from less than 5° in May to more than 8° in September. But at the end of the month that trend begins to reverse. On September 12th Jupiter halts its retrograde (westward) motion and slowly resumes direct (eastward) motion. Saturn does the same on the 29th. After that, the gap between the pair shrinks until December 21st when they have a remarkably close conjunction, just 0.1° apart.

The December event will occur rather low in evening twilight, but for now the two planets are well placed for telescopic observation. During September, Jupiter fades from magnitude –2.6 to –2.4, and Saturn from +0.3 to +0.5 — both still impressively bright. Meanwhile, Jupiter's angular diameter decreases from 44.3″ to 40.7″, while Saturn's disk shrinks from 18.0″ to 17.2″. Both planets are still large enough for detailed, high-magnification views.







Saturn's glorious rings remain favorably tilted earthward at an angle of 23°.

ALL NIGHT

Neptune, farthest and faintest of the major planets, comes to opposition in Aquarius on September 11th. Light from the distant, 7.8-magnitude world takes almost exactly 4 hours to reach Earth this month. For more on Neptune (including a finderchart), turn to page 48. Fellow ice giant, **Uranus**, rises near the end of evening twilight and shines at magnitude 5.7 in Aries.

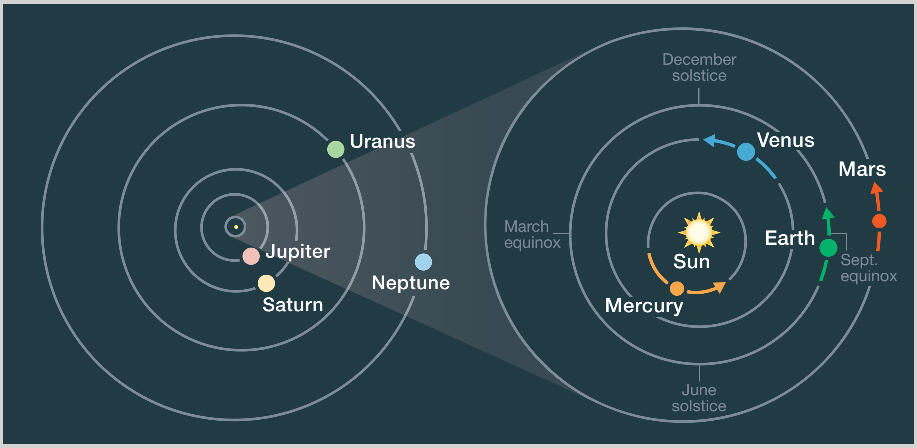
ALMOST ALL NIGHT

During September, **Mars** grows ever more imposingly luminous, and captivatingly big for telescope users. This most fascinating of worlds rises about 2 hours after sunset as the month begins and less than 1 hour after sunset as it concludes. The campfire-colored glow of Mars burns in Pisces throughout autumn, but on September 9th the planet halts its direct motion, reverses course, and begins to retrograde.

The month starts with Mars half as bright as radiant Jupiter. But in September the magnitude of the Red Planet improves from –1.8 to –2.5, slightly brighter than Jupiter by month's end. Do remember, however, that atmospheric activity on both planets can increase their magnitudes slightly. But let's hope that Mars doesn't brighten because of a planet-wide dust storm that hides its surface features from our telescopes.

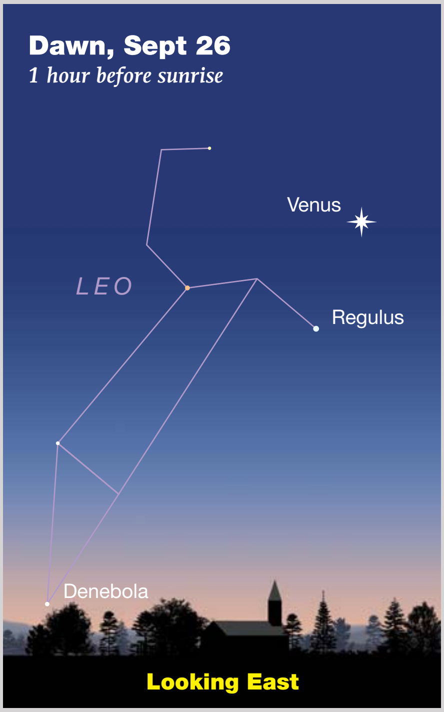
Mars's apparent angular diameter increases from 18.9″ to 22.4″ in September. During the month, its culmination hour backs up from about 4 a.m. to 2 a.m., local daylight-saving time.

Mars has its closest approach to Earth on October 6th. We'll have detailed observing coverage in next month's issue.



ORBITS OF THE PLANETS

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



PRE-DAWN AND DAWN

Venus was at greatest elongation on August 13th, but throughout September the resplendent planet still rises around 3½ hours before sunrise and at that time achieves an altitude of almost 40° for observers at mid-northern latitudes. Venus starts the month in Gemini (9° south of Pollux), crosses Cancer and pulls up close to Regulus in Leo by month's end. During that time, Venus dims from –4.3 to –4.1, and its disk decreases from 19.5″ to 15.6″ as its phase increases from 60% to 72% illuminated.

◀ 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.

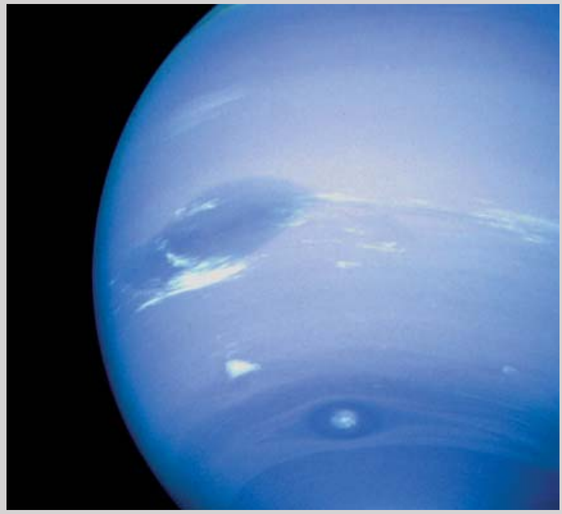
EARTH AND MOON

Earth reaches the September equinox point in its orbit at 9:31 a.m. EDT on September 22nd, marking the start of autumn in the Northern Hemisphere.

The **Moon** is full at 1:22 a.m. EDT on September 2nd. That's far enough away from the September equinox to lose out to the October 1st full Moon for the title of Harvest Moon. The waning gibbous Moon has a fine conjunction with Mars when it passes ½° south of the Red Planet around midnight (EDT) on the night of September 5–6. Observers on the East Coast get the best view, but the two objects will be close for locations all across North America. The Moon occults the planet for those in Central America, northeastern South America, northern Africa, and southernmost Europe. (See page 50 for additional details.)

A waning lunar crescent hangs well to the lower left of Venus at dawn on September 14th, and above Regulus on September 15th. A waxing gibbous Moon shines lower right of Jupiter at dusk on September 24th, and lower left of Saturn on September 25th.

■ **FRED SCHAAF** wrote his first book, *Wonders of the Sky: Observing Rainbows, Comets, Eclipses, the Stars and Other Phenomena*, 40 summers ago.



▲ During its August 1989 flyby, NASA's Voyager 2 spacecraft imaged Neptune's Great Dark Spot accompanied by several bright, white clouds. Each feature moves eastward at a different velocity, only occasionally lining up as they did at the time of this photo.

NASA / JPL

Voyaging to Neptune

The most distant planet is at opposition this month.

With summer ending, nights are getting cooler — a perfect time to embark on a mission to Neptune, coldest and most distant planet in the solar system. Thankfully, you'll probably only need to wear a sweater for a backyard visit with your telescope, but if you could transport yourself to this distant world, a well-heated spacesuit would be an absolute must. Neptune's atmospheric temperature averages around −212°C (−350°F), which is cold enough to turn carbon monoxide and methane into ice crystals.

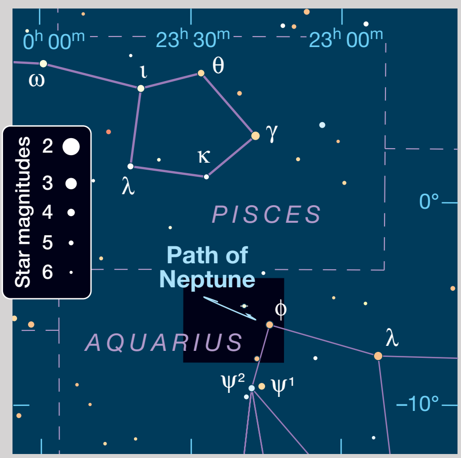
Indeed, it's methane that first catches your attention at the eyepiece. Neptune's upper atmosphere comprises 1.5% methane, which absorbs red light from the Sun and reflects blue, making it the solar system's "other" blue planet. When I observe this pale dot, I sometimes like to imagine I'm viewing our own planet from afar.

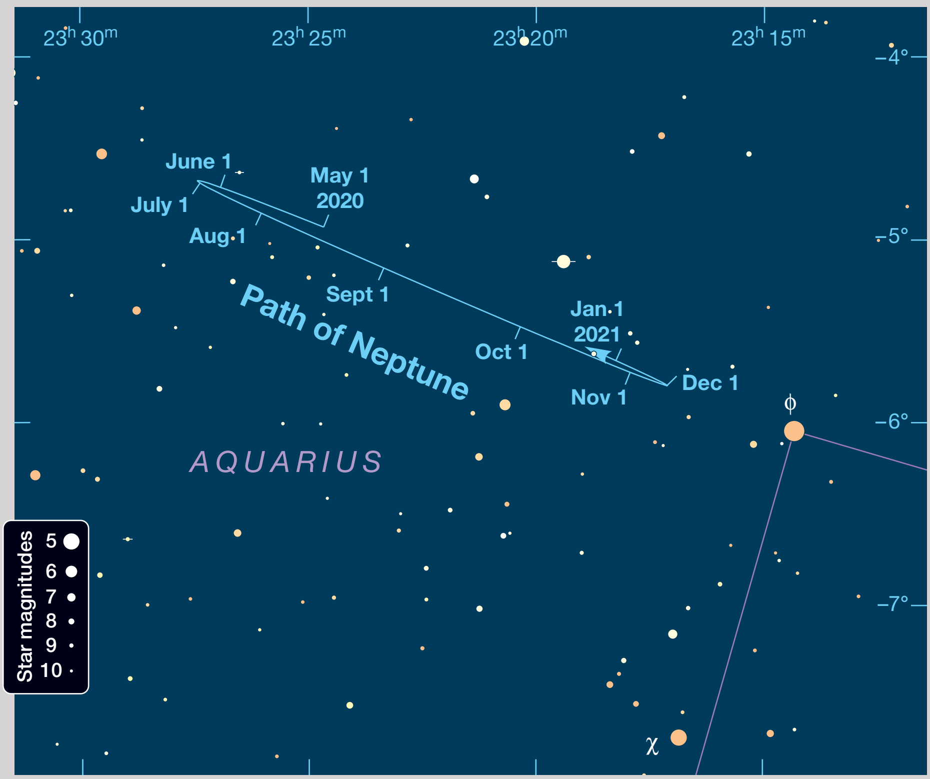
Neptune reaches opposition on September 11th, when it shines at magnitude 7.8 from 4.3 billion kilometers away. It's bright enough to see easily in binoculars from a dark-sky location. Neptune spans just 2.4″, which means a small telescope is required to discern its disk. At 50× it looks suspiciously different from stars of similar brightness. Increase the magnification to 100× or greater, and there's no question you're seeing a planet rather than a glittering stellar point.

Amateur photographs captured with red and infrared filters reveal mottled dark regions and brighter spots on Neptune's surface, but to the eye its disk appears essentially featureless in a telescope. I'm aware of a couple of observations of limb darkening, but no confirmed cloud sightings.

As with other minimalist astronomical objects, it's what you bring to the eyepiece that matters most. For example, knowing that it'd take 165 Earth years before you could celebrate your first birthday on Neptune, or that it's the windiest place in the solar system, helps add character to the planet's bland visage.

Neptune has six spindly rings, though these aren't visible in ama-





teur telescopes. The planet also has 14 named moons, the largest of which is 2,707-km-wide Triton. It orbits the planet backwards (in retrograde) and may be a captured Kuiper Belt object (KBO). Since the only other KBO within reach of backyard scopes is Pluto, this is a rarity worth observing. At magnitude 13.5, Triton is slightly brighter than Pluto and, being positioned next to an 8th-magnitude planet, is much easier to find.

During its 5.9-day orbit, Triton's angular distance from Neptune varies from about 9″ to 16″. When it's at greatest elongation, Triton is very easy to see in an 8-inch telescope. At 200×, the planet and moon have the appearance of an unequal double star. Triton's orbital tilt of 157° relative to Neptune's equator means the moon makes a wide ellipse around the planet without being obstructed by it. You can find its position for any given time by checking *Sky & Telescope*'s Triton Tracker at **https://is.gd/tritontracker**.

As our charts on the preceding page show, Neptune spends autumn in eastern Aquarius within a degree or two of 4th-magnitude Phi (φ) Aquarii. Early in September the planet is high enough to observe at 10 p.m. local daylight-saving time, and it can be appreciated an hour earlier by month's end.

As you cozy up to this remote planet, spare a thought for Galileo. He recorded Neptune's position on two occasions (in December 1612 and January 1613) when it was near Jupiter, but failed to recognize it as a planet with his modest telescope. The person ultimately credited with Neptune's discovery was German astronomer Johann Galle, who spotted it on September 23, 1846. But that's another story . . .

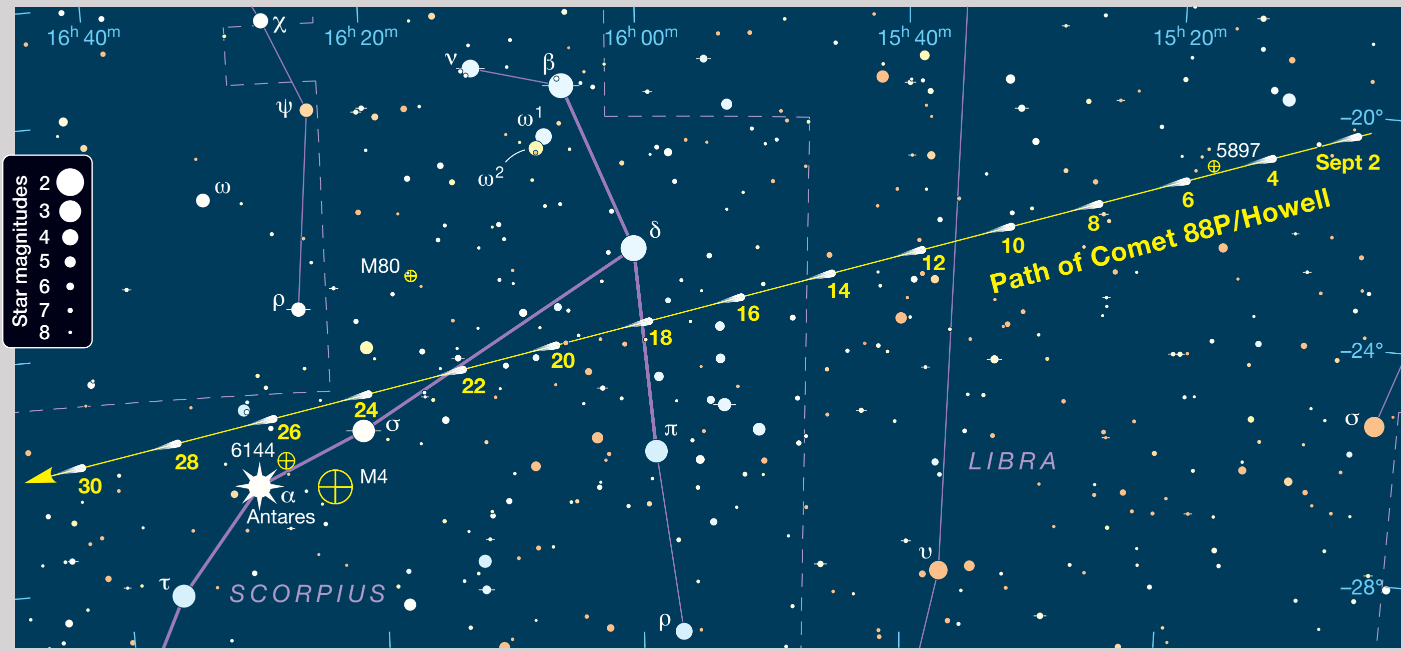
Something to Howell About

THIS YEAR HAS PRODUCED several new discoveries of relatively bright comets, plus visits from a few familiar faces. One of those is Comet 88P/Howell. Discovered by Ellen Howell with the 0.46-m Schmidt telescope at Palomar Observatory in August 1981, the comet has an orbital period of just 5.5 years and has been observed on multiple returns. The 2020 apparition will be a good one, with the comet reaching magnitude 9 around the time of its September 26th perihelion.

This month the comet treks from Libra across northern Scorpius, low in the southwestern sky at the end of evening twilight. While it's visible from mid-northern latitudes, observers in the Southern Hemisphere will enjoy the best views. On the evening of September 4th (September 5th UT) Howell is just 14′ southwest of the 8.4-magnitude globular cluster NGC 5897, offering an interesting photographic opportunity. On the evenings of the 26th and 27th (UT), the comet passes roughly 1° north of brilliant Antares.

Comet 88P/Howell was the destination of the proposed Comet Rendezvous, Sample Acquisition, Investigation, and Return (Corsair) mission submitted to NASA in 2017. Corsair would have gathered samples from the comet and returned them to Earth for analysis. Although the mission didn't make the cut, you can show Comet Howell some love on clear September evenings.

▼ Comet 88P/Howell is an early evening object low in the southwest throughout September. Its position is plotted for the dates indicated at 0^h UT, which corresponds to 8 p.m. EDT the preceding day.



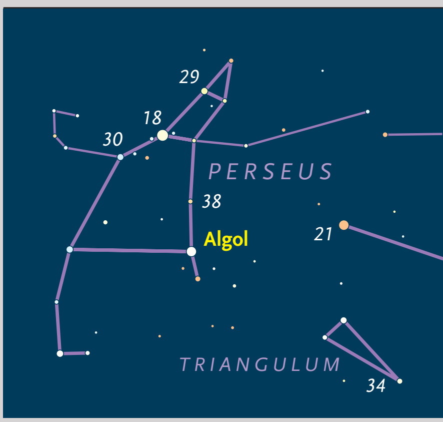
Mars and Beta Scorpii Eclipsed

SEPTEMBER FEATURES two occultations involving the Moon. First, on the night of September 5–6, skywatchers in North America can see the waning gibbous pass just south of brilliant Mars. However, observers across the middle of South America, as well as the northern half of Africa, southernmost Europe, and the Middle East get to watch the lunar disk cover the Red Planet. For South America the occultation takes place during night on the 5th, while it will occur in broad daylight or twilight on the 6th for most other locations. (Timings for many cities are posted on the International Occultation Timing Association's website: **https://is.gd/2020MarsOccultation**.)

Second, on September 21st, you can watch the waxing crescent Moon eclipse the double star Beta (β) Scorpii. The event is visible across much of North America, excluding the East Coast. Those located in the middle of the continent (including Mexico and much of Central America) will get the best view. From the West Coast, the beginning of the occultation occurs in daylight, and the star reappears in bright twilight.

Find a spot with a good view to the southwest, as the Moon will be low in the sky. This should be an eye-catching event with the stellar pair (magnitudes 2.6 and 4.5) disappearing stepwise along the Moon's dark limb.

▲ A waxing crescent Moon eclipses the double star Beta Scorpii on the evening of September 21st. This simulation shows the double star moments before the occultation, as seen from Chicago at 8:45 p.m. local daylight-saving time.



▲ With the end of summer in the Northern Hemisphere, Perseus climbs in the northeastern sky in the evening. Every 2.7 days, Algol (Beta Persei) dips from its usual magnitude 2.1 to 3.4 and back. Use this chart to estimate its brightness in respect to comparison stars of magnitude 2.1 (Gamma Andromedae) and 3.4 (Alpha Trianguli).

Minima of Algol

Aug.	UT	Sept.	UT
1	23:59	2	12:53
4	20:47	5	9:42
7	17:36	8	6:30
10	14:25	11	3:19
13	11:13	14	0:08
16	8:02	16	20:56
19	4:50	19	17:45
22	1:39	22	14:33
24	22:27	25	11:22
27	19:16	28	8:11
30	16:05		

These geocentric predictions are from the recent heliocentric elements Min. = JD 2445641.554 + 2.867324*E*, where *E* is any integer. For a comparison-star chart and more info, see **skyandtelescope.org/algol**.

Action at Jupiter

AT THE START OF SEPTEMBER, Jupiter rises before sunset and transits the meridian around 9:30 p.m., local daylight-saving time, when it's well placed for telescopic viewing.

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

All the September interactions between Jupiter and its satellites and their shadows are tabulated on the facing page. Find events timed for late at night in your time zone, when Jupiter is at its highest.

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

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

September 1: 3:10, 13:05, 23:01; **2**: 8:57, 18:52; **3**: 4:48, 14:44; **4**: 0:40, 10:35, 20:31; **5**: 6:27, 16:22; **6**: 2:18, 12:14, 22:10; **7**: 8:05, 18:01; **8**: 3:57, 13:52, 23:48; **9**: 9:44, 19:40; **10**: 5:35, 15:31; **11**: 1:27, 11:22, 21:18; **12**: 7:14, 17:10; **13**: 3:05, 13:01, 22:57; **14**: 8:53, 18:48; **15**: 4:44, 14:40; **16**: 0:36, 10:31, 20:27; **17**: 6:23, 16:18; **18**: 2:14, 12:10,

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22:06; **19**: 8:01, 17:57; **20**: 3:53, 13:49, 23:44; **21**: 9:40, 19:36; **22**: 5:32, 15:27; **23**: 1:23, 11:19, 21:15; **24**: 7:10, 17:06; **25**: 3:02, 12:58, 22:53; **26**: 8:49, 18:45; **27**: 4:41, 14:36; **28**: 0:32, 10:28, 20:24; **29**: 6:20, 16:15; **30**: 2:11, 12:07, 22:03

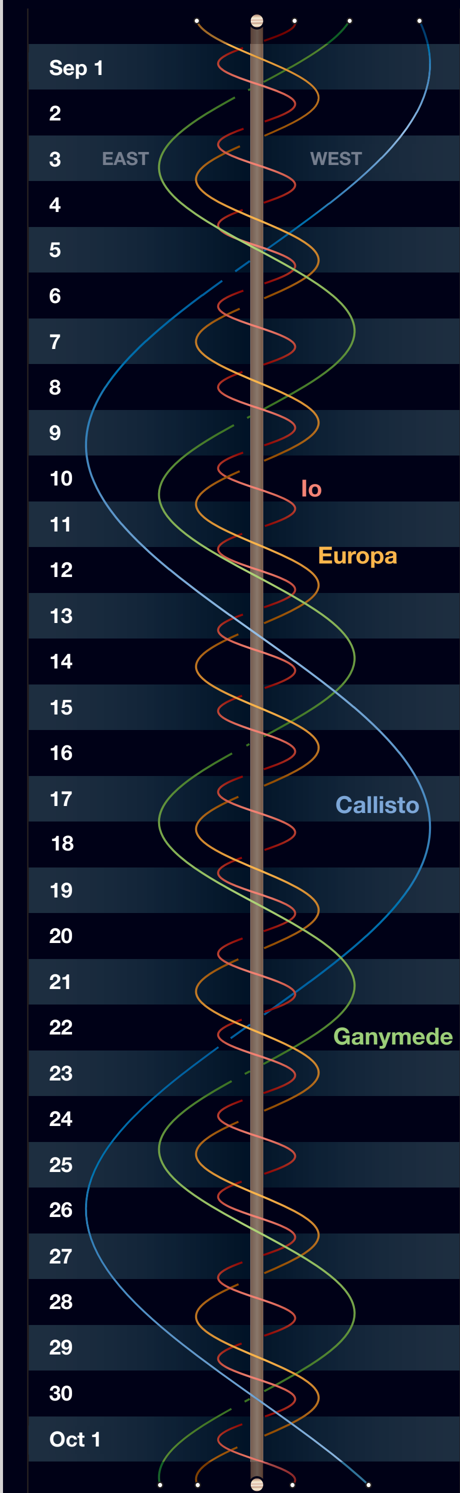
These times assume that the spot will be centered at System II longitude 340° on September 1st. If the Red Spot has moved, it will transit 1⅔ minutes earlier or later for each degree less or more than 340°.

Phenomena of Jupiter's Moons, September 2020

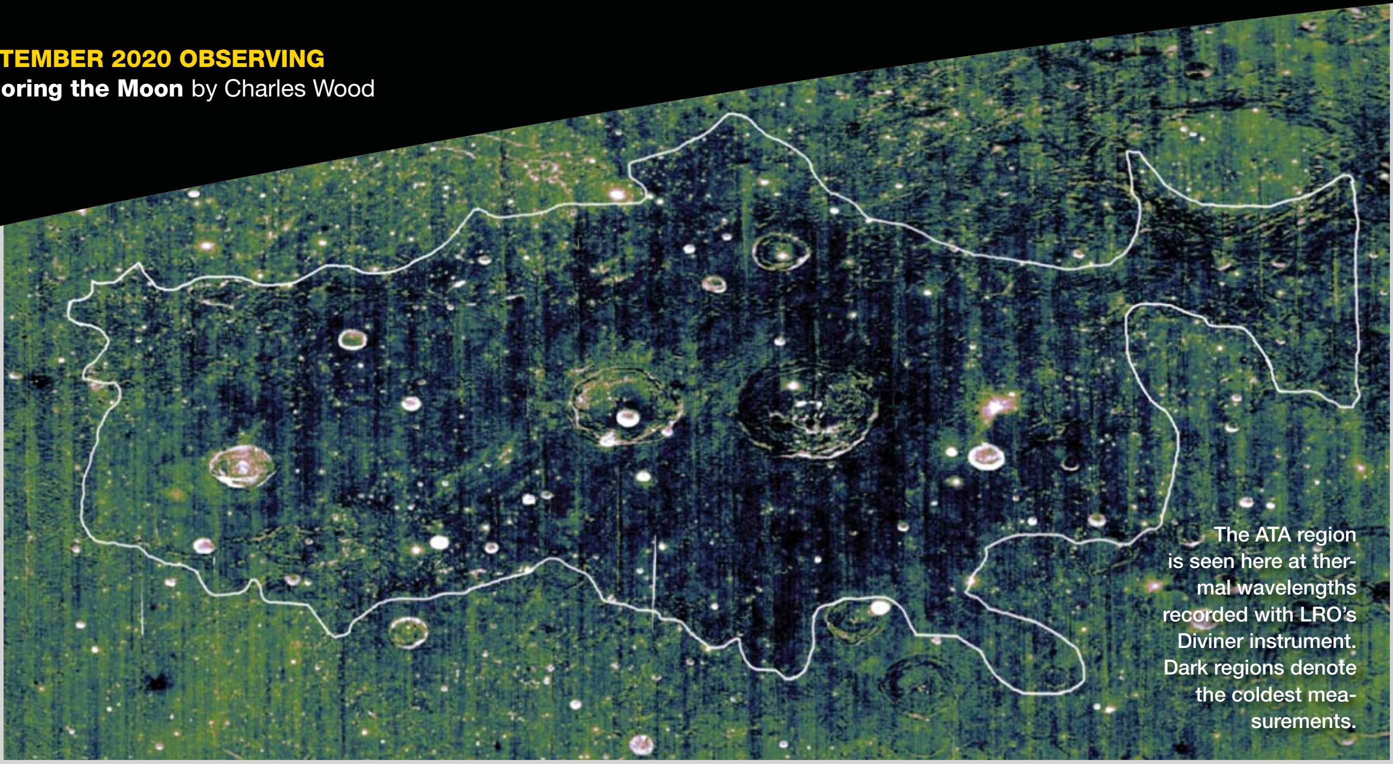
Sept. 1	1:53	I.Ec.R
	5:29	II.Tr.I
	7:32	II.Sh.I
	8:16	II.Tr.E
	10:21	II.Sh.E
	19:54	I.Tr.I
	20:22	III.Oc.D
	20:56	I.Sh.I
	22:10	I.Tr.E
	23:13	I.Sh.E
	23:42	III.Oc.R
Sept. 2	0:34	III.Ec.D
	4:00	III.Ec.R
	17:01	I.Oc.D
	20:22	I.Ec.R
Sept. 3	0:31	II.Oc.D
	5:31	II.Ec.R
	14:21	I.Tr.I
	15:25	I.Sh.I
	16:37	I.Tr.E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



The ATA region is seen here at thermal wavelengths recorded with LRO's Diviner instrument. Dark regions denote the coldest measurements.

The Moon's Biggest Cold Spot

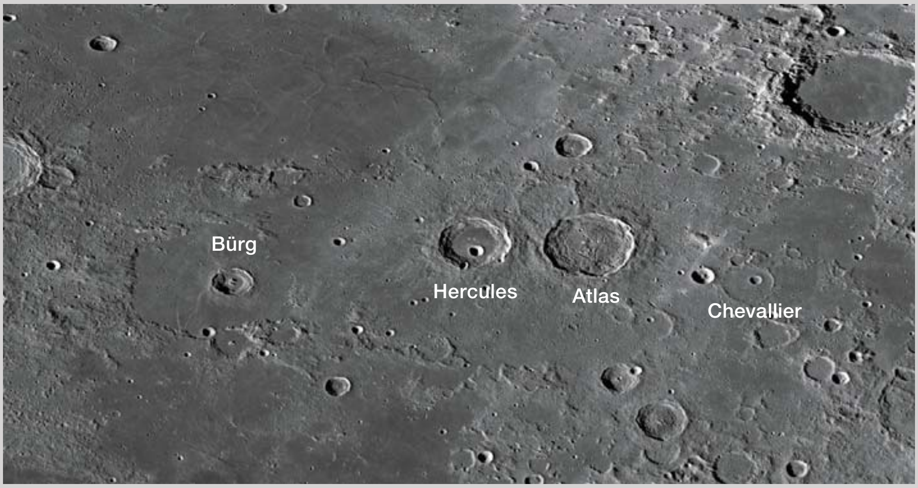
This popular lunar region hides an enduring mystery.

For more than 350 years, scientific examination of the Moon was limited to observations made at visible wavelengths. Beginning in the 1960s, instruments coupled to telescopes and flown aboard lunar orbiting spacecraft began to detect previously unknown surface characteristics in images recorded at visible wavelengths and beyond. Perhaps the most famous are false-color images revealing brightness variations within lava flows due to different chemical compositions in the lunar maria. The most prominent example is the dark band of lavas along the outer edges of **Mare Serenitatis**. Spectral imaging analysis identified this dark band as titanium-rich lavas, while the lighter-hued lavas seen elsewhere on the Moon were found to be titanium-poor.

Furthering this trend of discovering previously unknown features beyond those apparent in visible light, the Diviner Lunar Radiometer Experiment on board NASA's Lunar Reconnaissance Orbiter spacecraft continues to reveal the thermal structure of the lunar regolith. High-resolution, high-sensitivity mapping in thermal infrared wavelengths at 13 to 400 micrometers demonstrates that the upper few centimeters of regolith has a generally uniform surface temperature. Notable exceptions are distal areas around small, young impact craters, and older pyroclastic deposits, both of which are distinctly colder. The late researcher Joshua Bandfield, formerly of the Space Science Institute in Boulder, Colorado, and his colleagues call these enigmatic areas "cold spots." The spots are not fully understood but are thought to be made up of areas containing mainly fluffed-up, loose regolith that loses its daytime heat much quicker than the surrounding materials do.

Cold spots are usually associated with identifiable surface features (ejecta from small, bright impact craters, and larger, dark pyroclastic deposits of

▼Although undetectable at visual wavelengths, the ATA is a region in the northwest section of the Moon that stretches from Bürg crater in the west to past Chevallier crater in the east, as seen in this LRO mosaic.



NASA / GSFC / ARIZONA STATE UNIVERSITY (2) volcanic ash), with the sole exception of the most unique cold spot: a broad area stretching from west of the crater **Bürg** to east of **Atlas** that is much larger than other cold spots and whose existence is inconspicuous in images recorded at visual wavelengths.

A recently released abstract from the cancelled 2020 Lunar and Planetary Science Conference by Joshua Cahill of The Johns Hopkins University Applied Physics Laboratory and colleagues presented the first detailed study of this region, dubbed the Atlas Thermophysical Anomaly (ATA), for the crater nearly centered within it. Besides the ATA's large extent, the group discovered other unique characteristics.

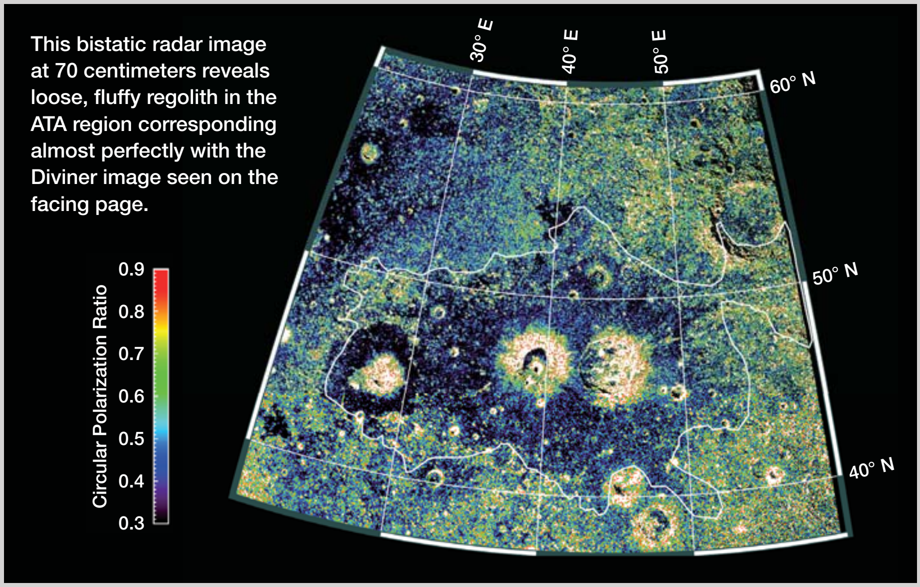
Normally, lunar cold spots are undetectable in radar images, but the dark surface of the ATA is quite noticeable. Another strange characteristic is that most large craters surrounded by radar-dark collars are nearly indistinguishable in Diviner thermal data. Atlas, **Hercules**, and Bürg are all radar-dark halo craters inside the ATA that are, as we've seen, unusually conspicuous in Diviner images. Dark areas in radar images indicate that the upper meters of regolith contain fewer boulders than typical regolith found elsewhere on the Moon.

Both Atlas and Hercules are popular targets for lunar observers because they are big enough to be readily observable while also having small features that are challenging to image.

Atlas is an 88-kilometer-wide crater with a floor that averages about 3.3 km below its uneven rim. The reason the floor is relatively shallow is that Atlas is a floor-fractured crater, deformed by rising magma that lifted the floor, creating roughly concentric fractures and two tiny dark-halo craters. Nearby Hercules is 10 km smaller but about 1 km deeper than Atlas. Unlike Atlas, magma that rose beneath Hercules erupted onto the crater floor, creating a dark, skating rink-like surface with one major hazard: 14-km-wide crater, Hercules G. The reason magma erupted onto the floor of Hercules and not into neighboring Atlas may be due to Hercules residing directly above the edge of a buried magma mega-dike revealed by a gravity anomaly linking **Mare Frigoris** and Mare Serenitatis. Although geologically interesting, it's not clear that the anomaly is related to the ATA.

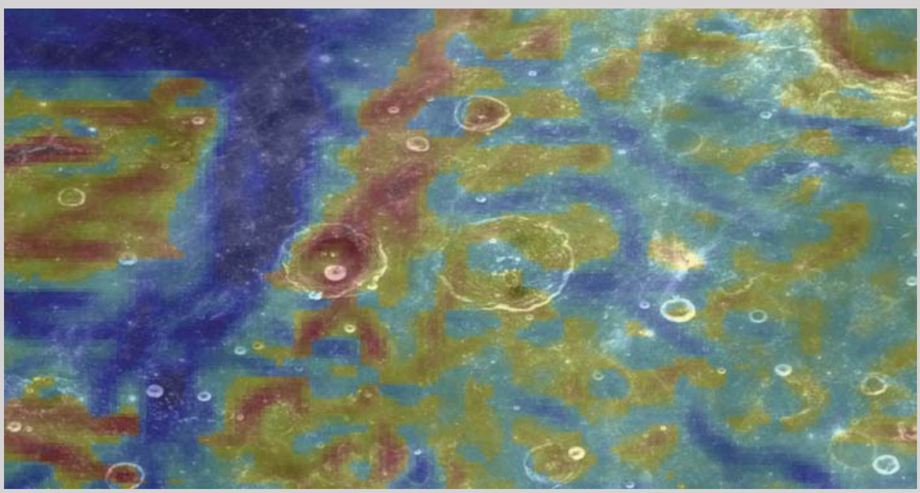
The ATA adds another attraction for observers. Although the cold thermal anomaly and radar-dark halos are invisible in your telescope, these oddities must be related to Atlas, Hercules, and Bürg. Small volcanic dark-halo craters and ejecta along rilles cutting across the eastern floor of Atlas are *just* observable under high Sun illumination. But there is no evidence for similar volcanism outside Atlas, so the extensive ATA cold spot is unlikely to be due to a widespread pyroclastic deposit. It's possible that the ATA is caused by an overlap of radar-dark halo-crater ejecta, but if so, why are all the other dark-halo craters indistinguishable in thermal images? No one fully understands this anomalous terrain, yet you have the privilege of observing the region before scientists can explain it.

■ Contributing Editor **CHUCK WOOD** has studied the Moon for more than five decades.



This bistatic radar image at 70 centimeters reveals loose, fluffy regolith in the ATA region corresponding almost perfectly with the Diviner image seen on the facing page.

▼Atlas (center right) and Hercules (center left) appear here as shown in the LRO QuickMap, with a color overlay of the GRAIL gravity gradient map. The broad purple swath seen on the left is thought to be a buried dike that once distributed mare basalt magma to Mare Frigoris (top left) and Mare Serenitatis (bottom left). The edge of the dike lies below the western edge of Hercules and may have supplied the magma that flooded that crater's floor.



RADAR: CAHILL ET AL 2020 LPSC #2936; GRAIL OVERLAY: NASA / GSFC / ARIZONA STATE UNIVERSITY

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 Berkeley Clusters

These groupings are rarely observed but often rewarding.

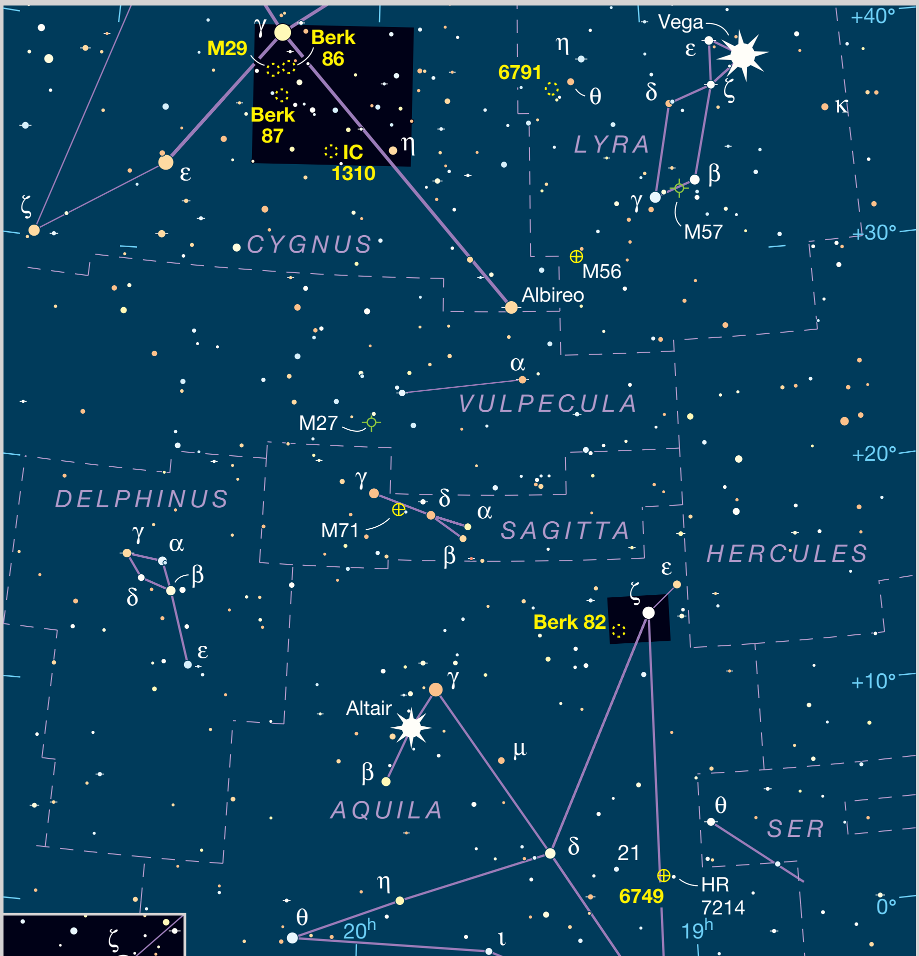
In 1962 Arthur F. Setteducati and Harold F. Weaver of the University of California, Berkeley, published a two-part paper entitled *Newly Found Star Clusters*. It contains the list of 104 objects that now bear the designation Berkeley. The paper is rather rare, and I was quite pleased when Canadian amateur Pierre Paquette sent me a scanned copy from the Gerstein Science Information Center in Toronto. This inspired me to observe Berkeley clusters that are well placed at this time of the year, and I've selected some noteworthy examples for this month's sky tour.

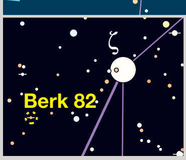
Let's start in Aquila with Berkeley 42, the only globular cluster among the Berkeleys. It's more commonly known as **NGC 6749**. The Setteducati and Weaver paper includes some objects with NGC (*New General Catalogue*) designations that had been "overlooked in the recent literature." Despite the more common NGC designation, this is not an easy Berkeley cluster. In fact, it might be the most difficult one we'll visit, because it's camouflaged in a rich Milky Way star field.

NGC 6749 lies one-sixth of the way (26′) from the 5.8-magnitude star HR 7214 to 5.1-magnitude 21 Aquilae, as shown in the chart at left. Through my 130-mm refractor at 63×, it's fairly apparent as a low-surface-brightness puff flanked by two 11th-magnitude stars. The stars are 5.8′ apart and aligned almost east-west, with the globular nearly nudging the eastern star. At 102×, the 3′ ghostly ball of light rests on a 2′ trapezium of 12th- and 13th-magnitude stars, the star at its northwest corner closely guarding the fringe of the cluster. NGC 6749 is slightly brighter in the center, and there's a very faint star superposed in the northeast.

None of the stars I saw belong to the cluster, whose brightest members shine at magnitude 16.5. Their feeble light is not due to distance — NGC 6749 is about the same distance from us as the much more easily resolved Great Cluster in Hercules (Messier 13). But while our window to M13 is relatively clear, the stars of NGC 6749 suffer 4.7 magnitudes of extinction from intervening dust clouds. Setteducati and Weaver comment: "Although it is described as a cluster in the NGC, later attempts to identify it photographically were unsuccessful, presumably because of the very heavy obscuration."

Next, let's leap northward to Lyra, where we'll find open cluster **NGC 6791** (Berkeley 46) sitting 58′ east-southeast of golden Theta (θ) Lyrae and 29′ northeast of a pair of 6th-magnitude stars. My 130-mm refractor at 37× shows a





▲The objects discussed here are scattered over a wide swath of sky. The main chart shows stars to magnitude 6.5, and the close-up for Berkeley 82 shows stars to magnitude 9.5.

◀ NGC 6791 is 29′ northeast of a pair of 6th-magnitude stars.
▼ NGC 6749 lies 26′ east and a little north of the star HR 7214.

pretty gathering of several faint to very faint stars awash with haze. At 102×, 14 stars fleck a subtly textured glow 10′ across. Some must be foreground stars, since only a few the cluster's probable members shine brighter than 14th-magnitude. In my 10-inch reflector at 170×, the haze glitters with many barely visible motes of light, while my 14.5-inch scope unveils a grand flurry of faint suns.

NGC 6791 is an exceptionally ancient and populous open cluster, roughly 8 billion years old with 3,000 stars. It lies about 13,000 light-years away — half the distance of NGC 6749.

The Berkeley list contains one object that bears an IC (*Index Catalogue*) designation, **IC 1310** (Berkeley 50). Setteducati and Weaver note that IC 1310 inhabits a nebulous region of the sky and had been previously listed as a diffuse nebula.

Although a sweep 2.8° east from golden Eta (η) Cygni will take you straight to IC 1310, this region of Cygnus is so crowded with stars, clusters, and nebulae that a careful star-hop using the chart on page 56 may be necessary to pinpoint the cluster's location. It lies 10′ northwest of an 8.3-magnitude star and 6′ south of an 8.9-magnitude star, as shown in the photo at the top of page 56 and the star chart on the same page.

My 130-mm scope at 102× displays three faint stars arrayed in an equilateral triangle. A patch of haze is centered on the southern star and reaches as far as the northeastern one. Two additional stars dot the haze. At 164× the star tally reaches eight, and the cluster appears to span 2½′.

When I view the cluster through my 10-inch scope at 213×, each star of the triangle has a companion, and a wider star pair to the southeast gives the group the shape of a lower-case y. In total I count 20 faint to extremely faint stars within a 3½′ circle. Most of the stars crowd the joint of the y, where a touch of mist remains. IC 1310 is about 6,800 light-years away, with an age of 250 million years — half as distant and only 3% as old as NGC 6791.

The three Berkeley clusters above are from Setteducati and Weaver's list of 59 "obvious clusters." The next three are from their list of 45 "probable clusters" and are original discoveries by the Berkeley team.

The first is **Berkeley 82**, located 1.6° east-southeast of Zeta (ζ) Aquilae. A curvy line of 7th- to 9th-magnitude stars leads you most of the way from Zeta to the cluster, which appears as a little arc of three dim stars through my 130-mm scope at 37×. The stars are prominent at 102× and line the northwest rim of a 2′ cloudy patch dotted with four very faint stars. The southernmost star seems elongated, and a magnification of 164× shows it to be double while adding several faint stars to the scene.

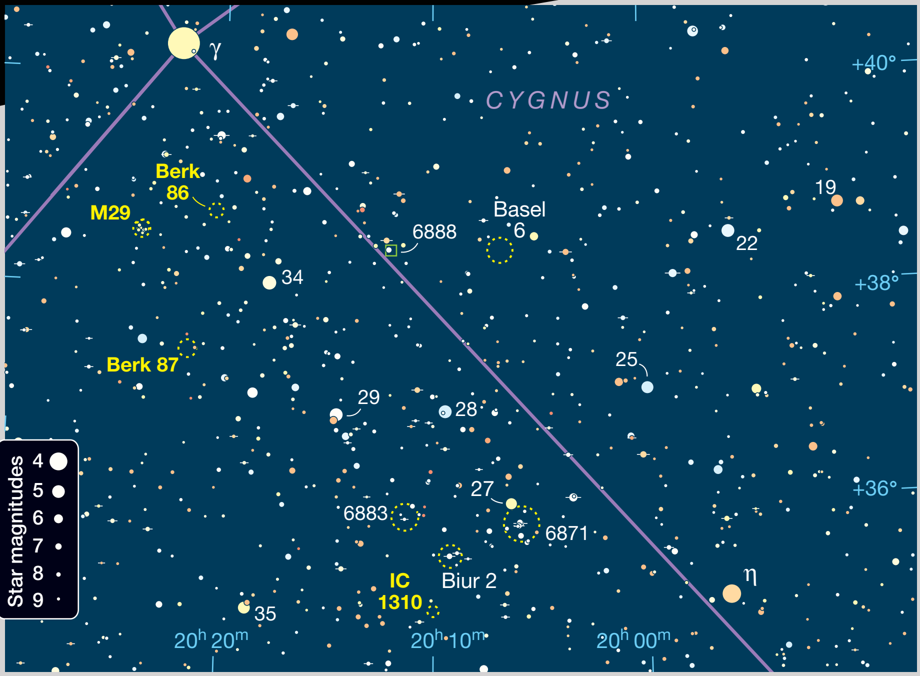
Berkeley 82 is a nearby cluster at 2,800 light-years, and it has a youthful age of 30 million years. It seems to have

An Assortment of Berkeley Clusters

Object	Mag(v)	Size	RA	Dec.
NGC 6749	12.4	4′	$19^h\ 05.3^m$	+01° 54′
NGC 6791	9.5	10′	$19^h\ 20.9^m$	+37° 46′
IC 1310	~10	4′	$20^h\ 10.0^m$	+34° 58′
Berk 82	~9	4′	$19^h\ 11.3^m$	+13° 07′
Messier 29	6.6	10′	$20^h\ 24.1^m$	+38° 30′
Berk 86	7.9	7′	$20^h\ 20.2^m$	+38° 41′
Berk 87	~7	10′	$20^h\ 21.6^m$	+37° 24′

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.

POSS-I / STSCI / CALTECH / PALOMAR OBSERVATORY (2)



▲ IC 1310, the tight knot of stars near the center, is shown here 6′ almost due south of an 8.9-magnitude star and 10′ northwest of an 8.3-magnitude star, both of which are plotted on the star chart at left. The 8.3-magnitude star is a double with components 4″ apart.

formed at the shock front of an expanding supershell of compressed hydrogen driven by stellar winds and supernovae explosions.

To find our next Berkeley cluster, let's start at **Messier 29**, which is fairly easy to sweep up in 7×42 binoculars as a small, granular glow. My 6-inch reflector at 68× shows back-to-back arcs of three bright stars each, and an entourage of dimmer stars plumps the cluster to about 7½′.

From M29, it's a short hop 46′ west-northwest to **Berkeley 86**. With my 6-inch scope at 44×, I see a dozen moderately bright to faint stars, most in a skinny V about 5′ tall. The eastern arm of the V is longer, and a 5′ line of 3 stars proceeds east-northeast from its top. Two of the group's brightest stars appear yellow to my eye. My 10-inch scope at 187× exposes 25 stars in 7′. The star at the point of the V is not generally considered part of the cluster.

Messier 29 is also a good guide to our final cluster, **Berkeley 87**. Dropping 1° due south from M29 will take you to a 6th-magnitude star, the brightest in the area. Berkeley 87 is centered 26′ west-southwest of this star and is a fairly obvious knot of stars through my 105-mm refractor at 28×. The brightest star rests at the west-northwestern edge and glows orange.

A dozen stars are visible at 87×, most forming a lowercase Greek letter chi (χ), although it's mirror-reversed in the refractor's field of view. Another orange spark ornaments the center of the χ. My scope at 118× shows about 25 stars, 9th magnitude and fainter, assembled in an area 10′ across.

Messier 29, Berkeley 86, and Berkeley 87 are generally thought to be concentrations in the Cygnus OB 1 association, a loose stellar grouping that extends across 4° × 3½° of sky and is dominated by massive young stars. The association is centered approximately 5,000 light-years away, and its stars range from about 2 million to 10 million years old.

■ Contributing Editor **SUE FRENCH** wrote this column for the September 2011 issue of *Sky & Telescope*.

Messier 29, by far the brightest cluster described in this article, is relatively easy to spot in a small telescope. Both Berkeley 86 and 87 within a degree to the northwest and southwest are more of a challenge.

IC 1310: POSS-I / STSCI / CALTECH / PALOMAR OBSERVATORY; M29: SEAN WALKER

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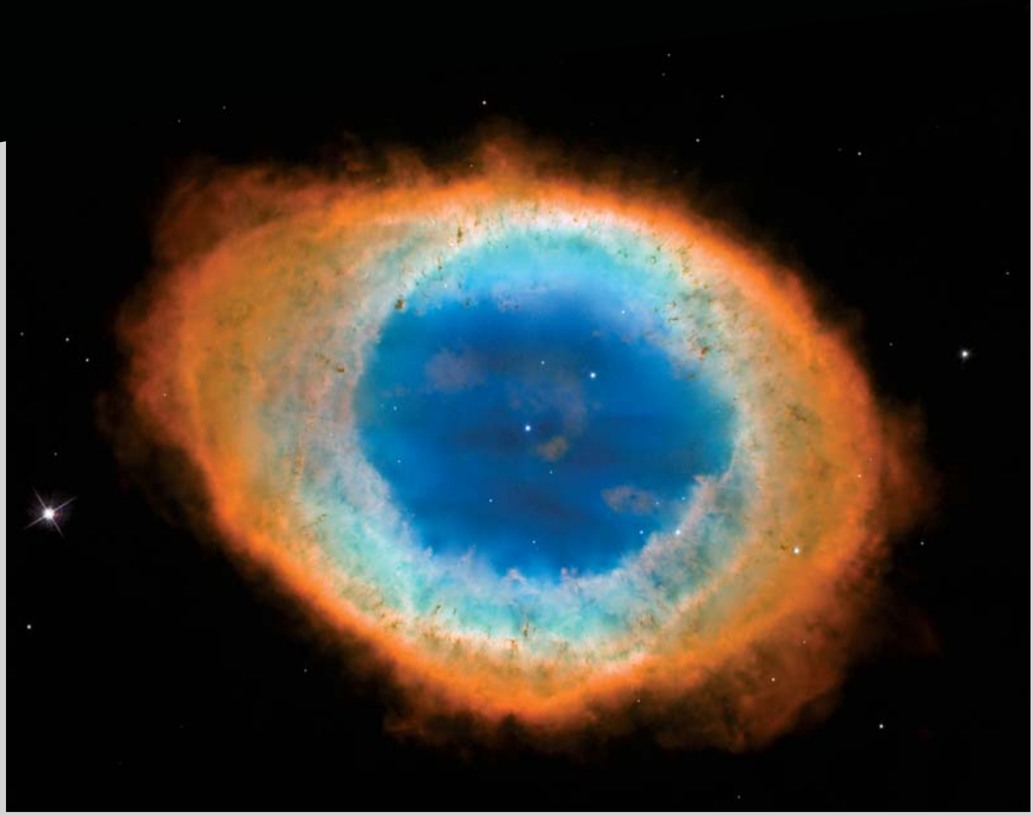


▲ **ETHEREAL BUBBLE** The Ring Nebula floats in Lyra about 2,400 light-years away. At first glance the object appears to consist of a torus of nebulosity, akin to a donut, but there's more to its structure than meets the eye. North is up in all images unless specifically mentioned.

The Ring and I

This well-known planetary nebula is a favorite deep-sky target for beginners and veterans alike.

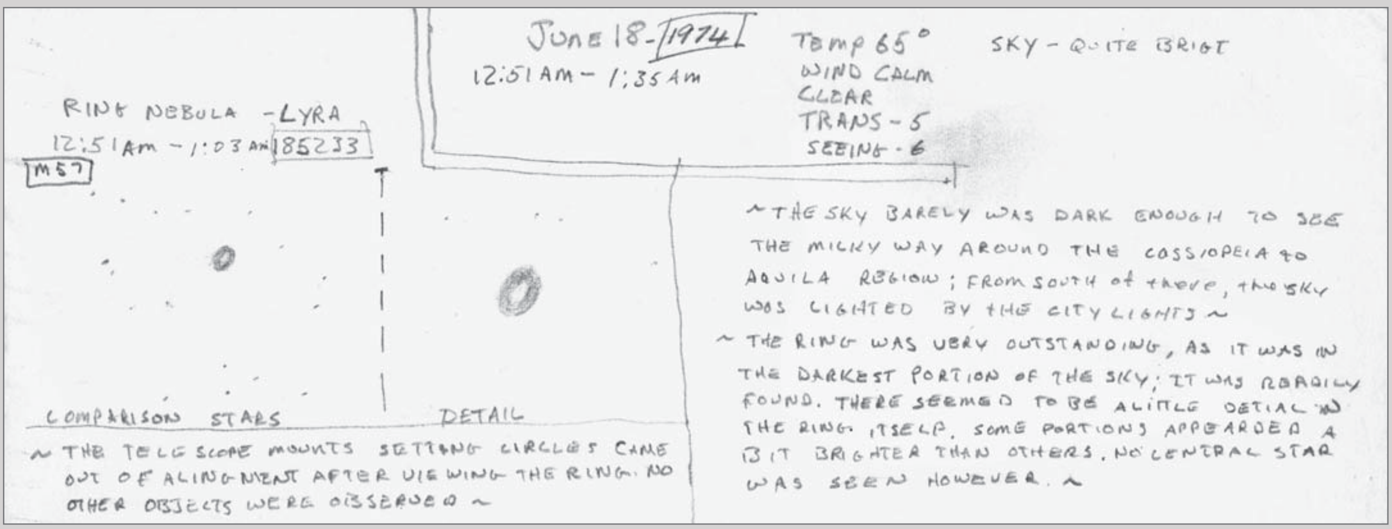
The Ring Nebula and I go way back. Despite my lousy star charts, it was still the first deep-sky object I ever found. I'd been looking for **M57**, as it's also designated, with my 3-inch f/15 Tasco refractor for weeks without success until I finally swept up the 8.8-magnitude treasure between Beta (β) and Gamma (γ) Lyrae. Wow, was that exciting! It was 1968 and seeing that tiny, surreal oval with its dark central hole for the first time ignited my passion for deep-sky observing.

I also wondered what it might look like in a larger scope. Would I be able to see its famously difficult central star? I proceeded to order a mirror-making kit from Edmund Scientific — an event that ushered in my aperture fever.

With that kit I built an 8-inch f/4 Newtonian during the summer of 1969, and five years later I started sketching deep-sky objects at the eyepiece. Again, the Ring Nebula was my first choice. During the early morning of June 18, 1974, I wrote:

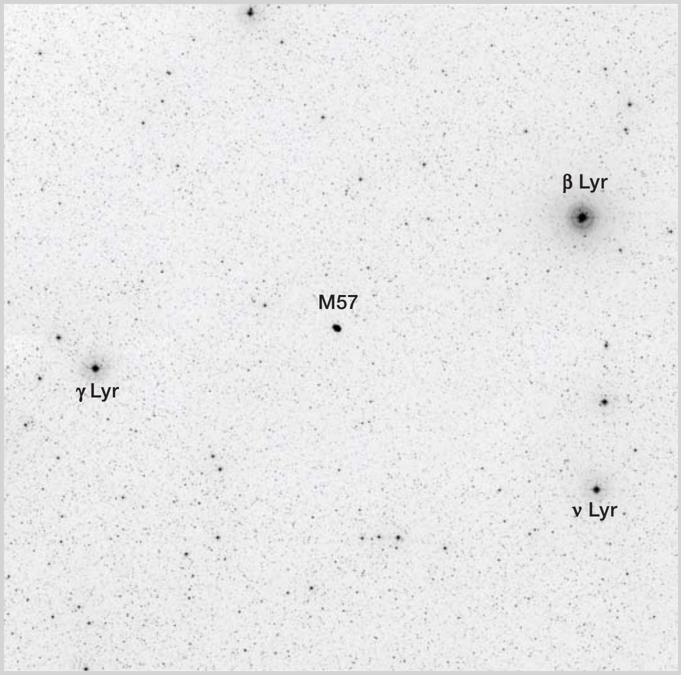
"The Ring was very outstanding, as it was in the darkest portion of the sky; it was readily found. There seemed to be a little detail in the Ring itself. Some portions appeared a bit brighter than others. No central star was seen however."

I've observed M57 many times since



▲ **FIRST-EVER DEEP-SKY SKETCHES** At magnitude 8.8 and with a size of 1.8′ × 1.4′, the Ring Nebula is a bright and easy catch in an 8-inch scope. Although I didn't record the magnification I used for these sketches, the low-power view was probably sketched at 41× and the detailed view at 160× or so. Note how I sketched the dark center as distinctly oval, just like the perimeter of the main ring. North is to the left in both sketches.

M57: NASA / ESA / C. ROBERT O'DELL; FIRST SKETCHES: HOWARD BANICH



▲ **FINDING THE RING IS EASY** Look for M57 about halfway between Beta (β) and Gamma (γ) Lyrae at 18^h 53.6^m, +33° 02′.

then and gradually discovered more to it than its bright, readily apparent ring and its tiny pinprick of a central star. One of the Ring's more fascinating characteristics is its namesake shape. But is it really a ring? Or might it be an illusion of perspective?

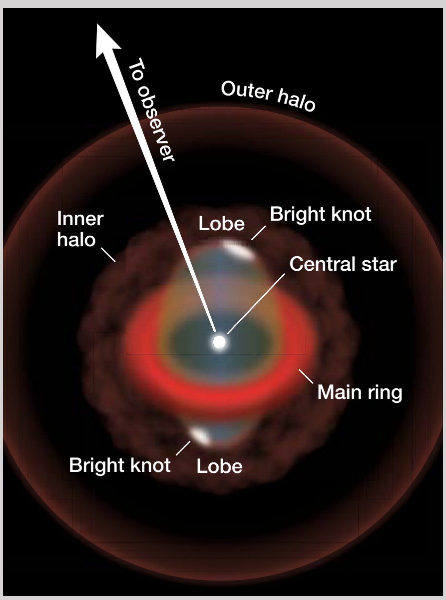
The Main Ring

Contrary to what I wrote a couple of years ago in an article on M27 (*S&T:* July 2018, p. 66), the 3D shape of the Ring Nebula isn't similar to that of the Dumbbell Nebula. Instead, recent studies of M57 show that the bright, oval main ring is a nebulous torus that we see nearly face on.

The Ring is brightest and most sharply defined along its minor axis because this material is closer to the central star. Note (for example in the Hubble image on page 58) how the fainter major axis ends of the Ring seem to taper as they fade outward, as compared to the brighter and more sharply defined minor axis arcs.

These details are obvious in larger scopes, but a careful look with an 8-inch instrument at high power will show this brightness difference, too. I've also found that nebula filters don't bring out hidden features of the main ring, but they do make it appear brighter.

At first glance, I see the northeast end of the main ring as the most elongated, but with averted vision the southwest end pushes out a little farther. In short, the main ring is a cosmic Cheerio with slightly squashed ends.



▶ **VISUALIZING THE NEBULA** This 3D diagram portrays the geometry and structure of M57 as viewed from a perspective different to that of an observer on Earth. It shows the two halos in relation to the main ring and its internal, lozenge-shaped bubble. What we see as the "ring" is in fact the brightest part of the nebula.

The Dark Center

The Ring's dark center is more circular than oval. It's a striking feature, but, curiously, what I first noticed was the subtle, gently glowing nebulosity within.

The brightest parts are two evenly spaced, parallel bands of nebulosity stretching through the dark center along the Ring's major axis. Although visible in most images, I find that the bands can be detected visually only when the sky is exceptionally transparent. The first time I saw them was on August 6, 1983, with my 12.5-inch f/7.9 Dobsonian:

I thought I might glimpse the central star tonight as the sky was clear, dark and M57 was in the darkest part . . . When I first looked at 117× I thought I saw it — my heart nearly stopped! At 240× I examined the Ring very closely — but nothing! Well, not exactly — looking at the Ring is hardly "nothing!" Nebula structure was visible with averted vision in the central hole. Looking at M57 is always time well spent.

FINDER FIELD: POSS-II / STSCI / CALTECH / PALOMAR OBSERVATORY; 3D DIAGRAM: GREGG DINDERMAN / S&T, SOURCE: NASA / ESA / A. FEILD (STSCI)

During the summer of 2019 I saw just a single, wide band with my 28-inch scope. Although the outer edges of this band were distinct, no matter the magnification, filter or no filter, I couldn't see a dark lane dividing it in two. The wide band's edges and the bright inner borders of the Ring form two dark gaps that highlight the band. Although I saw it unfiltered, a UHC-style filter boosted contrast.

Whether one band or two, they're a feature of the Ring's polar axis bubble. Imagine a lozenge-shaped bubble of delicate nebulosity, girded in its middle by the main Ring, with its major axis more or less pointed in our direction. The banded features are on both the approaching and receding surfaces of the bubble, so they only *appear* to be inside the dark center because of our perspective. I love this stuff!

Not One but Two Stars

The very hot white dwarf (120,000 kelvin) at the center of the Ring is responsible for ionizing the surrounding nebula. The star was at the top of my must-see observing list for more than 20 years. It wasn't until first light with my 20-inch f/5 Obsession reflector on September 14, 1991, from my suburban backyard that I finally saw it. M57 was my first deep-sky object with this scope, too:

> *I worked up to 507× (!) before I finally caught a series of fleeting glimpses — this is a faint star! Under a dark sky it should be easier, but I don't think it will be easy because the surrounding nebula in the center of the Ring will be brighter too. I spent an hour on this; just to show how tough it is.*

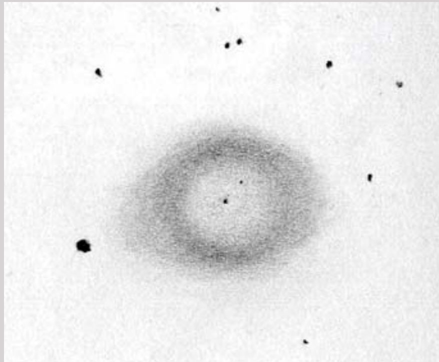
I've since learned that much smaller scopes can show the central star. In fact, the German astronomer Friedrich von Hahn reported in 1800 that he had discovered it several years prior with a 12-inch reflector. Many observers with comparably sized instruments since then have also spotted it. I *could* have seen it with my 12.5-inch scope some years earlier if only I'd used more magnification.

A combination of good seeing and high magnification is essential for spotting the white dwarf. At magnitude 15.7, it's a tiny spark that looks even fainter due to the Ring's surrounding brightness. Reduced contrast with the subtle nebulosity in the nebula's center doesn't help either. This star is worthy of its tough reputation. That said, on the very best nights, the white dwarf's light-blue color can be seen in large scopes.

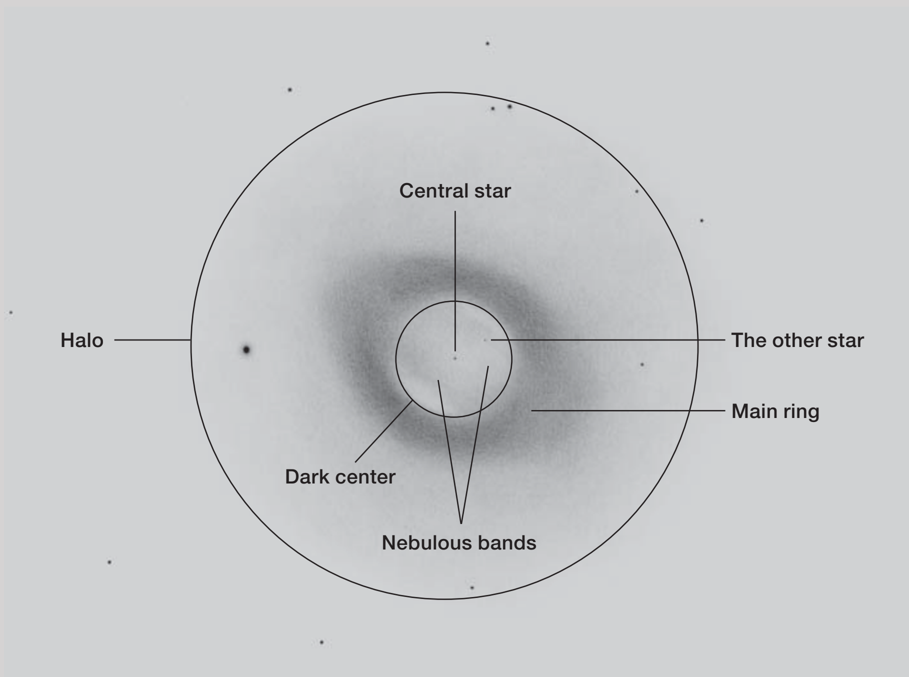
Northwest of the white dwarf a magnitude-16.2 star that's unrelated to M57 peeps through the Ring's dark center. I figured this star should be visible nearly as often as the central star — it's only half a magnitude fainter — but it took me another 15 years to see the darn thing. My notes from August 23, 2006, when observing with the 28-inch read:

> *The second star is finally, definitely seen! Wahoo! Averted vision is needed, but with the real central star so easy with direct vision (and a definite tinge of blue) and the seeing quite excellent, this had to be the night. Best view was at 1422× and 1138× — but 1422× was the most impressive. Chuck [Dethloff, cofounder of the Oregon Star Party] saw it too so we're both excited. How cool is this!!*

In short, this is a *much* more difficult catch than the central star. Good luck.



◀ **THE OTHER STAR** This eyepiece sketch shows that the planet-size white dwarf is in the exact center of the dark oval and the other star is just to its northwest. The latest Gaia DR2 data release indicates that the second star is nearly four times farther away than the central star — and pins down their magnitudes.



▲ **DISSECTING THE RING** The large circle shows the visible extent of the inner halo, which has a diameter of 1.5 light-years. The main ring — the most visible part of the Ring Nebula — is about 1 light-year across its major axis and 0.7 light-year along its minor axis.

HOWARD BANICH (2)

GRAND FINALE This sketch of M57 as seen through my 28-inch telescope combines the low-power (subtle colors and inner halo) and high-power (infamous white dwarf) views as described in the article. Note the central star's light-blue color and how tiny it seems, both of which are realistically portrayed. This drawing also shows the approximate image scale you'll need to magnify the Ring to have a good chance of seeing this tiny spark of a star.

HOWARD BANICH

The Halo

The Ring's subtle halo consists of two parts, inner and outer. You'll likely only see the brighter, inner portion, and you'll need dark, transparent skies. It shows best in my 28-inch scope with moderate magnifications around 155× to 253×. A nebula filter helps, but on a good night I can see the inner halo without one.

The outer halo was ejected more than 25,000 years ago by the white dwarf progenitor's stellar wind when it was on the *asymptotic giant branch* (the final evolutionary stage of low- to intermediate-mass stars). The inner halo was likely ejected more than 14,000 years ago, well before ionization of the main Ring began about 7,000 years ago. The feeble glow of the combined halo is called *fossil radiation* because it's no longer being ionized by the central star.

The inner halo — the one you'll likely see — has a diameter of 1.5 light-years and is composed of a series of bubbles enveloping the Ring. As you can note from my sketch, the inner halo approximately doubles the visual extent of the Ring before fading away into the seemingly invisible outer halo.

The Ring in Color

Kids almost always say the Ring looks "bluish-green with a pink border" through my 28-inch. Although delighted by their descriptions, I've also been secretly miffed because all I could see was grey.

That changed during the summer of 2019 when I gave my 28-inch primary mirror a fresh spray-silver coating. Suddenly, colors appeared. They're subtle, but as long as the sky is transparent, I see them nearly as well from my backyard as from a super-dark site. I also found that the lower the humidity, the more obvious these colors appear.

On July 30, 2019, during the Oregon Star party I observed the Ring in a superb sky:

At 114× and 135× (no Paracorr) the colors were obvious. The brightest parts of the Ring were greenish-blue tinged with orange along its outer perimeter. Best with my right eye, but easily seen with my left as well. Flashing my right eye with white light made the colors even more apparent, and a beautiful sight. 22.00 SQM.

So, it seems that young eyes or new mirror coatings along with the lowest available magnifications are the ticket for seeing colors in the main ring. The different hues are due to varying levels of ionization from the central star, with the orange perimeter being the ionization boundary. The effect in the eyepiece is spellbinding.

But then, everything about the Ring Nebula is that way. Like many exceptional objects it seems both new and familiar at the same time and is as fascinating to explore with a large telescope as with a small one. Folded into all this, the Ring is a special object for me because it was my first step into the depths and glories of the deep sky and has unexpectedly — and delightfully — challenged me ever since.

■ Contributing Editor **HOWARD BANICH** can be reached at **hbanich@gmail.com**.

FURTHER READING: Find out more about the evolution and 3D structure of the Ring Nebula at **https://is.gd/odell2013**. For a 3D animation of the ring's structure go to **https://is.gd/m57_3d**.

DEEP-SKY DELIGHTS by Ken Hewitt-White

The Andromeda

▲ **EDGE-ON ISLAND UNIVERSE** The large but relatively faint galaxy NGC 7640, located in northwestern Andromeda, is fairly close in cosmic terms — around 30 million light-years away. However, the edge-on system is dimmed by the gas and dust in our own galaxy, as it lies very close to the band of the Milky Way.

ESA / HUBBLE / NASA

My bookshelves are full of treasured astronomy resources I've collected throughout several decades of observing. One of my favorite oldies is the original two-volume *Night Sky Observer's Guide* by George Kepple and Glen Sanner, published in 1998 (a third volume covers the southern heavens; the recently published fourth volume is titled *Glories of the Milky Way to –54°*). The black-and-white photos in those 1998 editions can't compare to today's colorful digital images, but the handpicked descriptions by top deep-sky enthusiasts still interest me and I enjoy perusing them.

Last September, I had an itch to explore what I call the Andromeda Outback. An inconspicuous tract of celestial real estate stretching from the Great Square of Pegasus to Cassiopeia, the region is often overlooked and I hadn't visited it in years. Opening *Volume 1* of the *Guide*, I found what I needed on Finder Chart 2-6 (page 23). In a square of sky 10° by 10°,

Outback

Exploring northwestern Andromeda reveals subtle but satisfying wonders, such as the Blue Snowball Nebula.

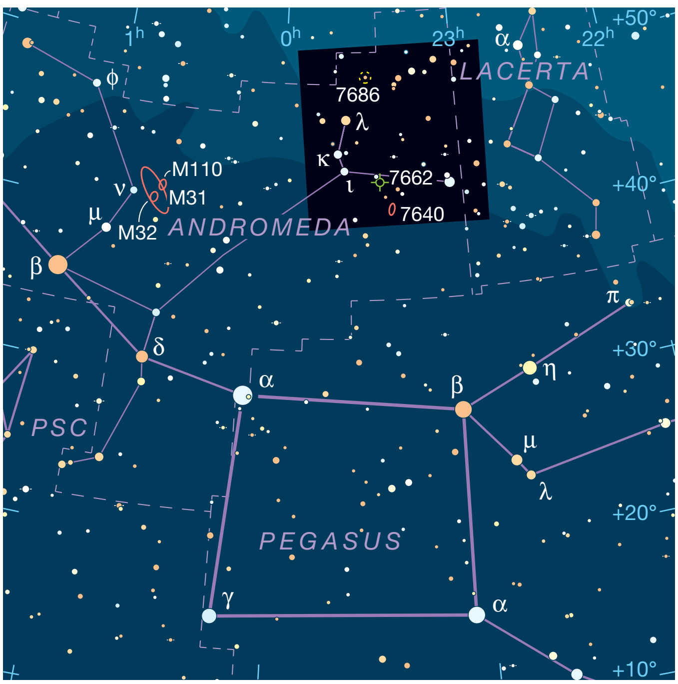
the chart plots a sparse open cluster (NGC 7686), a prominent planetary nebula (NGC 7662), a sizable edge-on galaxy (NGC 7640), and several double stars. I attacked the field from a high-elevation "dark park," employing my 18-inch f/4.5 Dobsonian, then later from my suburban yard using smaller scopes. Surprisingly, the city observations weren't futile.

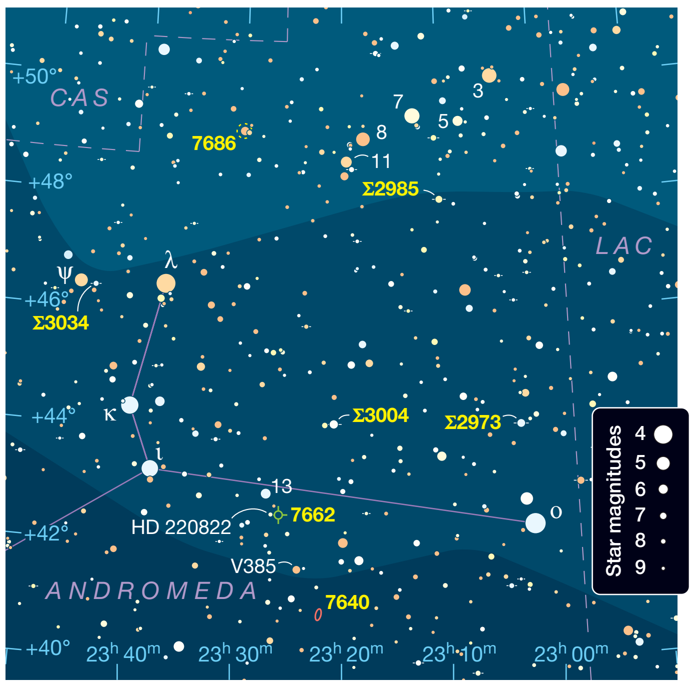
Hiding in Plain Sight

First, the country views. A dedicated star-hopper, I planned my route around the 4th-magnitude stars Lambda (λ), Kappa (κ), and Iota (ι) Andromedae located about 15° north of the Great Square. The trio bends northwestward toward a ragged and less conspicuous curve highlighted by 3, 5, 7, 8, and 11 Andromedae. I familiarized myself with the area in binoculars, then grabbed my voice recorder and took to the telescope.

After locating 5th-magnitude 8 Andromedae in my 8×50 finderscope, I shifted the 18-incher eastward 2° to an important pair of stars just shy of 5′ apart. Orangey 6.2-magnitude HD 221246 and creamy-white 7.7-magnitude HD 221203 overlie the open cluster **NGC 7686**. Unfortunately, the brighter beacon — HD 221246 — almost obliterates this relatively obscure group. Indeed, there's no firm agreement that NGC 7686's several dozen stars, scattered across 15′ of sky (and of uncertain distance), add up to a true cluster. And yet, as my tape-recorded initial impression attests, "I'm glad I tracked this down. There's definitely something here."

Officially, NGC 7686 shines at magnitude 5.6, but this value includes my two beacon stars. Many of the members are fainter than 9th magnitude. In the big Dob at 69× (my lowest magnification), I traced a raggedy zigzag of perhaps a dozen 9th- to 12th-magnitude stars running west-northwestward across the cluster's northern perimeter. I followed a tighter chain of eight or nine 11th- to 13th-magnitude stars trending in the same direction from HD 221203. In between the approximately parallel chains, I detected some weaker pinpricks plus a grainy background suggesting more stars. Wanting to zoom in for a better look while still containing the entire cluster in one pleasing view, I selected an ultra-wide-field eyepiece of 13-mm focal length. Delivering 158×, the ultra-wide resolved the grainy mixture into at least two dozen stars, though the ones closest to the orange beacon were trying awfully hard not to be seen!





▲ **PEGASUS POINTS THE WAY . . . TO THE ANDROMEDA OUTBACK** The author's starting point for his exploration of what he fondly calls the Andromeda Outback is a trio of stars located about 15° north of the Great Square of Pegasus. Lambda, Kappa, and Iota Andromedae, identified here, are also plotted (though not labeled) on this month's centerfold star chart.

◀ **ODDBALL OPEN CLUSTER** Two likely foreground stars — the orangey 6.2-magnitude star HD 221246 (left of center) and HD 221203, the brighter star to its southwest — dominate the sparse, relatively faint star cluster NGC 7686.

Hardly a robust specimen, NGC 7686 nevertheless presented an interesting arrangement of stars, and its pleasant setting on the edge of the Milky Way added to its appeal. Four favorable factors — black sky, decent aperture, medium magnification, and the generous field of view — allowed me to appreciate this modest cluster hiding in plain sight.

Celestial Snowball

Continuing my ramble in the Andromeda Outback, I re-aimed my finderscope at the big bent line of Lambda, Kappa, and Iota. From the latter star, and with my eye glued to the finder, I pushed 2° westward to sweep up 6th-magnitude 13 Andromedae. Switching to the main telescope (still operating at 158×), I inched ⅓° southwest to pick up 8.2-magnitude HD 220822, then nudged 8′ farther west to spot the 8.3-magnitude Blue Snowball Nebula, **NGC 7662**.

This superb object was discovered in 1784 by William Herschel. In fact, it was Herschel who likely coined the term *planetary nebula*. The great English astronomer had found numerous tiny spherical fuzzies that reminded him of the planet Uranus, which he himself had discovered in 1781. Herschel described NGC 7662 as “bright, round, a planetary [with a] pretty well-defined disk.” What Herschel didn’t realize is that the “disk” is actually a ballooning shell of gas sloughed off from the atmosphere of a dying, shriveled star. Like most planetaries, NGC 7662 sports more than one shell. Its pale outer bubble measures about 29″ × 26″ (sources vary), but the “well-defined disk,” or inner shell, is barely half as large. (Herschel noted in his log: “15″ diameter with a 7 feet reflector.”) Regardless of size, the Blue Snowball is surely among the top ten planetaries in the northern heavens.

In truth, I’m not fond of the Blue Snowball moniker. Yes, low magnification delivers a bluish “snowball,” but the high-power view is more complex. Peering into the 18-incher last fall, I exclaimed, “Hey, this is a miniature Ring Nebula!” (See page 58 for more on M57, the Ring Nebula.) At 158×, my baby-blue Ring appeared essentially round, its northeast half a tad brighter than its southwest half. Although of high contrast, the annular disk was diffuse around the edge, and its famous blue hue, though undeniably evident, was somewhat attenuated. An arc of three dim stars — one of 14th magnitude, two of 15th — flickered close by to the east-northeast, yet I couldn’t detect the nebula’s feeble (and possibly variable) central star.

Illusion in the Eyepiece

Oxygen emission lines in the blue-green part of the spectrum (responsible for the aqua tint of NGC 7662 and other planetaries) dominate the light output of planetary nebulae. We can take advantage of the strong oxygen emission by threading a doubly ionized oxygen (O III) narrowband nebula filter onto the end of an eyepiece. Such filters transmit most of a planetary’s luminosity while blocking unwanted starlight (and light pollution). The increased contrast usually enables us to tease out fine detail in faint nebulae. Filtering NGC 7662 at 158× and examining it carefully with averted vision (deliberately glancing away from the object because the periphery of the human eye is more sensitive to faint light), I was able to perceive the tenuous halo, or outer shell. But the O III filter produced no extra features in the smaller annular shell, and it killed the color. Overall, I preferred this especially luminous planetary unfiltered.

At 228× (unfiltered), the hole in the disk became hazy — another impediment to glimpsing the central star — and the nebula took on a slightly elliptical shape. Its northeast side was definitely brighter than the southwest side, and both sides outshone the ends. Alas, I had my “sides” and “ends” mixed up — at least in visual terms. I assumed the shinier

◀ **COMPLEX SNOWBALL** As this Hubble Space Telescope portrait of NGC 7662 shows, bright green crescents form the ends of an elongated inner shell. The dimmer portions to the northwest (below-right) and southeast (above-left) form the sides. In high-resolution images, the southeast side glows nearly as brightly as the crescents to give the nebula a “croissant” shape. The nebula’s central star, clearly visible here, is difficult to detect in amateur telescopes. The red FLIERs (from Fast Low-Ionization Emission Regions) around the periphery of the halo are extremely challenging features to sight visually. Overall, the Blue Snowball exudes a blue hue to some observers and blue-green to others.

NGC 7686: MARKUS BLAUENSTEINER / CCDGUIDE.COM; NGC 7662: BRUCE BALICK / JASON ALEXANDER / ARSEN HAJIAN / YERVANT TERZIAN / MARIO PERINOTTO / PATRIZIO PATRIARCHI / NASA / ESA parts must be the sides and the darkish parts the ends of a marginally elliptical nebula whose major axis, to my eye, was leaning northwest. Wrong! I was off by 90° — images show the annulus leaning northeast. Also, the disk is more strongly elliptical in photographs than the hollowed-out "snowball" I examined visually. Appearances can be deceiving. The bright northeast and southwest portions I saw mark the *ends*, not the sides, of the elongated structure.

So, my characterization of NGC 7662 as a mini-Ring wasn't quite correct. True, both objects are elliptical, and they share similar orientations (their major axes are tipped approximately 45°). However, while M57 displays the expected shiny sides and dusky ends, NGC 7662 does the opposite. My bias toward bright sides caused an optical illusion that fooled me completely.

Each observer registers their own impression. Admiring NGC 7662 later in a 20-inch f/4 Dobsonian at 406× (unfiltered), I sensed the annular ring was gently rippled, or scalloped, all around the edge. The scope's owner commented that, to him, the Snowball "looked like a rose." It was a deeply appealing description. A Blue Rose, anyone?

Ghostly Galaxy

My final stop in the Andromeda Outback was **NGC 7640**, a two-armed, barred spiral galaxy around 30 million light-years from Earth. The 11.3-magnitude edge-on system is located a mere 1.8° south-southwest of the Blue Snowball. Finding the galaxy would be a piece of cake, right? Wrong again. At the time, my chosen area of sky was skirting the zenith (the dreaded "Dobby Hole"), and with so many stars crowding my reversed-image, right-angle finderscope, I could easily miss the prize — and I did!

Consulting my best charts, I settled on a simple star-hop beginning at 13 And, which had guided me earlier. From that star, an imaginary arrow shoots southwestward past NGC 7662 and through the orangey 6th-magnitude variable star V385 Andromedae, grazing the southern tip of NGC 7640. Employing a wide-field eyepiece yielding 69×, I made a slow sweep toward the galaxy until I encountered a nebulous feather. No wonder I missed it the first time. The object's *surface brightness* is very low — 14.4 magnitudes per square arcminute — which conspires against any quick catch.

NGC 7640 is oriented essentially north-south in a busy starfield on the periphery of the Milky Way. In photographs, the galaxy is a generous 12′ × 2′ in size; however, my telescope at 69× registered a slender wisp only half as long, captured in a 5′-wide triangle of 11th-magnitude stars. My at-the-ocular comment was "a willowy tendril in an attractive setting." Stars were everywhere. I noted a 14th-magnitude pinprick off the galaxy's southern tip and a 12th-magnitude star 6½′ farther south. Another 11th-magnitude star glimmered a few arcminutes off the galaxy's northern tip.

Changing to my ultra-wide 158× eyepiece resulted in NGC 7640 extending (as images confirm) a bit outside the triangle mentioned above. The galaxy was curiously asymmetrical, the northern third slightly outshining its southern counterpart. Averted vision came to the rescue again, as it helped me trace the extent of that thin southern flank. The central hub was obvious, but I saw no dark line of dust bisecting it (though images do confirm a dust lane). A faint star overlaid the galaxy immediately southeast of the hub. Several dimmer stars were superimposed over the whole splotchy, misty mass.

Increasing the magnification to 228× stretched NGC 7640 an additional arcminute in each direction, but the pallid subject was becoming very dim at that power. Excellent sky conditions and a patient eye are required to fully appreciate

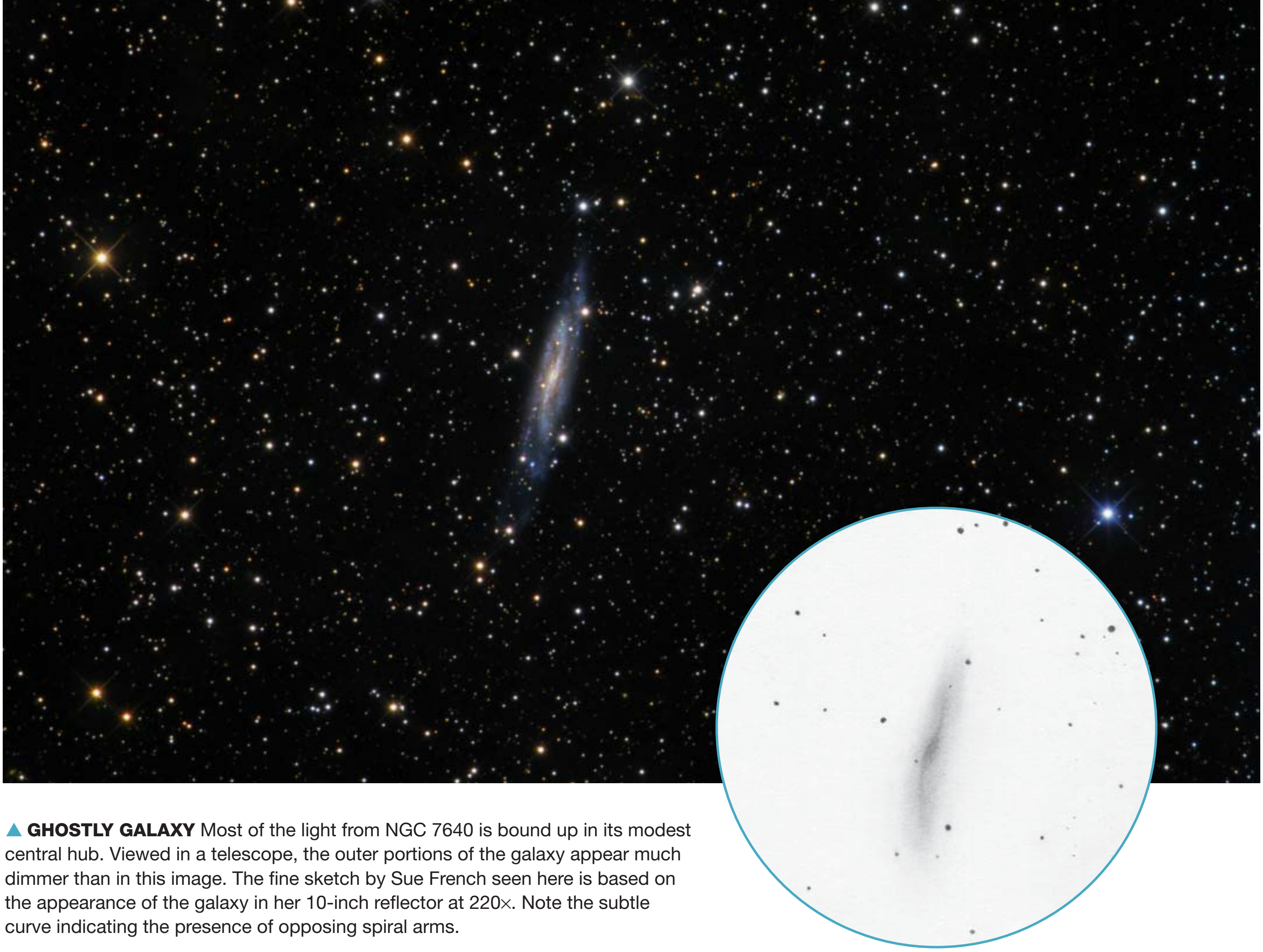
▲ **RINGS IN THE SKY** The Blue Snowball Nebula (NGC 7662, *left*) and the Ring Nebula (M57) present elliptical shapes of similar orientation on the sky. But while M57 exhibits bright sides, NGC 7662 displays bright ends. These images aren't to the same scale.

MASIL IMAGING (2)

Delights in Andromeda's Outback

Object	Type	Mag(v)	Size/Sep	RA	Dec.
NGC 7686	Open cluster	5.6	15′	$23^h\ 30.1^m$	+49° 08′
NGC 7662	Planetary nebula	8.3	29″ × 26″	$23^h\ 25.9^m$	+42° 32′
NGC 7640	Spiral galaxy	11.3	12′ × 2′	$23^h\ 22.1^m$	+40° 51′
Struve 2985	Double star	7.2, 8.0	15.7″	$23^h\ 10.0^m$	+47° 58′
Struve 3034	Double star	7.7, 9.9	5.7″	$23^h\ 44.5^m$	+46° 23′
Struve 3004	Double star	6.3, 10.1	13.5″	$23^h\ 20.7^m$	+44° 07′
Struve 2973	Double star	6.4, 10.1	7.5″	$23^h\ 02.8^m$	+44° 04′

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.



▲ **GHOSTLY GALAXY** Most of the light from NGC 7640 is bound up in its modest central hub. Viewed in a telescope, the outer portions of the galaxy appear much dimmer than in this image. The fine sketch by Sue French seen here is based on the appearance of the galaxy in her 10-inch reflector at 220×. Note the subtle curve indicating the presence of opposing spiral arms.

FRANZ KLAUSER / MANFRED WASSHUBER / CCDGUIDE.COM

this mostly ghostly galaxy. In her Deep-Sky Wonders column, *S&T* Contributing Editor Sue French once reported a "gentle S curve" — a hint of spiral structure — in NGC 7640 (*S&T:* Nov. 2008, p. 71). Maybe next time I'll see that subtle curve.

The Outback from the Backyard

At home one dewy autumn evening, I issued myself a challenge: to revisit my Andromeda friends under my light-blighted suburban sky. The faintest naked-eye stars in the target region were the 4th-magnitude trio of Lambda, Kappa, and Iota. Even so, the cluster and nebula were easy pickings for my 10-inch f/6 Dobsonian, as were a quartet of double stars in the area. (I made no attempt on the galaxy!)

First, the doubles. I always get a kick out of digging for double stars near my chosen deep-sky treasures. I found **Struve 2985** 1¾° southwest of 11 Andromedae. After that, I moved to Lambda and turned east for 1½° to 5.0-mag Psi (ψ) Andromedae. Guarding Psi to the west are two minor stars, 7′ apart, north-south. The upper one is **Struve 3034**. Then it was down to Kappa. From Kappa, I hiked 3½° west to a 10′-wide pair aligned east-west. The western star is **Struve 3004**. And 3¼° farther west is **Struve 2973**. All four duos showed perfectly at 64×.

Still at 64×, the 10-inch revealed the cluster NGC 7686, though I needed 169× to pull in the previously noted ragged zigzag of stars and portions of the tight star chain parallel to it. The faintest cluster members weren't visible, but I spotted a half dozen stars near my orange beacon HD 221246. The city view wasn't bad. And I was amazed at how well the planetary NGC 7662 punched through the light pollution. At 169×, unfiltered, it was again a mini-Ring. Doubling to 338×, I beheld a big, dim doughnut, its northeast half dominating. Hugging that side was a single faint star (the brightest of the arc of three I saw in my 18-inch Dob). An O III filter knocked out the star but greatly improved the nebula's contrast.

Finally, on a whim, I decided to try for the planetary with my 4¼-inch f/6 reflector. It was a tough assignment for a little scope under a grey sky. At low power (22×), NGC 7662 seemed virtually stellar (the 8th-magnitude star HD 220822, just 8′ eastward, was helpful for comparing). The O III filter sealed the deal, as it blunted the stars and left the nebula shining gamely.

NGC 7662 rewarded me with one last satisfying impression. Working at 93×, my humble 4¼-incher produced a teeny-weeny, barely bluish disk that was suggestive, not of a snowball, but of some far-off planet. William Herschel would've been pleased.

■ Contributing Editor **KEN HEWITT-WHITE** has been probing the night sky for many years from sites dark, and not so dark, in southern British Columbia, Canada.

S&T Test Report by Alan Dyer

The Sharpstar Hyperbolic Astrograph

We test a 6-inch astrograph promising sharp images across a wide field. Does it deliver?

Sharpstar 150-mm f/2.8 HNT Hyperbolic Newtonian Astrograph

U.S. Price: $1,995
agenaastro.com

What We Like

Excellent speed and edge correction

Good focus stability

Light weight

What We Don't Like

Inconvenient camera rotation

Limited filter options

Abundance of diffraction spikes

SHARPSTAR, A NEW BRAND in the astronomy market, is offering an attractive line of premium refractors and two unique reflectors specifically for astrophotography. The larger astrograph is the Sharpstar 8-inch (200-mm) PNT Newtonian, which offers a focal ratio of f/3.2 using a traditional parabolic primary mirror coupled with a coma-correcting lens.

We tested the smaller reflector, a 6-inch (150-mm) f/2.8 Newtonian. Agena AstroProducts, a U.S. dealer for Sharpstar, supplied our sample unit. The 150 f/2.8 HNT (Hyperbolic Newtonian Telescope) is designed specifically for imaging.

While a supplied adapter allows an eyepiece to be attached, any eyepiece with a focal length longer than about

▶ The Sharpstar 150 HNT comes with metal lens caps, a thin adapter ring that features a male 48-mm thread for wide-aperture T-rings, the lens spanner wrench, and a conical eyepiece adapter for collimation. A handle bolts onto the top of the tube rings, and both Vixen-style (shown) and Losmandy-style dovetail bars are supplied.

ALL PHOTOS BY THE AUTHOR

◀ The Sharpstar's 420-mm focal length and f/2.8 speed are ideal for capturing wide-field targets, offering a field of view of 4.8° by 3.2° with a full-frame sensor. This deep image of M45, the Pleiades, is a stack of eight 8-minute unfiltered exposures at ISO 400 with a Canon EOS Ra mirrorless camera. *Inset:* The author tested the Sharpstar Hyperboloid Newtonian astrograph using a Canon EOS Ra camera, on an Astro-Physics Mach1GTO mount guided with the now-discontinued SG4 standalone autoguider from Santa Barbara Instruments.

16 mm or so will produce a view with a dark shadow from the large secondary mirror floating in the middle of the field. This is not an instrument intended for wide-field views of the night sky. However, it does work superbly for its intended purpose: wide-field astrophotography.

Optical Performance

Jiaxing Ruixing Optical, the company manufacturing the Sharpstar line, has created an instrument with an optical design similar to the legendary Takahashi Epsilon 130 and 180 Newtonian astrographs. Like the two Taks, the Sharpstar 150 HNT uses a hyperbolic primary mirror matched to a corrector lens in the focuser to yield a wide field largely free of off-axis coma and on-axis spherical aberration, all while offering tremendous speed at f/2.8 for a focal length of 420 mm.

The HNT projects an image circle I measured to be 55 mm, though the more conservative specifications state a fully illuminated field of 44 mm. The latter is sufficient to fill a full-frame (24 × 36 mm) sensor. I performed most of my testing using the full-frame Canon EOS Ra mirrorless camera I recently reviewed (*S&T:* Apr. 2020, p. 64).

However, while the corners of the frame were certainly illuminated, some minor light fall-off occurs toward the frame edges, as should be expected with such a fast optical system. I measured just over one stop of darkening at the extreme corners of a full-frame image, a surprisingly low level of vignetting for an f/2.8 reflector. The generously sized 70-mm (minor axis) secondary mirror is one key factor to keeping the vignetting low. Users can compensate for the vignetting with the usual practice of taking and applying flat-field calibration frames.

Stars were also tight to the corners, though not perfect. With the corrector at its factory-installed position down the focuser, stars did exhibit a slight amount of what looks like coma at the extreme corners. Even so, the amount of aberration was no more than what I see with some of the refractor and field-flattener combinations I use.

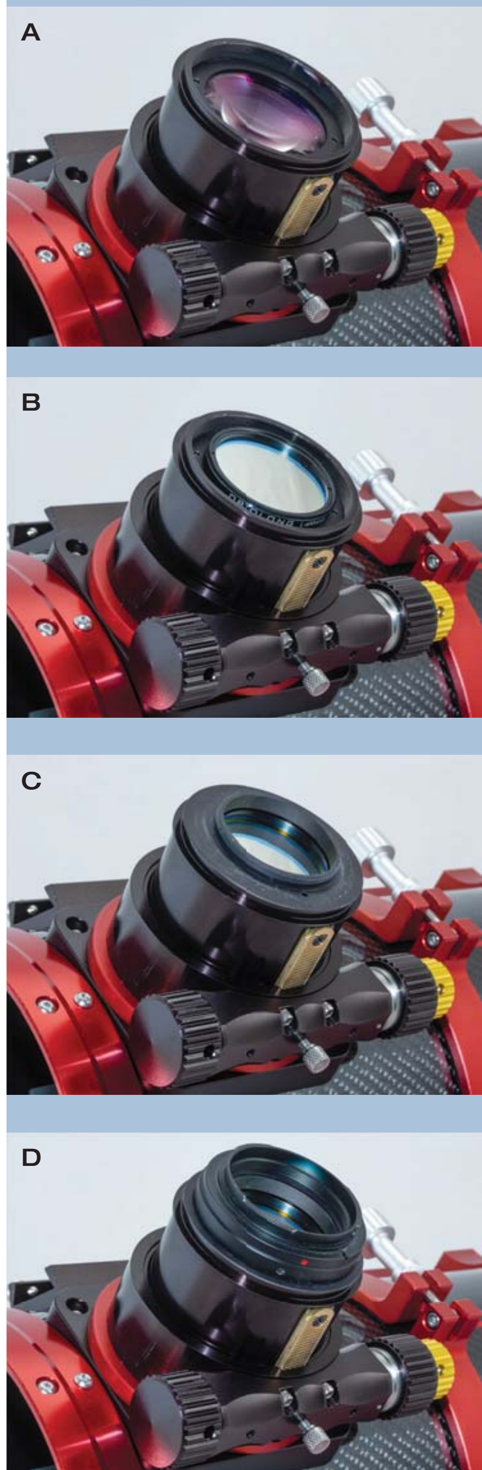
Achieving that level of performance did require careful collimation of the primary mirror — not surprising after the instrument had been shipped across the continent. Out of the box, images exhibited asymmetrical aberrations, with stars on one side of the frame more distorted than on the other.

To collimate the HNT, the instructions recommend removing its corrector lens. As this is threaded directly into the focuser, I was reluctant to remove it early on in the testing, not knowing if I could replace it properly. As it turned out, my fears were groundless, though removing and replacing the corrector is not an operation I'd want to perform in the field.

As a result, I left the corrector in place and used the eyepiece adapter to inspect a star at high power, while adjusting the primary mirror's collimation screws to make the star's image symmetrical both in and out of focus. That did the trick.

In subsequent testing the instrument never traveled farther than from my house to the backyard each night, so I did not subject it to field trips on rough roads. But over two months of testing on cold winter nights I found no need to re-collimate the HNT. Performance remained consistent and reliable.

I shot several fields, such as the Belt of Orion, that included bright stars. I did see dim blue ghost reflections from bright stars in some cases. However, the multi-coated three-element corrector did a good job suppressing flares. With bright stars in the field, what I did see were diffraction spikes. These spikes were not just around the stars themselves, a characteristic of any reflector



▲ (A) The astrograph's corrector lens comes threaded into the barrel of the focuser. (B) A recessed well on the corrector lens accepts 48-mm filters that sit on the corrector. (C) The included thin M63-to-M48 adapter ring then holds the filter in place. (D) A user-supplied T-ring with 48-mm threads screws onto the adapter for attaching DSLRs. Mirrorless cameras require a custom adapter or additional extension.

with spider vanes holding the secondary mirror in the optical path. Diffraction spikes were evident across the field far removed from the source star. While "content aware" cloning during image processing could take care of these, they are an annoying artifact to deal with.

Filter Use

The fast photographic speed of the HNT makes using light-pollution and narrowband filters more necessary but also practical. Even using dense filters, exposures can still be reasonably short, allowing the capture of lots of images in a single night. But how do you physically place a filter in the path? There is no filter drawer or camera adapter onto which you can thread a filter.

Instead, the top of the corrector lens in front of the camera has a slight recess into which you can drop a standard 2-inch (48-mm) filter, which is then held in place by the supplied thin M63-to-M48 adapter ring, which in turn accepts a 48-mm threaded T-ring or 48-mm nosepiece.

The method works but requires removing and replacing the camera for each filter change. For DSLRs and mirrorless cameras, using a clip-in filter in the camera body itself is another choice, but one that still requires removing the camera to swap filters (and adds more vignetting into the optical path). Cooled astronomical

▶ The primary mirror cell contains three collimation screws and matching lock knobs. All are recessed so the tube can be placed on its end or inserted into its case without accidentally affecting the collimation.

cameras with thin filter wheels between the camera and focuser should come to focus with the 150 HNT.

The issue is that, unlike most other telescopes with add-on field-flattener lenses, the HNT's corrector lens doesn't just slip into or screw onto the focuser — it is screwed directly within the threaded interior of the focuser.

While the corrector lens can be removed outright (as suggested for collimating the mirrors) or adjusted in its position, doing so requires using a supplied lens spanner wrench. I tried raising the corrector up the focuser, reducing the distance from the lens to the camera sensor by a few millimeters, to see if that improved the field flatness. It did. As such, users may wish to experiment with the spacing.

In my case, I would have left it there except that decreasing the lens-to-camera spacing meant that when a 2-inch filter was placed on top of the corrector lens, the camera's T-ring would not screw onto the focuser as far as it would without the filter in place, placing the camera at a very different rotation angle. This made shooting aligned sets of filtered and unfiltered images virtually impossible. The image examples here were all taken with the corrector at its "factory-set" position down the focuser.

Mechanical Features

The telescope's focuser is a 2½-inch, dual-speed rack-and-pinion design with 30 mm of travel. A DSLR with its back-focus requirement of approximately 55 mm reaches focus with the focuser extended only 10 mm. So while the HNT is optimized for DSLR use, there's enough travel and back focus to accommodate most other cameras. The focuser proved solid and precise, and it locked down well to prevent slippage.

The one feature the focuser lacks is a convenient camera-angle adjuster. Turning the camera to frame fields requires loosening three slot-headed screws at the base of the focuser, most not very accessible, and with slots so wide I found my attempts to turn them strip-

▼ *Left:* The corrector lens can be removed but only by unthreading it with the supplied spanner wrench. Collimation is still possible using a star test with the corrector in place. Using a laser collimator will require removing the lens. *Right:* The gold slot-headed screw is one of three that allow the focuser to rotate for framing the field. However, access to them is awkward, making camera rotation inconvenient.

▲ *Left:* With an inside diameter of 185 mm, the HNT's oversized tube is lined with black flocking to reduce internal reflections. The focuser and fittings do not intrude into the light path. While the secondary mirror supports are sturdy, their width introduces bright, long diffraction spikes to images with bright stars. *Right:* The tube rings have multiple bolt holes for attaching user-supplied plates and rings, or one of the two supplied dovetail bars. The Losmandy D-style plate is shown here.

ping the slots. Instead, I set the T-ring so my camera clicked onto the focuser with north up (my preferred orientation for most shots) and just left it there for all my testing. A better method of rotating the camera would increase the versatility of the instrument, particularly for an astrograph.

The HNT's tube has a small dovetail bracket that will accept the standard mounting shoes on many finderscopes or small guide scopes. The slotted carrying handle on the top could also be used to bolt on a guide scope.

The telescope's tube rings each have five ¼-20-threaded holes on their top and bottom surfaces for adding your own mounting plates and dovetail bars if needed. The HNT, however, does come with two: a narrow Vixen-style and a wider Losmandy-style dovetail bar.

The tube assembly is light, at only 5.8 kilograms (12.8 lbs) and so will work well on lighter and affordable mounts

▲ A raw image with only a mild contrast boost applied shows the HNT's level of vignetting over a full-frame image with the mirrorless Canon EOS Ra. Blow-ups of the corners show the degree of aberrations present with the corrector lens at its default position at the bottom of the focuser.

▲ Using an Optolong L-Enhance filter (reviewed in the May issue, page 70) brought out faint nebulosity in this blend of six 8-minute frames at ISO 1600 with the filter and six 5-minute exposures at ISO 800 without the filter. Additional 30- and 60-second unfiltered exposures at ISO 400 added the bright core region. All were captured with a Canon EOS Ra.

such as the Celestron AVX, Sky-Watcher HEQ5, or iOptron CEM25.

All the tube fittings are dressed in a beautiful red anodized finish, a color popular these days with many brands of mounts and accessories. The HNT looks superb and is sure to catch the eye of admirers on the observing field. An included foam-lined and metal-trimmed travel case makes it easy to transport to dark sites.

Adding to the polished finish is the carbon-fiber tube. It not only looks good but helped significantly to stabilize focus. On sub-freezing winter nights, once the scope had settled down from being in the warm house, I found I could focus once and not worry about refocusing over the next two or three hours of shooting — impressive for such a fast reflector.

◀ Included with the Sharpstar 150 is a solid storage and traveling case measuring 23½ by 13 by 11½ inches and weighing 11.5 kg (25.4 lbs) with the instrument.

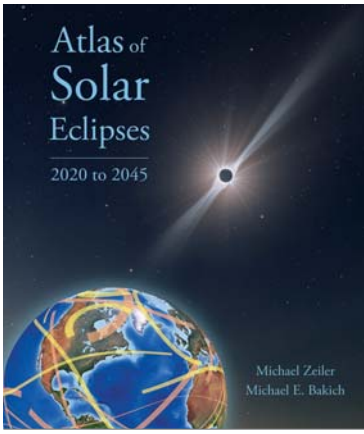
Recommendations

Once I sorted out the initial issues of camera orientation and collimation, I soon set testing procedures aside and just used the 150 HNT to take what I considered some of my best shots of popular northern winter sky targets, often using filters.

The current generation of multi-band filters really makes nebulae pop when shooting with one-shot-color and DSLR cameras, even under dark skies. On most nights I took filtered and unfiltered shots to blend together later in processing. The HNT's f/2.8 speed made it possible to get all the shots needed for not only one but several targets each night.

While I've been a fan of apochromatic refractors for decades, this is a reflector astrograph I soon came to appreciate and enjoy using. I can certainly recommend it.

■ Contributing Editor **ALAN DYER** can be contacted through his website at **amazingsky.com**.



◀ ECLIPSE ATLAS

Great American Eclipse has published a compendium of solar eclipses for the next 25 years. *Atlas of Solar Eclipses 2020 to 2045* by Michael Zeiler and Michael Bakich ($75) details 56 solar eclipses occurring over the next quarter century, with an emphasis on those that pass over heavily populated areas. The book is richly illustrated with detailed, full-color maps and useful data on each event, including the precise moment of second and third contact, from notable places of interest. The atlas also contains helpful information on choosing an optimal location to view each eclipse, as well as viewing advice, unique photographic opportunities, and the planets and stars visible during totality. 256 pages, ISBN 9781734549201.

Great American Eclipse
GreatAmericanEclipse.com

◀ APP FOCUS

Rigel Systems now offers a remote focusing system for Celestron Schmidt-Cassegrain telescopes. The wifi-nFOCUS ($269.90) is a modular system that connects to existing Celestron 6- through 14-inch SCT telescopes manufactured after 2006. The system includes a motor and gear that connects to your existing telescope's focus knob and produces 4,300 steps per revolution. An included control box with manual buttons and Wi-Fi receiver accepts remote commands from your PC or smartphone, allowing you to precisely focus your scope with a touch or a click. Download a free *wifi-nFOCUS* PC program to control your remote setup or use the control apps available on the Apple and Android app stores. Adapter brackets are available for users with Starlight Instruments replacement MicroTouch SCT focus knobs. Base price includes focus motor and gear kit, wifi-nFOCUS control box, USB-to-12V DC power cable, and a standard USB 2.0 PC connection cable.

Rigel Systems
rigelsys.com

◀ CENTER-BALANCED PRECISION

iOptron introduces a new medium-duty equatorial mount to its series of center-balanced Go To mounts, the CEM70 ($2,548). The mount head weighs just 30 pounds (13.6 kg) yet can support loads of up to 70 lbs. It features precision stepper motors and 248-tooth worm gears in both axes. The CEM70 advertises low periodic error (+/- 3.5 arcseconds), and the premium model CEM70G ($2,948) includes iOptron's new iGuider onboard autoguiding system complete with guidescope and camera. Aligning either mount is easy with the integrated iPolar electronic polar finder, and users can quickly swap telescopes using its Universal Self-Centering Saddle plate, which accepts both Vixen- and Losmandy-style dovetail bars. iOptron's Go2Nova hand controller controls both versions of the mount and includes a database of more than 350,000 objects. The mount comes with a heavy-duty stainless-steel tripod, counterweight shaft, and a hard case.

iOptron
6F Gill St., Woburn, MA 01801
866-399-4587; ioptron.com

New Product Showcase is a reader service featuring innovative equipment and software of interest to amateur astronomers. The descriptions are based largely on information supplied by the manufacturers or distributors. Sky & Telescope assumes no responsibility for the accuracy of vendors' statements. For further information contact the manufacturer or distributor. Announcements should be sent to nps@skyandtelescope.org. Not all announcements can be listed.

◀ The lenses and housing used to make a homemade eyepiece can be made of pretty simple stuff.

Homemade Eyepieces

Make your entire optical train yourself.

LONG AFTER I'D BEGUN grinding my own mirrors and building my own telescopes, I began to wonder if it would be possible to make the entire optical train myself, including the eyepieces. I knew that John Dobson had famously repurposed binocular eyepieces for use in his sidewalk telescopes, but I wanted to go a little deeper. I wasn't ready to grind my own lenses yet, but I contemplated whether if it might be possible to assemble an eyepiece out of commercially available lenses.

Turns out the answer is "Yes." Or perhaps a more enthusiastic "Boy howdy!"

The tipping point came when I built a 2× scale version of the Edmund Scientific Astroscan (*S&T:* Sept. 2011, p. 64) and couldn't find a 2-inch eyepiece that looked like the Edmund RKEs included with the original classic telescope. So I decided to make one myself.

Surplus Shed (**surplusshed.com**) sells lenses by the ton. They also sell lens sets selected by master eyepiece designer Paul Rini, which saves you from having to design the eyepiece yourself. I chose their 26-mm Modified Plössl set (# L3973), also billed as a "super Kellner." Since the Edmund RKE is a "reverse Kellner," I figured this would be as close as I could come to a scaled-up version of that.

The lens set came with minimal instructions — basically, "Put them in this order and orientation, as close together as possible without touching." The trick, then, was making spacers and finding a tube the proper diameter to hold them.

I found that a travel-size contact lens solution bottle was the perfect size to hold the lenses, and a larger size saline solution bottle made the perfect outer housing. Cardboard rings held the inner tube centered within the outer one, and spacers made from strips of plastic held the lenses the right distance apart. I simply slid the lenses into the tube in the right order, anchored them into place with a dot of glue on the edge of the spacers, slid the small tube inside the big one, stuck a cardboard, 2-inch-diameter tube on the bottom, and I had my eyepiece.

I didn't put a field stop in it, so it has a super-wide field. There's some distortion out at the edges, but it's not objectionable. For a whopping $8.50 in materials, it can't be beat.

Virginia amateur Red Henry took a different approach. He takes eyepieces out of old binoculars, puts 1.25-inch and 0.965-inch barrels on them, and gives them away for outreach. He has given away more than 300 of these eyepieces so far, leaving him with a lot of surplus binocular objectives. So he figured out a way to make what he calls a "Double Plössl" with the leftover glass.

A Plössl eyepiece uses two doublets

▼ *Left:* The finished scaled-up eyepiece (left) seen here next to the original Edmund RKE. The grip ring came from Tele Vue and was a perfect fit. *Right:* Red Henry's eyepiece design uses two pairs of binocular objectives — 30- to 60-mm objectives work particularly well.

ALL IMAGES BY THE AUTHOR

▲ A finished Red Henry eyepiece has a wide field and tons of eye relief. The eyepiece on the left uses 50-mm objectives and the one on the right 40-mm objectives.

with their most-curved sides facing each other. That doesn't provide a short enough focal length for an eyepiece made with binocular objectives, but stacking a second pair below the first pair works like a charm. The result usually comes out to about a 50- to 60-mm focal length, so it provides a nice, wide, low-power view. And here's a bonus: Its eye relief is a comfortable inch or more. You can wear eyeglasses with these eyepieces and not even bump them against the top lens.

Having that much eye relief adds an interesting sense of depth to the view. Rather than looking like dots at the other end of a long pipe, stars in these eyepieces look to me like, well, like stars floating in space. They have a three-dimensionality to them that usually only comes when observing through binocular scopes.

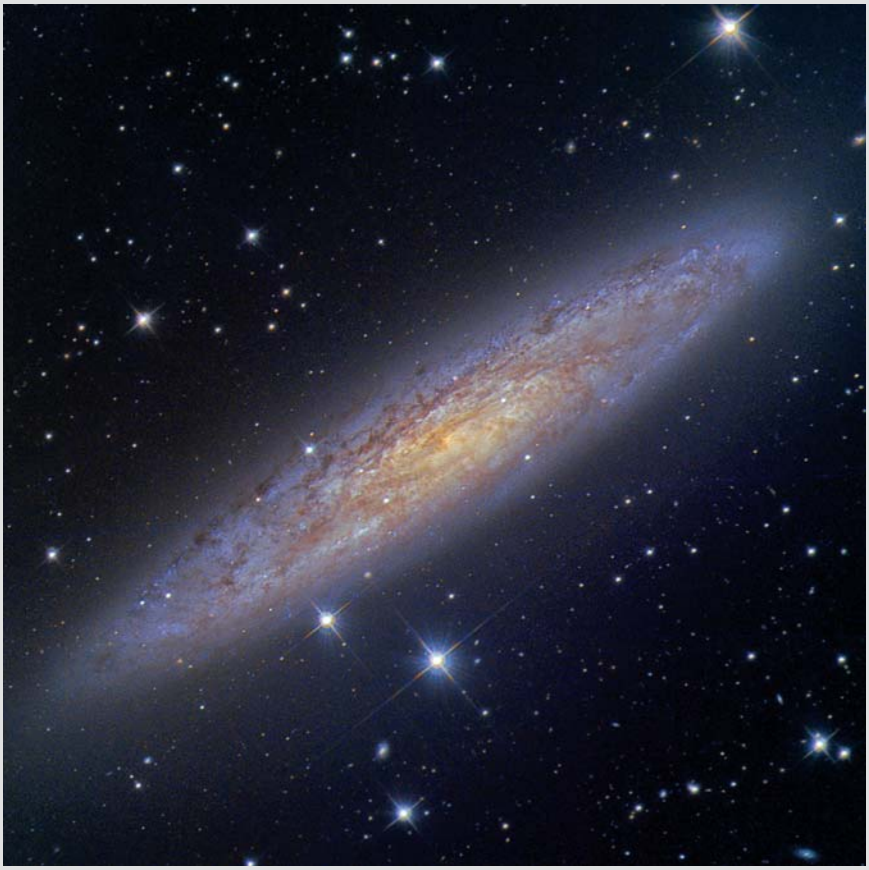
As with my "super Kellner," the directions for making one of these eyepieces are simple: Just put the pairs together with their most-curved sides facing one another and pack all four lenses as close together as you can without the elements touching. Red wraps his in black electrician's tape so he doesn't even need an outer tube assembly.

Making your own eyepieces is easy, fun, and rewarding. Give it a shot! You'll be pleasantly surprised at how well a homemade eyepiece can work.

For more information about Red Henry's eyepieces, visit his Facebook page at **https://is.gd/redhenryeps**.

■ Contributing Editor **JERRY OLTION** has too many eyepieces . . . no, that's impossible.

GLOBULAR OR GALAXY?
Terry Hancock and Kim Quick
Long thought to be the largest globular cluster in the Milky Way, Omega Centauri (NGC 5139) is actually the core of a dwarf galaxy, as recent findings suggest.
DETAILS: *PlaneWave Instruments CDK17 astrograph with FLI PL16803 CCD camera. Total exposure: 4 hours 56 minutes through LRGB filters.*



◁ SILVER DOLLAR GALAXY

Franck Jobard & Utkarsh Mishra

NGC 253 is a large, bright spiral galaxy in Sculptor currently undergoing a period of intense star formation. Its complex dust lanes are visible in larger telescopes under dark skies.

DETAILS: *12½-inch Ritchey–Chrétien telescope with SBIG STL-11000M CCD camera. Total exposure: 21½ hours through LRGB filters.*

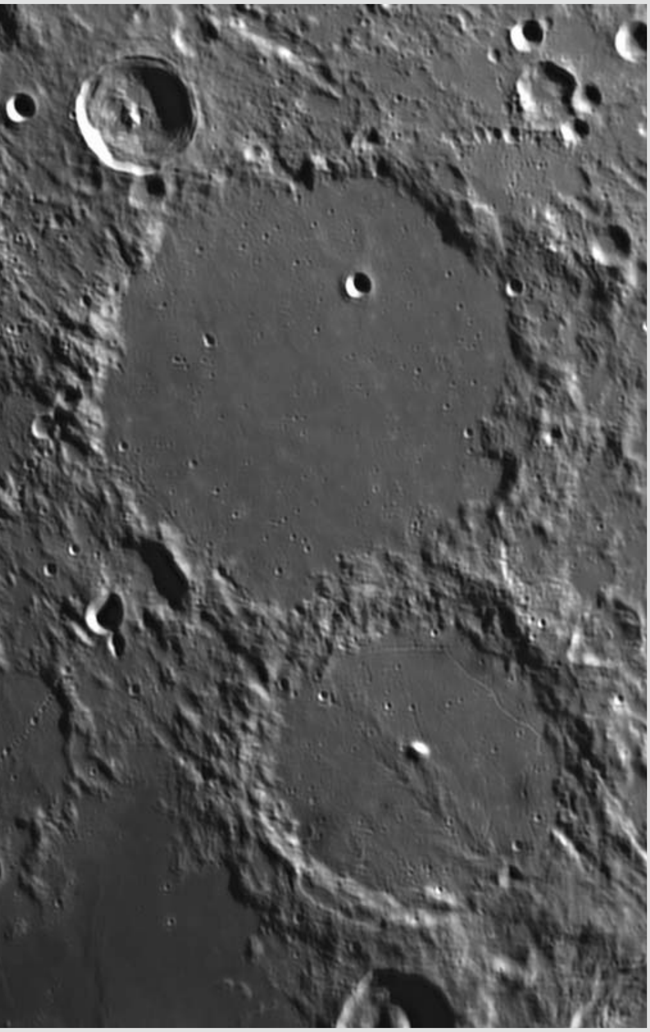
▽ COMETARY LINEUP

José J. Chambó

Modestly bright Comet PanSTARRS C/2017 T2 passes by the bright galaxies M82 (left) and M81 (right) in Ursa Major on the evening of May 22nd. North is at left.

DETAILS: *GSO 8-inch f/3.8 Newtonian reflector with Atik 383L+ CCD camera. Total exposure: 39 minutes through LRGB filters.*

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



△ JOINED AT THE RIM

Steve Thornton

Lunar craters Ptolemaeus (top) and Alphonsus (lower right) display thin rilles along their western and eastern floors, respectively.

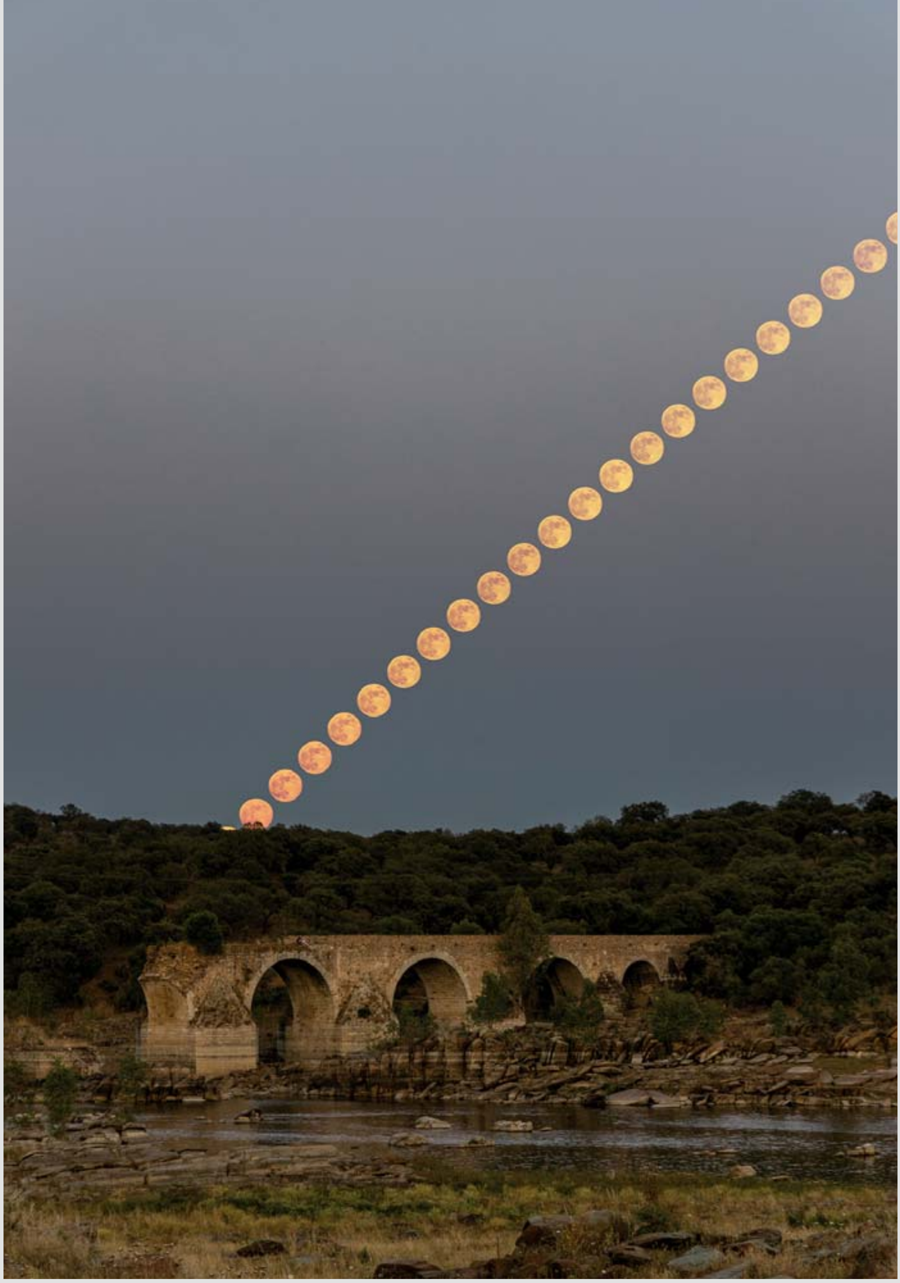
DETAILS: *Celestron C9.25 Schmidt-Cassegrain telescope with ZWO ASI120MM video camera. Stack of several hundred frames.*

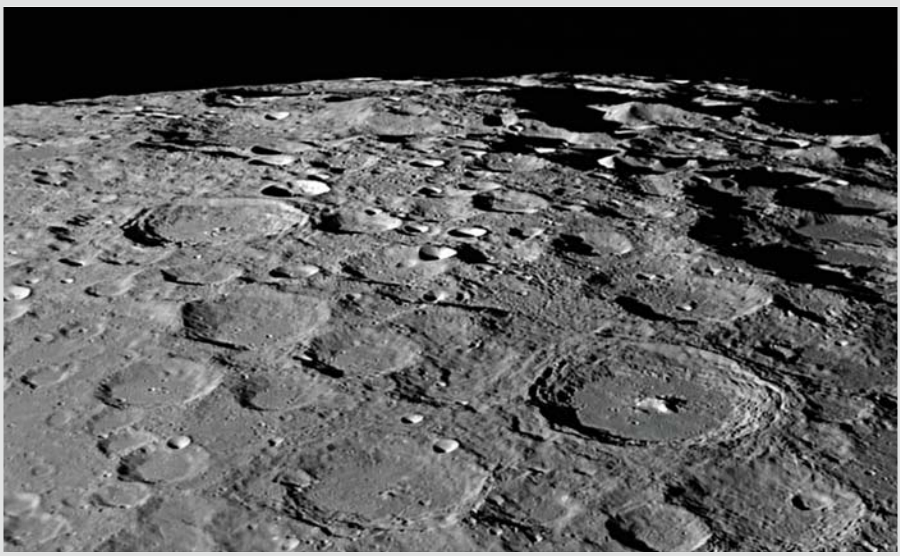
▷ SOUTHERN FLYOVER

Ron McKnight

Prominent terraced craters Schomberger (left), Curtius (bottom), and Moretus (lower right) are visible in this sharp image that resembles the window view from an imaginary lunar orbiter.

DETAILS: *Celestron C11 Schmidt-Cassegrain telescope with Celestron Skyris 132C video camera. Stack of 500 out of 5,000 frames.*





◁ STRAWBERRY MOONRISE

Sérgio Conceição

The full Moon of June 5th rises above the Spanish side of the Ponte da Ajuda along the border between Portugal and Spain.

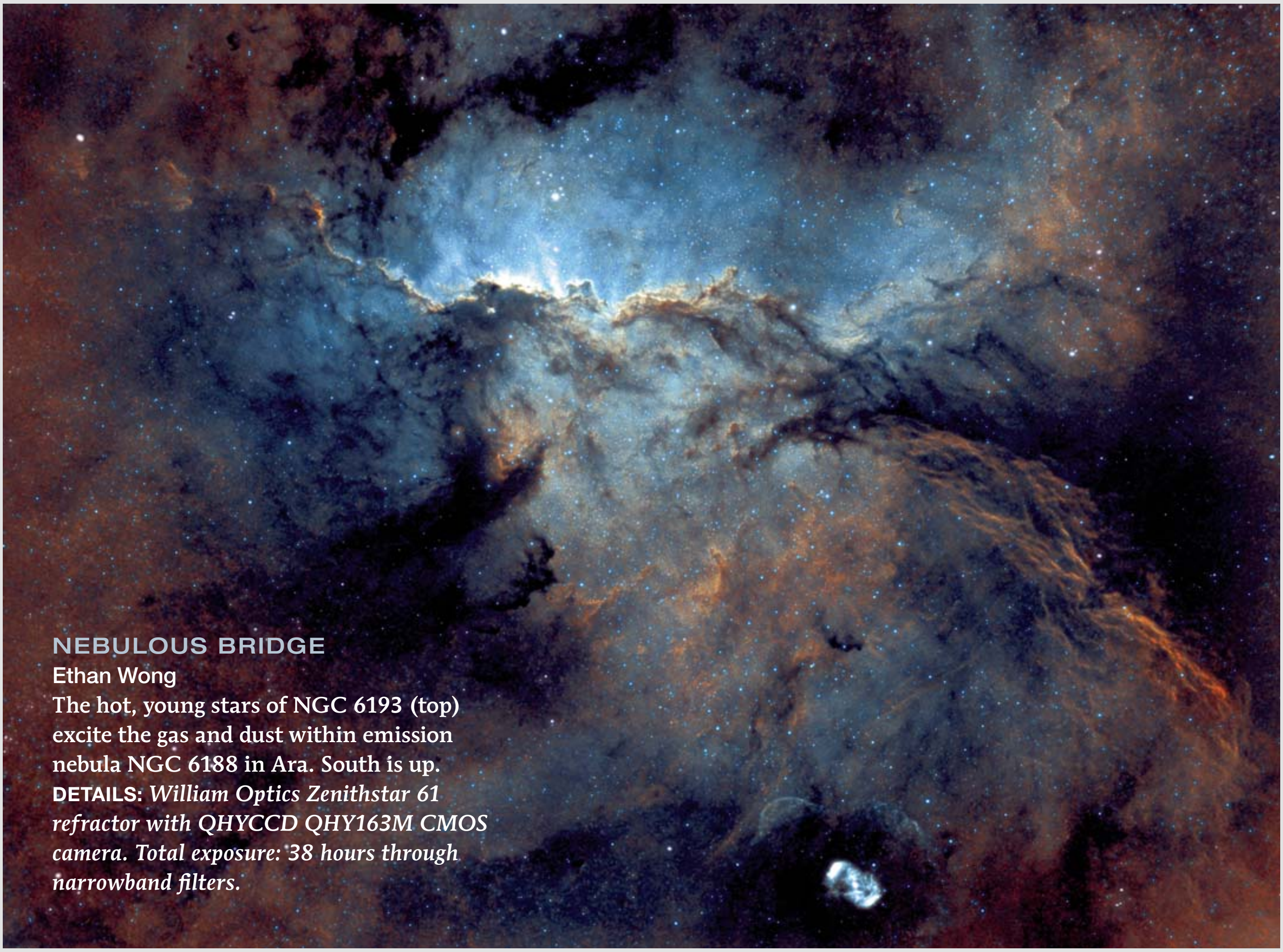
DETAILS: *Canon EOS R Mirrorless camera with 92-mm lens at f/6.3. Composite of 23 exposures, each 1⁄250-second at ISO 400.*

▷ DUSTY REFLECTIONS

Greg Ruppel

Delicate reflection nebulae vdB 48 (left), IC 426 (center), and IC 423 (lower right) are found just above Orion's Belt. The second-magnitude star Mintaka is located just outside of the field to the right.

DETAILS: *AstroSysteme Austria ASA 10N f/3.7 Newtonian astrograph with SBIG STL-11000M CCD camera. Total exposure: 9.7 hours through LRGB filters.*



NEBULOUS BRIDGE

Ethan Wong

The hot, young stars of NGC 6193 (top) excite the gas and dust within emission nebula NGC 6188 in Ara. South is up.

DETAILS: *William Optics Zenithstar 61 refractor with QHYCCD QHY163M CMOS camera. Total exposure: 38 hours through narrowband filters.*

SKY & TELESCOPE

Market Place

Your essential source for astronomical products

ACCESSORIES

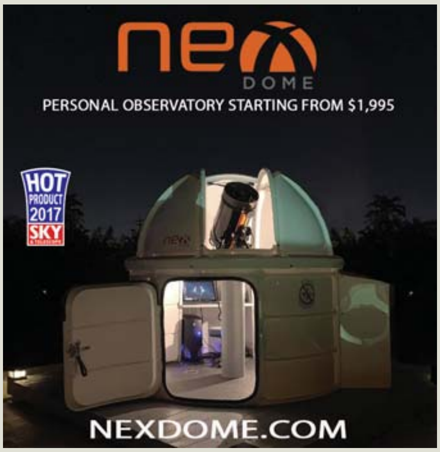
BOOKS

CAMERAS

MISCELLANEOUS

MISCELLANEOUS (cont.)

OBSERVATORIES/DOMES (cont.)



SOFTWARE

OBSERVATORIES/DOMES

OPTICS

skyandtelescope.org

TELESCOPES

CLASSIFIEDS

SOUTHWEST NEW MEXICO: Casitas de Gila Guesthouses. Dark skies, great accommodations; power, wifi, and pads available. casitasdegila.com/astronomy.html. 575-535-4455.

FOR RENT: 3BR/2BA furnished home in ARIZONA SKY VILLAGE PORTAL, AZ. Specatcular observing/birding! irkitzman@gmail.com www.arizona-dreaming.com 520-203-8500

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Classified ads are for the sale of noncommercial merchandise or for job offerings. The rate is $1.75 per word; minimum charge of $28.00; payment must accompany order. Closing date is 10th of third month before publication date. Send ads to: Ad Dept., Sky & Telescope, 90 Sherman Street, Cambridge, MA 02140.

INSIDE This Issue

Specialty astronomy equipment dealers and manufacturers are an important resource for amateur and professional astronomers alike — patronize our advertising dealers in this issue and enjoy all the benefits of their expertise.

Product Locator

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 19–24~~ **CANCELED**
NEBRASKA STAR PARTY
Valentine, NE
nebraskastarparty.org

~~August 13–16~~ **CANCELED**
STELLAFANE CONVENTION
Springfield, VT
stellafane.org/convention

~~August 14–18~~ **CANCELED**
ALMOST HEAVEN STAR PARTY
Spruce Knob, WV
ahsp.org

~~August 14–23~~ **CANCELED**
SUMMER STAR PARTY
Plainfield, MA
rocklandastronomy.com/ssp.html

~~August 15–23~~ **CANCELED**
MERRITT STAR QUEST
Loon Lake, BC
merrittastronomical.com

~~August 16–22~~ **CANCELED**
MAINE ASTRONOMY RETREAT
Washington, ME
astronomyretreat.com

August 18–23
NORTHERN NIGHTS STAR FESTIVAL
Palisade, MN
https://is.gd/northernnightsfest

~~August 19–24~~ **CANCELED**
SASKATCHEWAN SUMMER STAR PARTY
Maple Creek, SK
sssp.saskatoon.rasc.ca

~~August 20–23~~ **CANCELED**
STARFEST
Ayton, ON
nyaa.ca/starfest.html

~~August 21–23~~ **CANCELED**
NORTHWOODS STARFEST
Fall Creek, WI
cvastro.org/northwoods-starfest

~~September 11–13~~ **CANCELED**
CONNECTICUT RIVER VALLEY ASTRONOMERS CONJUNCTION
Northfield, MA
philharrington.net/astroconjunction

September 11–19
OKIE-TEX STAR PARTY
Kenton, OK
okie-tex.com

September 12–14
NORTHEAST ASTRONOMY FORUM
Suffern, NY
rocklandastronomy.com/neaf.html

~~September 16–20~~ **CANCELED**
ACADIA NIGHT SKY FESTIVAL
Mount Desert Island, ME
acadianightskyfestival.com

September 17–19
ILLINOIS DARK SKIES STAR PARTY
Chandlerville, IL
sas-sky.org

September 18–20
ALBERTA STAR PARTY
Starland County, AB
calgary.rasc.ca/asp2020.htm

• For an up-to-date listing, including coronavirus-caused cancellations, visit https://is.gd/starparties2020.

Eclipsing an Eclipse

Nature gives us a bounty of marvels — just not always where we expect.

I'D ALWAYS WANTED TO go to Tahiti. The allure was legendary: the craggy volcanic peaks of Bora Bora, tropical breezes swaying palms over black-sand beaches, the exotically beautiful, friendly people.

So when I learned that a total solar eclipse would pass near Tahiti in July 2010, I started planning. Initially I was signed up for a flight to one of only a few atolls along the eclipse path with an airstrip. Then came the chance to be on a sailboat. Now you're talking!

It was a small boat, a 15-meter catamaran. Just eight passengers and three crew. Perfect. For a few days, we explored lagoons around Tahiti. The snorkeling was amazing. I swam with sharks and rays. I lazed around on deck soaking up the Sun. I ate like a king. Each sunset was more picturesque than the last.

The morning before eclipse day I watched the razor-thin crescent Moon rise just ahead of the Sun. *Yep, she's coming*, I thought. That night we set sail due south into open ocean for our date with her umbra. The Sun rose the next morning into a partly cloudy sky that fortunately soon cleared, much to our relief. We had arrived.

I knew what to look for, but experiencing my first eclipse was another thing entirely. *When will the stars start to come out? Do I look for the approaching umbra in the air or on the water? Should I focus instead on Baily's Beads?* So much to see, and I saw so much: the delicate tendrils and patchy pink inner edge of the corona, the eerily dark sky overhead with blue towards the vast horizon, the shadow bands on deck of our star twinkling back at us. It was spectacular! We cheered and celebrated.

But wait. That wasn't even the best part of our eclipse voyage. Rewind about half a day, into the wee hours of our sail. "That night we set sail due south into open ocean . . ."

Now, I'd sailed before, but never at night and never in open ocean. The swells built to two meters, not enough to be rough but enough for Mother Nature to let us know she was in charge out there. I'd seen skies so pristine the entire zodiacal band reached out to grab my attention. I'd been in Tahiti for nearly a week and had looked up at a moonless southern sky I'd never seen before. But nothing, *nothing* could have prepared me for *this*.

By 1 a.m. I was lying on the starboard deck wearing nothing but a pair of shorts and a hoodie. Behind us, the faint glow of Pape'ete beyond the horizon, and the soft, sparkly green trail of millions of tiny sea critters stirred by the passage of our hull. And ahead . . . words cannot describe what I saw, what I felt.

There was no sound but the wind in the sails and the waves lapping at the hull. The Large Magellanic Cloud sprawled across several binocular fields. I watched in awe as the grandeur of the southern Milky Way slowly revealed itself past the sails. The warm, heavenly tropical night enveloped me. Nothing else existed. I was so honored. I felt a gentle sob as I breathed it all in.

Eventually I succumbed to Mr. Sandman. The coming day would be a big one, after all.

■ **SCOTT EWART** is an award-winning amateur telescope maker living in upstate New York, where the skies are pretty good.

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