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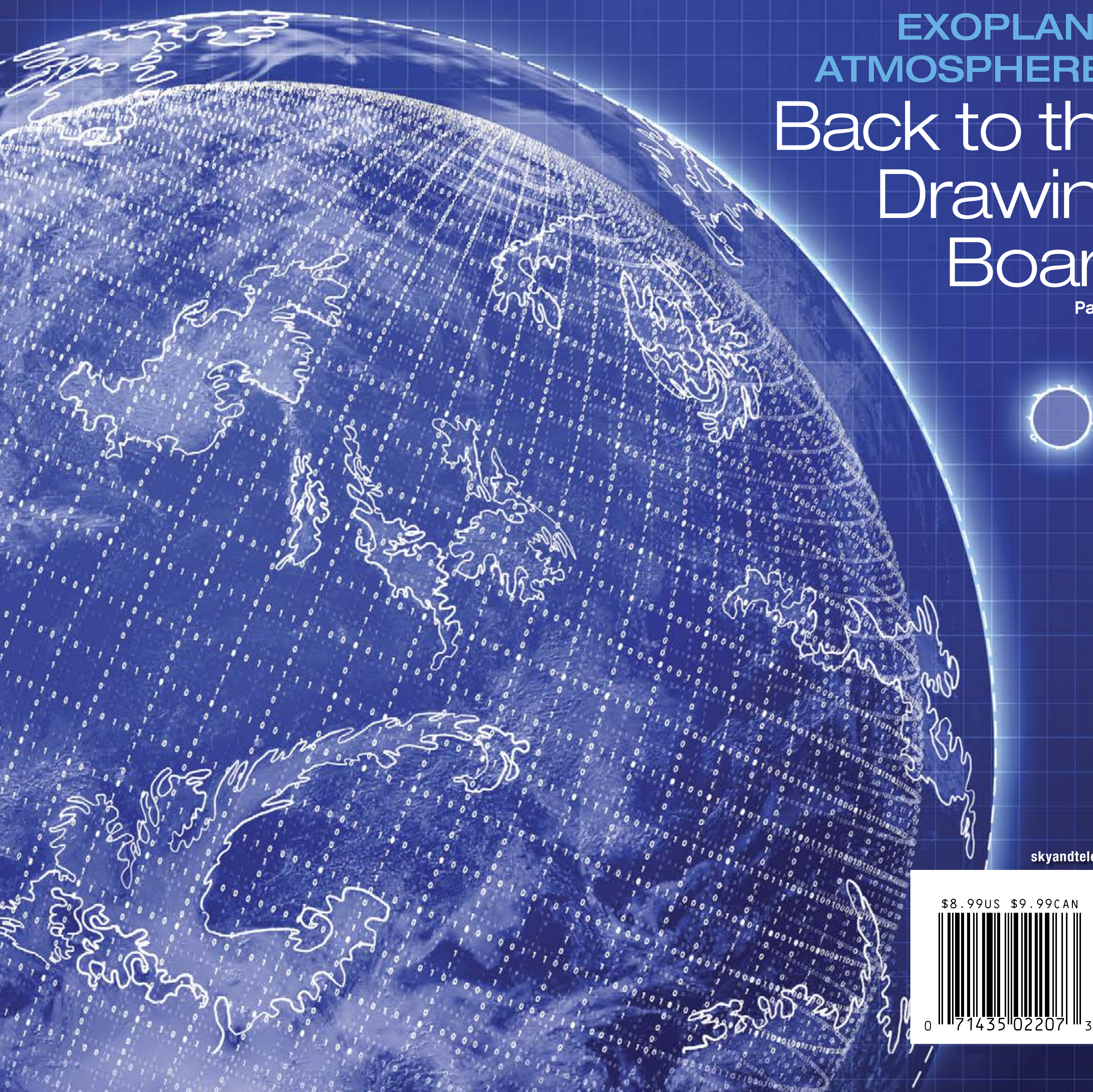
SKY & TELESCOPE

THE ESSENTIAL GUIDE TO ASTRONOMY

DECEMBER 2024



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SKY&TELESCOPE
THE ESSENTIAL GUIDE TO ASTRONOMY

December 2024 VOL. 148, NO. 6


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ESA / HUBBLE & NASA / P. SELL, ACKNOWLEDGEMENT: L. SHATZ

ON THE COVER

Our blueprints of exoplanet atmospheres are incomplete.
ILLUSTRATION: SAYOSTUDIO

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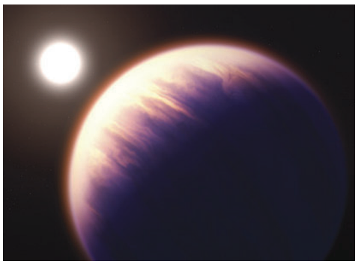
A Spectral Surprise

EVEN THOUGH IT LIES 700 light-years away, we know a lot about WASP-39b. In the first decade after astronomers reported the exoplanet's discovery in 2011, our land- and space-based instruments supplied valuable data with which to infer much about it.

We know it's a scalding, bloated gas giant larger than Jupiter but bearing less than one-third as much mass. It takes just four Earth days to orbit its *G*-type star, being closer to its host than Mercury is to the Sun. As a result, its dayside temperature is a broiling 900°C (1600°F). So life as we know it is not a possibility for WASP-39b.

But astronomers are interested in it for reasons other than the search for life. The exoplanet can tell us a lot about how gas giants like it form and evolve as well as what kind of atmosphere it has. In 2018, scientists used the Hubble and Spitzer space telescopes to study starlight sieved through WASP-39b's skies. They detected a large amount of water vapor — three times as much as Saturn has. They decided that the gas giant must have formed far away from its star, where lots of icy material would have bombarded it early on.



▲ The exoplanet WASP-39b in an artist's concept

NASA / ESA / CSA / JOSEPH OLMSTED (STSCI)

By the end of the 2010s, scientists could feel rightly proud of how much they knew about this far-off giant — a world we can't even image with our best telescopes.

Then the James Webb Space Telescope secured its own spectrum of WASP-39b's atmosphere (see page 38) — and, as Shannon Hall recounts in her cover story beginning on page 34, the new data set scientists back on their heels.

Theorists, in particular, felt humbled. JWST's spectra were so exquisitely rich — revealing a plethora of atoms and molecules along with evidence of active chemistry and clouds — that their computer models suddenly proved inadequate. They found themselves confounded by what they saw.

Hall does a masterful job explaining precisely how and why theorists are laboring to make sense of what JWST is revealing about WASP-39b and other exoplanets. Using phrases like "to make matters more difficult" and "in reality, it's not so simple," Hall guides us through the gauntlet that modelers are running — and, in so doing, she provides a fascinating look at how science works.

Are the theorists daunted? Not as much as they're jazzed. Scientists are never so happy as when they have a problem to solve — especially when the problem is excellent data that need explaining. Here's to some, well, model remodeling.

Peter

Editor in Chief

Editorial Correspondence
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Life Beyond Earth

I just read "Our Fundamental Ignorance" by Edward Zanders (*S&T:* July 2024, p. 84), and I found the article fascinating. I have been interested in the possibility of life existing elsewhere in the universe for more than 60 years. To this end, I recently went back to college and studied both organic chemistry and biochemistry. As a result of studying these subjects, I became convinced that carbon was the only possible element that could be the basis of life. Carbon has the proper abundance, valence, bond strength, and electronegativity necessary to assemble the mega-molecules needed for life to exist. I would be very interested in Zanders' thoughts and opinion on this aspect of potential extraterrestrial life.

Patrick Donnelly
Morgan Hill, California

Edward Zanders replies: *You have highlighted a key topic in astrobiology, namely the chemical composition of organisms that might be detected elsewhere. In principle, we should avoid assuming that just because our life is based on carbon, all other life must be as well. In practice, however, our detailed knowledge of the chemical elements and their compounds makes it difficult, as you have pointed out, to see how alternatives to carbon could provide the necessary structures and reactivity for making large molecules with biological functions.*

There are plenty of elements — silicon, for example — that could be incorporated into bioactive molecules, but not as a complete replacement for carbon. Otherwise, since silicon tends to form mineral-like structures in conjunction with oxygen, you could end up with the unlikely scenario of living rocks. So given the current knowledge, it's hard to see how life could exist without a foundation in carbon chemistry.

I enjoyed reading Edward Zanders' article regarding the origins of life on Earth and its possible exclusivity. One idea that he didn't mention is that regardless of whether we believe that life originated spontaneously on Earth, or whether the beginnings were dropped here by a passing comet or asteroid, or whether an unknown omnipotent power started life here, it seems highly unlikely that, among the 1 to 2 trillion galaxies in our universe, that the same thing didn't happen somewhere else. Numbers alone would overwhelmingly argue for other life to exist among the vastness in which we are only a speck of dust.

Mark S. Donnell
Silver City, New Mexico

I enjoyed reading Edward Zanders' article about our basic inability to say with certainty that life exists beyond Earth. But rather than wondering how likely it is that life *does* exist beyond Earth, it may be worth considering how likely it is that life *doesn't* exist anywhere else. And in that vein, I have created an analogy. Imagine that on some beach somewhere on Earth there is one single grain of sand, and only one, that can talk. To me, that's about as likely as Earth being the only planet in the universe with life.

Jerry O'Shaughnessy
Vienna, Virginia

Edward Zanders has a PhD in biochemistry and decades of life-science experience, but his outstanding quality is his mastery of the pen. In this marvelous article, he invites us to take a step or two backwards, distancing ourselves a moment from the daily commotion of this data-cluttered activity we call science and delving into the profound meaning of our existence.

Thank you, Edward Zanders, and whatever you might do, I beseech you not to let your noble quill run dry.

Patrick Kavanagh
Naucalpan, Mexico

Championing Chandra

David Dickinson's "Chandra Observatory Faces Premature End" (*S&T:* Aug. 2024, p. 10) includes an image of the Crab Nebula (M1). Much of the data in this image are from one of my Chandra observations, and I was pleased to see the image in *Sky & Telescope*. It shows the central pulsar and circular flow of high-energy electrons and is an excellent example of the value of arcsecond resolution in X-ray.

Chandra is a unique resource for astronomy because of its mirrors: a set of four nested pairs of grazing-incidence reflectors, built to have 0.5-arcsecond resolution and large enough to collect useful signals from faint sources. It is difficult enough to build mirrors that will focus X-rays, but to build a set that brings the X-rays to such a sharp focus as Chandra does was a real challenge. The mirrors are the creation of Leon van Speybroeck (1935–2002). He was smart, conscientious, and precise. The mirror array was his baby. He designed it and followed every step of the manufacturing, testing, calibration, and installation. I quietly thank van Speybroeck every time I see an interesting new object pop up in a Chandra image. Indeed, the mirrors have given us 25 years of beautiful astronomical images.

Chandra's sub-arcsecond resolution is an order of magnitude better than that of other existing X-ray

K2-18B ILLUSTRATION: ESA / HUBBLE / M. KORNMESSER telescopes and considerably better than any planned for the immediate future. Alas, van Speybroeck is no longer with us, and when his mirror is gone, it's not coming back. Sub-arcsecond X-ray imaging could be lost for at least 10 years. New mirrors are being designed but will be tricky and time-consuming to build, and often resolution must be sacrificed for larger area.

Hopefully the NASA budget can be increased or rearranged to keep Chandra operational as new observations from the James Webb Space Telescope and other missions come in. The August *S&T* News Note concerning this issue was much appreciated.

Fred Seward
Concord, Massachusetts

The MAGIC Telescopes

I was just reading "Magic in the Air" by Javier Barbuzano (*S&T:* Aug. 2024, p. 12) and, as fascinating as the gamma-ray search is, one detail keeps nagging me that goes uncommented: They are building lightweight, 23-meter, optical-frequency telescopes with carbon fiber and actuators! Is this really the case, and can they be aimed at other deep-sky targets as well?

Joshua Stern
Los Angeles, California

Camille M. Carlisle replies: *Cherenkov telescopes like those of the Cherenkov Telescope Array Observatory cannot be used like optical telescopes: They focus at a distance of 10-15 km above the primary mirror, and their detectors are only sensitive to green-bluish light and designed to catch flashes that last for tens of nanoseconds at most — in other words, they're built to detect brief flashes of blue light in Earth's atmosphere, not to resolve the images of celestial objects like nebulae and galaxies. The angular resolution of any image would be rather poor when compared with dedicated optical instruments such as the 10-meter Gran Telescopio Canarias.*

Some astronomers have nevertheless explored the possibility of using the Cherenkov telescopes for catching optical transients or for imaging bright sources. But these are only ideas at this stage, and even if astronomers modified the receivers to be able to detect a wide range of wavelengths, the images would be blurred and defocused.

FOR THE RECORD

- Mars reaches opposition on January 16th, not January 12th as shown in the graph on page 72 of the September 2024 issue. Also, the graph does not include magnitude information, contrary to what is stated in the caption.
- On page 59 in the October 2024 issue, Herbig-Haro objects vary on time scales of a few years, not days.

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

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

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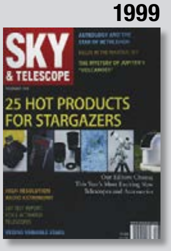
1974

1999



December 1949

Radio Astronomy "Mr. [Grote] Reber brought with him a large stack of tracings [of] radiation from the sky at a wave length of slightly less than two meters. . . . There was clearly [a surge] at the exact time the Milky Way passed over his antenna. An annoying factor was the presence of numerous violent and sharp disturbances which Mr. Reber explained to us were the result of various electrical appliances, such as a dentist's drill a block or two away, a trolley line on a street in his vicinity, or the faulty ignition of a passing car.

"As we continued our discussion [and] after G. P. Kuiper had visited him at his house in Wheaton, Ill., and inspected the remarkable radio telescope which he had built at his own expense . . . we began to see emerging before our eyes a completely new branch of astronomy."

So recalled Yerkes astronomer Otto Struve.

December 1974

Jupiter's Family "The 20th-magnitude moving object discovered near Jupiter in September [is now] confirmed to be a satellite of that planet. New photographic positions of Jupiter **XIII** were secured on the evenings of October 16th and 17th by Charles Kowal with the 48-inch Palomar Schmidt telescope . . ."

Finding this moon (later named Leda) opened the floodgates. Today, Jupiter has nearly 100 known moons, and Saturn half again as many as that.

December 1999

Dwindling Deuterium "One of the most eagerly sought numbers in cosmology is the density of *baryons*, the particles that make up atomic nuclei. By comparing the baryon density to censuses of visible galaxies, astronomers can tell whether ordinary matter is mostly luminous (that is, residing in stars) or dark (lurking unseen in black holes, gas clouds, or planets and brown dwarfs). New spectroscopic measurements support the notion that there are more baryons than meet the eye — implying that baryons constitute a significant fraction of the universe's dark matter.

"The most sensitive baryon indicator is deuterium, [which] was created in the Big Bang [but largely] destroyed as the primordial fireball expanded and cooled. The nuclear reactions that consumed deuterium would have run faster if baryons had been more abundant. Thus plentiful deuterium is a sign of low cosmic baryon density, and vice versa. But reading the cosmic deuterium meter is far from easy [because] 'there's always the worry that what appears to be the deuterium line is hydrogen at a different redshift,' says Todd M. Tripp (Princeton University)."

While studies to learn the cosmic abundance of deuterium go on, a step forward came in 2005 when Alan Rogers and colleagues at MIT's Haystack Observatory first detected it at radio wavelengths.

This nearby spiral galaxy (NGC 3972) was one of those observed by both the Hubble and James Webb telescopes to measure the Hubble constant.

COSMOLOGY

Hubble Tension Loosens

FOR ALMOST A DECADE, astronomers have struggled with a nagging mismatch between different ways of determining the *Hubble constant* — a measure of the current expansion rate of the universe. This mismatch, known as the *Hubble tension*, has led to claims that new physics might be needed to solve the issue (*S&T:* June 2019, p. 22). Now, new data may have resolved that tension.

The traditional way of determining the Hubble constant has been to gauge galaxies' distances using *standard candles*, for which both apparent brightness and true luminosity are known. The distance to these standard candles can then be compared to their galaxies' redshifts. Over the past decade, a team led by Adam Riess (Johns Hopkins University) has used this method to arrive at a Hubble constant of about 73 kilometers per second per megaparsec.

However, astronomers can also calculate the current expansion rate by analyzing properties of the *cosmic microwave background* (CMB), which yields a Hubble constant of just 67.4 km/s/Mpc.

Now, in a recent preprint (that is, a paper that hasn't yet undergone peer review), a team led by Wendy Freedman (University of Chicago) presents new JWST data on 11 galaxies. Like Riess and colleagues, Freedman's team used Cepheids, but they also looked at two other standard candles that involve not individual stars but whole populations of them. One is a class of old, low-mass stars, which undergo a sudden flash of helium fusion in their cores upon reaching the end of their red-giant evolutionary phase; these stars make up the so-called *tip of the red giant branch* (TRGB). Another is a type of carbon-rich pulsating stars, known as *JAGB stars* (short for J-region asymptotic giant branch).

Combining all three methods, the team finds a Hubble constant between 68.4 and 71.5 km/s/Mpc — a value higher than but consistent with theoretical predictions based on the CMB.

Freedman says the latter two methods are more accurate than using Cepheids, though she admits that there is no single perfect method. To analyze Cepheids, astronomers need to account for their temperatures and compositions as well as intervening dust. Moreover, since these supergiant stars are relatively young, they are found in galaxies' inner disks and densely populated spiral arms. So a star might appear brighter than it is because its light has blended with the light of neighboring stars.

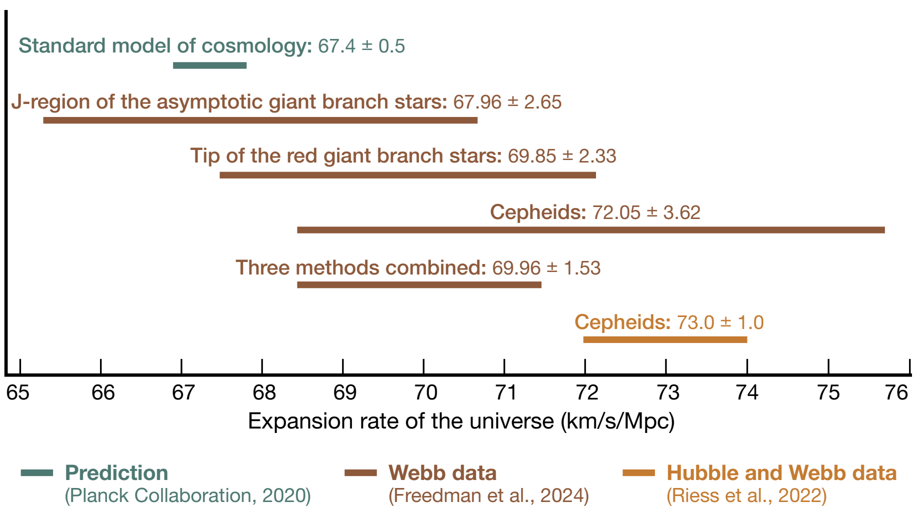
In contrast, red giant and JAGB stars, although intrinsically fainter than Cepheids, are found in galaxies' outer disks and halos. Using these stars yields values of the Hubble constant in "superb accord" with each other and consistent with CMB measurements, says Freedman, while the Cepheid method arrives at a somewhat higher value for the Hubble constant.

In a recent study, Riess's team used JWST data to show that crowding effects do not play a decisive role (*S&T:* July 2024, p. 11). Nevertheless, Freedman thinks that the divergent results for Cepheids might result from the stars' many associated complexities.

Cosmologist Richard Ellis (University College London) agrees, saying he's impressed by Freedman's TRGB work: "I really find [her] case convincing." Meanwhile, Riess has posted a rebuttal.

There's more work to be done, Freedman acknowledges: "So far, we've only scratched the surface. By observing more distant galaxies with JWST, we'll get to the bottom of it."

■ GOVERT SCHILLING



▲ Various methods and teams have measured different values for the Hubble constant.

NEARBY GALAXY: YUVAL HARPAZ, DATA VIA JWST; GRAPH: BEATRIZ INGLESSIS / S&T; SOURCE: FREEDMAN ET AL. / ARXIV: 2408.06153

STARS

Neutron Stars Might Be Squishy Inside

IN PINNING DOWN the properties of the closest and brightest neutron star observed so far, Devarshi Choudhury (University of Amsterdam) and colleagues have ruled out both the plainest and the strangest ideas describing the dense matter in neutron star cores.

When stars of a certain mass collapse into neutron stars, most of their atoms break down into neutrons. But conditions are weirder in the center, where the pressure can grow to the limits of unbearable. The key to understanding how weird lies in the *equation of state*, which describes how density changes with pressure.

If the densest matter is "stiff," then increasing a neutron star's mass, and thus its internal pressure, wouldn't cause many (or any) interior changes — the neutron star would simply grow in size. But if the equation of state calls for a "squishy" interior, then increasing mass would alter the core in some way, perhaps squeezing quarks out of neutrons. Depending on how squishy the matter is, a neutron star may stay the same size as mass is added, or it might even shrink.

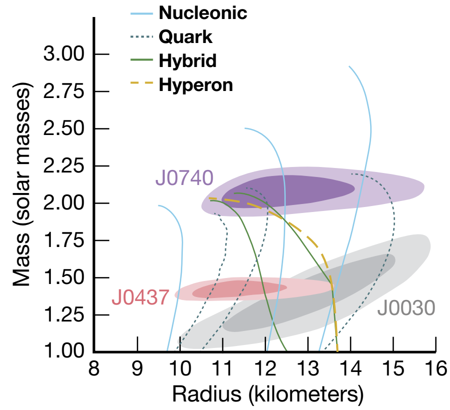
To unravel the equation of state, astronomers are measuring masses and radii of spinning neutron stars known as *pulsars* using the Neutron Star Interior Composition Explorer (NICER) on the International Space Station. To measure size and heft, NICER clocks the arrival of X-rays from hot regions near pulsars' magnetic poles as they whirl around like frenetic lighthouses.

NICER scientists have now obtained data on the closest pulsar from their list, PSR J0437–4715, 512 light-years away. It's fast, pulsing 174 times per second — quicker than the whirling knives of a kitchen blender — and it's bright, which makes for precise measurements. The astronomers find a radius between 10.7 and 12.3 kilometers (6.6–7.6 miles), and with the aid of previously gathered radio data, around 1.4 times the Sun's mass.

These measurements have placed some of the best limits yet on what kinds of material might exist inside neutron stars, ruling out scenarios on both extremes. "Our new result points us towards slightly softer (squishier!) equations of state," says team member Anna Watts (also at University of Amsterdam). "But the very softest are still unlikely, as are now the stiffest."

That means that neutron star cores are probably not just neutrons, though exactly what exotic particles might reside there is still up in the air.

■ MONICA YOUNG



▲ New mass and radius measurements from J0437 (red) and two other pulsars rule out the stiffest and squishiest states of matter. Also shown are some representative equations of state (cobra-shaped lines).

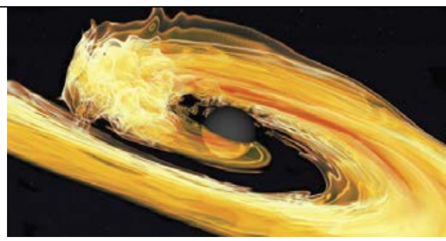
GRAVITATIONAL WAVES

Black Hole Ate Neutron Star (Probably)

GRAVITATIONAL-WAVE astronomers have identified ripples in spacetime from the collision and coalescence of a neutron star with what's likely one of the smallest black holes ever found.

When massive stars die in supernovae, their imploded cores can become neutron stars or — if they're big enough — black holes. Neutron stars top out at around 2½ solar masses; black holes file in beyond that.

But starting in the late 1990s, observers noticed a gap between the heaviest neutron stars and the lightest black holes, the latter of which tended to weigh in with at least 5 Suns' worth. Subsequent theoretical work suggested it's difficult for stars to make black holes of only a few solar masses.



▲ This simulation shows a black hole tearing a neutron star apart before merging with it, an event called tidal disruption.

Yet astronomers have found a handful of objects in this putative gap, and one of the hopes for gravitational-wave detectors is that they'll help us determine just how empty this gap really is. Now, scientists with the LIGO-Virgo-KAGRA (LVK) collaboration have found another object in the breach.

On May 29, 2023, the LIGO Livingston detector in Louisiana wiggled as gravitational waves passed through it in an event dubbed GW230529. (The other detectors were offline at the time or not sensitive enough to pick up the event.) Based on careful analysis of the signal, the collaboration concluded that the gravitational waves marked the merger of two objects: a smaller one with a mass between 1.2 and 2 Suns, and a larger one between 2.5 and 4.5 Suns.

The mass of the smaller one indicates it's almost certainly a neutron star. The larger one is most likely a black hole, the scientists conclude in the August 1st *Astrophysical Journal Letters*; however, they cannot completely rule out that it's a massive neutron star.

GW230529 is only one of more than 81 events detected during the first half of LVK's fourth observing run, which will continue until June 2025. These will join the roughly 100 already found in previous observing runs, either by the LVK collaboration or by independent teams trawling the data.

■ CAMILLE M. CARLISLE

OUTREACH

Young Astronomer Wins Stellafane Award

THE ORGANIZERS OF Stellafane, the century-old convention held annually in Springfield, Vermont, awards prizes every year to telescope makers (*S&T:* Aug. 2023, p. 60). This year, the convention introduced a new one: the Raymond Fairbanks Youth Outreach Award, named in honor of the youngest member of the original group of amateur telescope makers who founded Stellafane. And the honor couldn't have gone to a more deserving recipient.

Kaitlynn Goulette, of Westfield, Massachusetts, became interested in astronomy before she even started kindergarten, watching planetarium shows with her mother at the Springfield Science Museum. During those visits, Goulette learned about and ultimately joined the Springfield STARS, a local astronomy club. Her interest was such that her parents even bought her a telescope for her sixth birthday.

▲ Kaitlynn Goulette, the first-ever recipient of the Raymond Fairbanks Youth Outreach Award, holds her plaque with Carl Malikowski, Stellafane Club Outreach Director.

When Goulette, now a junior, started at Westfield High School, she founded the school's first astronomy club. But that wasn't *her* first astronomy club — it was her third! She had founded clubs at her elementary and middle schools, too. The three clubs even combine efforts for special astronomy events.

Goulette also created a monthly newsletter, *The Starry Scoop*, as a way for the members of her elementary school astronomy club to stay in touch during the COVID-19 pandemic. She expected it to be a small-scale publication, but now she continues to write and distribute it as its audience has grown.

At the Stellafane convention last August, Outreach Coordinator Carl Malikowski presented Goulette with the outreach award — much to her surprise.

"Stimulating interest in astronomy and telescope-making is our passion at Springfield Telescope Makers and our focus for our outreach programs," Malikowski says. "Recognizing youth who share this same passion and whose efforts are deemed exceptional by others in our astronomy community is what the Raymond Fairbanks Youth Outreach Award is all about. I cannot think of a more deserving person to be the first recipient of this Award."

■ **DIANA HANNIKAINEN**

OBITUARIES

David Crawford, 1931–2024

WITH THE PASSING OF David L. Crawford, at age 93, we have lost the person who taught the world about light pollution and warned us all of the threat it poses, not only to astronomy but also to the entire nocturnal environment.

Crawford didn't intend to become a crusader for dark skies. After receiving his doctorate in astronomy from the University of Chicago in 1958, he spent most of his career with the Kitt Peak National Observatory (KPNO). There, his research probed the structure and evolution of open star clusters and galaxies, and he soon found himself in charge of building a 4-meter telescope at Kitt Peak.

By then, Tucson had grown to a half million people — all living within 60 miles of Kitt Peak's growing telescope complex. Crawford, who also managed KPNO's dark-sky office, worked with the city's leaders to enact outdoor-lighting regulations protecting the pristine darkness over KPNO facilities. As part of this work, Crawford connected with amateur astronomer Tim Hunter, and together they founded the International Dark-Sky Association in 1988. So began a decades-long quest to change the world's approach to nighttime illumination.

By 2001, when I first met "Dr. Dave," he had retired from Kitt Peak and was devoting all his time to IDA as its unpaid executive director. He was disarmingly soft-spoken but clearly driven in his quest to save the night sky.

In 2008, after 20 years at the helm of IDA, Crawford retired to the San Diego area, where he and his wife, Mary, lived for many years near and with Lisa Crawford Bruhn, one of their three daughters. (Mary died in 2012.) Meanwhile, IDA (recently renamed DarkSky International) has only grown in size, reach, and stature. Today, it boasts members and advocates in all 50 U.S. states and more than 70 countries. "IDA has far outgrown its founders and surpassed our every hope for it," observes Hunter.

Among numerous awards, Crawford was honored with the Illuminating Engineering Society Medal in 2021 in recognition of decades of engagement with lighting professionals. In fact, Crawford's greatest legacy is the realization that light pollution is a problem not just for astronomers, but also for every aspect of the nighttime environment — from fireflies and pollinators to human health. As lighting engineer James Benya points out, "How far we have come and how much we have changed is, in the beginning, because of Dave."

■ **J. KELLY BEATTY**

KAITLYNN GOULETTE: DONALD GOULETTE; DAVID CRAWFORD: LISA CRAWFORD BRUHN


AAS
245

Shooting stars are more than a spectacle — they give us unique insights into the comets and asteroids they come from.

It was a frigid night in 2001. A teenage me sat with my parents outside the southern city of Guangzhou, China, staring at the sky. A Leonid meteor storm was predicted to occur that night, but none of us knew what to expect. Three years before, we had enthusiastically gone out for another promised Leonid "storm," only to learn the hard way that meteor-storm predictions are not easy.

Around midnight, a meteor as bright as Venus emerged and elegantly flew westward. "Wooooooah!" we all exclaimed. It was a prelude to an unforgettable — perhaps once-in-a-lifetime — show, during which we counted more than 2,000 meteors by the end of the night.

Meteors and meteor showers have long caught people's attention. The Lyrid meteor shower, for example, was recorded by the Chinese as early as the 7th century BC. However, it wasn't until the 19th century that scientists correctly proposed that the meteors in any given shower originate as clouds of particles in space, which burn up in our atmosphere as Earth plows through them. Astronomers reached this conclusion largely thanks to a series of storms from the Leonid meteor shower — the same shower that produced the storm that I saw in 2001.

Several comets found in the 1860s had orbits nearly identical to the paths traveled by some of the then-known meteoroid clouds, prompting scientists to conclude that comets were the "parents" of meteor showers. The discovery of the comet-meteor linkage, together with the successful (but, in retrospect, lucky) prediction of the Andromedid meteor storms in 1872 and 1885, gave the impression that astronomers could accurately predict meteor storms as easily as they computed the orbit of Neptune. The public was therefore vastly disappointed when the widely advertised Leonid storm in 1899 failed to appear. American astronomer Charles P. Olivier called it "the worst blow ever suffered by astronomy in the eyes of the public."

To be fair, the Leonids did put up a strong "sub-storm" in 1901, but the damage was done. Meteor scientists would spend most of the next century trying to recover from this humiliation, a journey that not only tells us a lot about meteor storms themselves but also reveals secrets about the objects that meteors come from — mostly comets, but sometimes misbehaving asteroids.

What Makes a Meteor Storm?

Since the misfortune of the 1899 Leonid (non-)storm, astronomers have learned that the return of a parent comet doesn't always lead to a spectacular performance for the associated meteor shower. For example, the Leonids produced great shows in 1833, 1866, and 1966, but they were relatively mediocre in 1899 and 1932, when their parent

GEMINIDS GALORE This composite image combines 48 frames to show a series of meteors raining down on a wintry landscape in the province of Heilongjiang in northeastern China on December 13–14, 2017. Photographer Jeff Dai braved temperatures of –28°C (–18°F) to capture the event.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comet 55P/Tempel-Tuttle also came around.

The fundamental understanding necessary for predicting meteor storms had already taken shape as early as the 1890s, and the essential theoretical framework was largely complete by the time Fred Whipple published his “dirty snowball” model for comets in 1950. The story unfolds like this: Comets are composed of collections of ice, rock, and dust. They warm up when approaching the Sun and launch dust particles into space. The dust particles orbit the Sun along with their parent comet. However, the combination of sunlight’s pressure and gravitational tugs from the major planets gradually amplify small differences in the particles’ trajectories, slowly turning the dust cloud into a stream along the comet’s orbit. This stream eventually dissipates into the interplanetary dust, which is itself primarily made of comet and asteroid debris, becoming part of the *zodiacal light* that we see under dark, pristine skies.

Predicting meteor showers’ behavior thus requires accurately projecting the evolution of these dust clouds forward in time, then finding the times when Earth intercepts them.

This work is a tricky endeavor: Planets and comets are single, solid bodies, but meteoroid streams are long, continuous structures made of countless particles. So instead of calculating the location of one representative dot, one needs to calculate the locations of many small bits, each representing a segment of the meteoroid stream. As you can imagine, these calculations were exceedingly difficult for astronomers relying on pencil and paper, however fantastic their computational skills were.

The development of modern computers provided critical help in solving this challenging problem. In 1962, John Davies and Władysław Turski of the University of Manchester in England pioneered the use of modern computers in meteoroid-stream simulations. They used the Ferranti Mercury computer — an early commercial computer that operated at a speed 100 million times slower than an iPhone 14 — to study past cometary ejecta. They found out that the Draconid meteor storms in 1933 and 1946 were caused by earlier cometary activity around the turn of the century.

In the following four decades, three groups of researchers across the globe independently developed a method to accurately predict future meteor storms. At the time, the researchers were unaware of one another’s work, in part due to difficulties with access to scientific publications in that era.

First came Edward K. L. Upton (University of California, Los Angeles), who in 1977 propagated cometary ejecta into the future and correctly predicted the 1999 Leonid storm that came two years before the storm I saw as a teenager. Upton’s work, however, was written as a popular-science article (it won first prize in the *Griffith Observer* writing contest that year) rather than as a research paper, and so it was not fully appreciated by the research community until years later.

Then, in 1985, Ekaterina Kondrat’eva and Evgenij Reznikov at Kazan State University in Russia independently devised a similar method based on a series of studies by themselves and other Russian scientists in the 1970s. They also correctly predicted the 1999 Leonid storm. However, their original paper was written in Russian and wasn’t widely known in other parts of the world for many years.

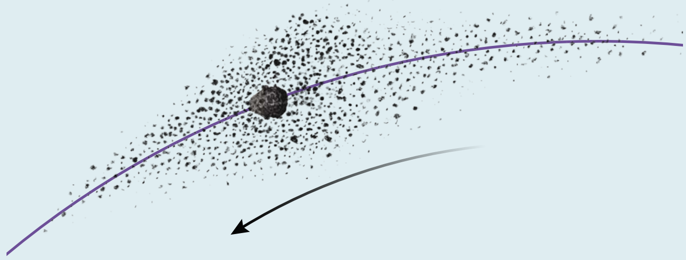
Finally, in 1999, David Asher of Northern Ireland’s Armagh Observatory and Robert McNaught of Australian National University also independently arrived at the same method and made the same prediction. They published their results in well-circulated journals. The earlier works by Upton and Kondrat’eva and others were subsequently noticed and finally received full attention. Meteor-storm prediction finally became a reality.

All of these works also explained why my family and I didn’t see a storm in 1998: That year, Earth simply missed the bulk of the meteoric material when it flew by.

BEATRIZ INGLESSIS / *S&T*

How Meteor Storms Form

A comet or asteroid coughs out a dust cloud when sunlight warms it.



The dust cloud envelops the comet and travels with it around the Sun.

Tracks in the Sky

Ten years after the 2001 Leonid storm, I moved to the University of Western Ontario in Canada to study meteor astronomy. I soon discovered the fun of winter, as the tropical Guangzhou never sees snow. One entertaining activity was to trace animal tracks in snow: By looking at the pattern, shape, and texture of the track as well as the weather and environmental conditions, one could figure out which animal had left the track, when the animal had passed by, and possibly in what circumstances.

The traceology of snow tracks is a nice analogy for what astronomers can do with meteors: By combining the characteristics and behavior of a meteor shower (equivalent to the snow track's appearance) with planetary dynamics (the environment around the snow track), one can sometimes tell the story of its parent comet or asteroid (the often unseen animal that left the snow track). When conditions are right, this approach can reveal a wealth of information about the history and evolution of the comet that is sometimes not otherwise possible to obtain.

How do we learn about a comet from its associated meteor shower? There are several ways. One is to use the strength of the meteor shower to infer the comet's past activity. ("Activity" means how much material the comet spewed into space at a given time.) It is not a coincidence that many well-known meteor showers originate from relatively bright comets: Orionids and Eta Aquariids from Halley's Comet, Taurids from Encke's Comet, et cetera. The Leonids' parent, Comet 55P/Tempel-Tuttle, was bright enough to be discovered in 1865, and a study of historical records later revealed that it was seen as early as 1366.

When predicting meteor showers' behavior, astronomers use the observed intrinsic brightness of the parent comet to make an educated guess about the strength of a forthcoming meteor outburst. Today, they can often achieve predictions close to what's observed, with hourly rates typically correct to within a factor of a few. They can also flip the script and use the observed meteor rate to constrain the past activity of the comet.

A comet's activity doesn't necessarily stay constant from return to return; it can fluctuate, and, in extreme cases, the comet can break up. Good fortune in predicting the rate of the Leonids between 1999 and 2002 suggests that the activity level of 55P/Tempel-Tuttle has stayed fairly constant over several returns. This is a useful conclusion, since the comet itself only comes around every 33 years and was not extensively observed until its most recent return in 1998. Hence, meteor observations serve not only as an effective window into past cometary activity, they are often our *only* peek into the parent comet's past.

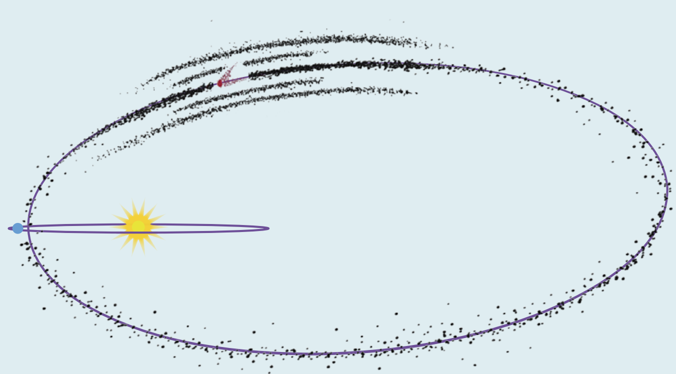
A fascinating case is the Geminids, which appear in December. Being the strongest annual meteor shower, the Geminids' cloud of particles follows a distinct orbit that comes very close to the Sun — less than a third of Mercury's average distance to our star, in fact. The Geminids are associated with a large near-Earth asteroid known as 3200 Phaethon. For a long time, numerous ground-based observations failed to find any signs of cometary activity on Phaethon. Then in 2009, astronomers realized that Phaethon ejects some material, but only when it passes closest to the Sun (when telescopes can't see the asteroid). Yet the amount of emission was way too small to explain the current intensity of the Geminids.

By combining observational evidence with meteoroid-stream models, astronomers concluded that Phaethon must have shed a large amount of material several thousand years ago. The event, if it occurred over a single apparition, would

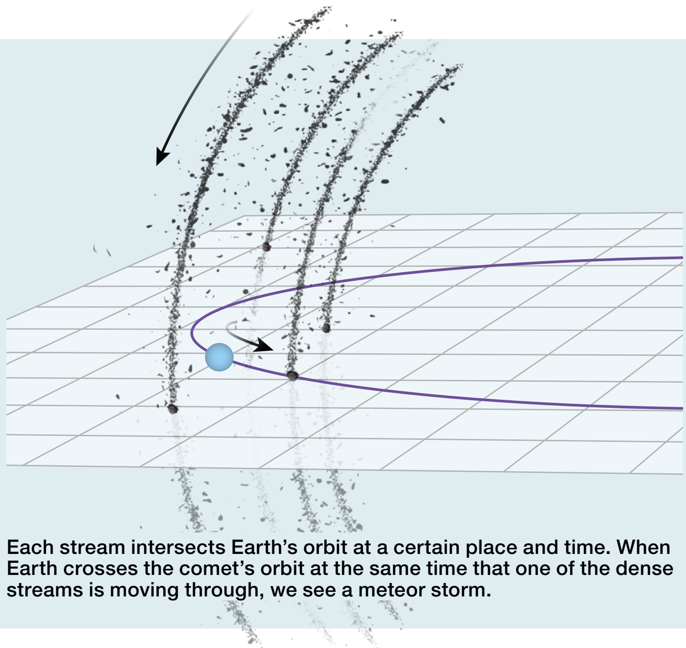
71%
Fraction of mass falling to Earth from meteoroid streams that arrives on Jupiter-family comet orbits

15%
Fraction of mass falling to Earth from meteoroid streams that comes from the Geminids

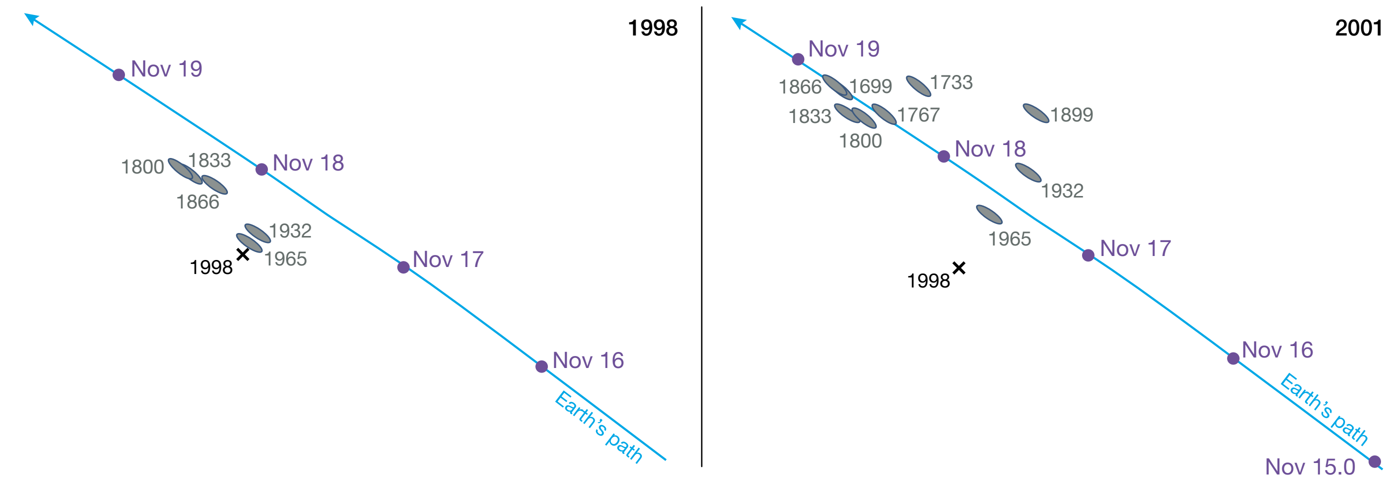
STATISTICS SOURCE: P. JENNISKENS ET AL. / *ICARUS* 2016



Over time, sunlight's pressure and the planets' gravity stretch the cloud into a stream along the comet's orbit. Many such streams travel with the comet, nudged to varying degrees away from the comet's path (offsets exaggerated here for clarity). The streams dissipate with time.



Each stream intersects Earth's orbit at a certain place and time. When Earth crosses the comet's orbit at the same time that one of the dense streams is moving through, we see a meteor storm.

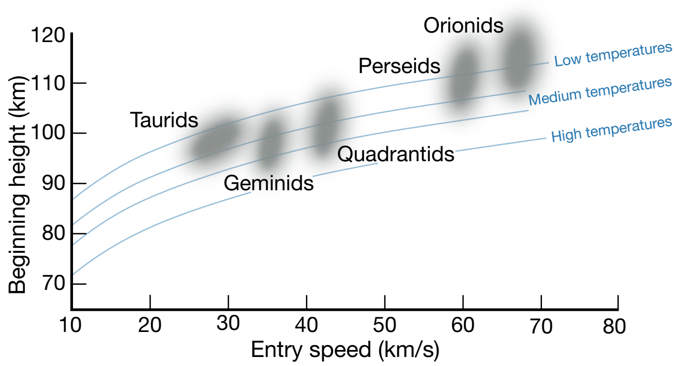


▲**NEAR MISS OR A HIT** Looking down on the ecliptic plane (the page is the plane), we see where each meteor stream intersects the plane (gray ellipses). In 1998, none of Comet Tempel-Tuttle's streams crossed Earth's orbit when the planet was passing by (*left*). But in 2001, Earth flew right through three streams (*right*). The X symbol marks where the comet crossed the plane in 1998, and ellipse years are for the outburst that created each stream.

have turned Phaethon into a "comet" of magnitude −5, on par with some of the greatest comets seen in history! An event of such magnitude would have caught the attention of ancient stargazers. Unfortunately, the event probably happened before civilizations began systematically recording celestial events, which would explain why no surviving historical records indicate its observation. Without the Geminids, we wouldn't have known that this dramatic event occurred.

Another strong annual meteor shower, January's Quadrantids, is also an interesting case. Astronomers long thought that the parent comet of the Quadrantids was either 96P/Machholz 1 or a bright comet observed in 1490–91. But neither was a perfect match to the Quadrantids' orbit. Then, in 2003, the faint asteroid 2003 EH_1 was found and emerged as a convincing candidate.

But the answer turns out to be more complicated than that. Years of work in meteor, comet, and asteroid sciences have gradually revealed the presence of a gigantic, complex system of parent bodies and debris now known as the *Machholz Interplanetary Complex*, which comprises Comet Machholz 1, asteroid 2003 EH_1, hundreds of smaller comets or perhaps asteroids, at least four annual meteor showers including the Quadrantids, and perhaps even the 1490 comet. These all progressively formed over a timescale of 12,000 to 20,000 years, presumably from the same parent object. The Quadrantids is the youngest component of the system, with its core formed perhaps only 200 to 500 years ago.



▲ **LOOK UP** Meteoroids start burning up in the atmosphere at different heights and surface temperatures. Those from comets tend to be more fragile and ablate at higher temperatures than asteroidal ones. Slower particles also dive deeper before they're hot enough to light up.

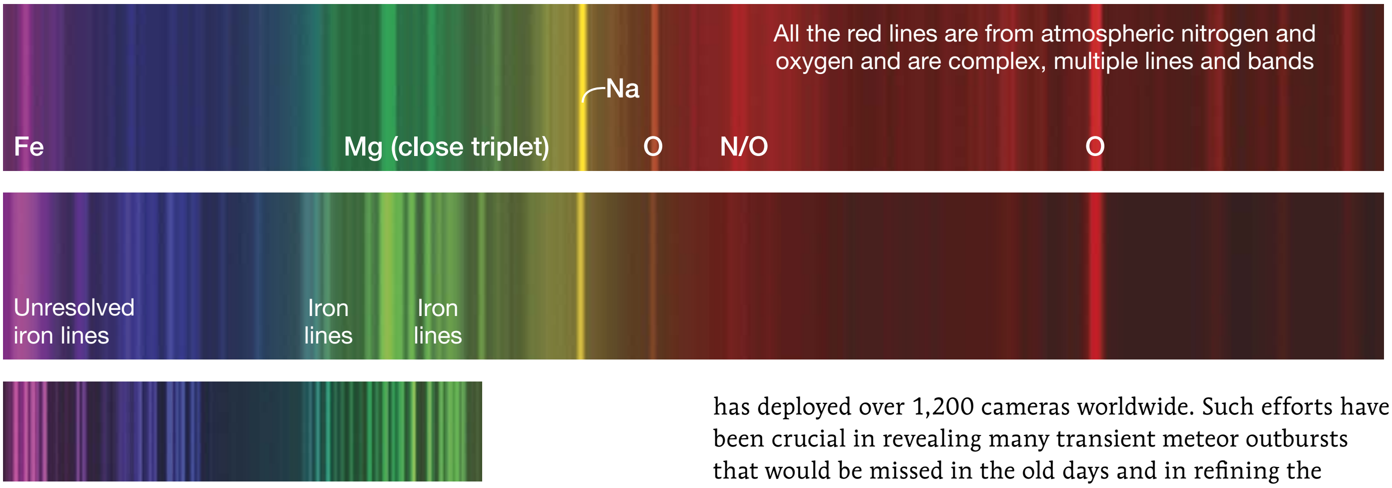
Sample-Return Missions by Mother Nature

No two meteors are the same: Some flare, some break into pieces, some are more colorful than others. These colors can range from orange and yellow to blue or just plain white, depending on the composition of the meteoroids. In a way, our atmosphere is a huge laboratory floating above us, autonomously processing meteoric samples that are delivered to us with the help of the Sun and planets. With specially built instruments, astronomers can learn about these cometary materials without leaving our planet.

Let us talk about the Geminids again. If you have seen the Geminids, you might notice that they are rarely orange in color. This is because they tend to miss an important contributor to the orangish hue: sodium. About 80% of spectrally observed Geminids are free of sodium, far higher than many other showers. Astronomers have long suspected that this is due to the unique, Sun-approaching orbit of the Geminids: Intense solar heating vaporizes rock on Phaethon and releases sodium atoms, which help carry dust away as vapor escapes from the asteroid to space. In 2022, the space-borne Solar and Heliospheric Observatory was temporarily repurposed to observe Phaethon, and its data convincingly demonstrated that Phaethon's recurring activity close to the Sun is, indeed, caused by escaping sodium atoms. The dots line up nicely!

You might remember the Draconids that Davies and Turski first modeled in 1962. Astronomers have long known that the Draconid meteors tend to appear at unusually high

METEOR INTERSECTIONS: BEATRIZ INGLESSIS / *S&T*, SOURCE: D. J. ASHER / *PROCEEDINGS OF THE INTERNATIONAL METEOR CONFERENCE* 1999; ABLATION: BEATRIZ INGLESSIS / *S&T*, SOURCE: P. JENNISKENS ET AL. / *ICARUS* 2016



▲**METEOR MAKEUP** From top to bottom, these colorized spectra show the compositional differences of Leonid, Geminid, and iron meteoroids. The top two spectra span the near-ultraviolet to the near-infrared (380 nm to 883 nm); their colors are scaled here to include the wavelengths outside our visible range. Note that this Geminid fireball shows sodium, which often isn't the case. The iron meteoroid spectrum spans 380 nm to 551 nm and is higher resolution. Nearly every line there is from iron.

DR. BILL WARD / INTERNATIONAL METEOR ORGANISATION / UNIV. OF THE WEST OF SCOTLAND

altitudes when they arrive in October — an indication that they are very fragile, because they break up even before diving into the denser part of Earth's atmosphere. Meteoroids from comets generally burn up at higher altitudes than those from asteroids, because they're less sturdy, but the Draconids are particularly delicate.

By combining multi-station camera data with aerodynamic models, astronomers can precisely measure the height and mechanical strength of these meteoroids. The results show that they can be weaker even than fresh snow! Data-modeling efforts like this one are becoming increasingly important, as they allow us to assess certain cometary (and sometimes, asteroidal) materials without expensive sample-return missions (*S&T:* July 2024, p. 20).

Looking Ahead

Meteor observations effectively use the whole atmosphere as the detector, and hence meteor science heavily relies on crowd sourcing the data from observers all over the world. As such, meteor science is one of the areas where contributions from citizen scientists remain crucial.

For many years, visual observation has been an important data source for meteor research. It requires no more than a pencil and a piece of paper (and preferably an armchair). Observers still submit their counting data and fireball sightings to the International Meteor Organization (IMO; **imo.net**) and the American Meteor Society (AMS; **amsmeteors.org**).

On another front, the miniaturization of cameras and computers in the last decade has helped the rise of digital surveillance networks. The Global Meteor Network (GMN; **globalmeteornetwork.org**), for example, has developed a low-cost, open-source system based on commercially available CMOS cameras and Raspberry Pi computers. The GMN has deployed over 1,200 cameras worldwide. Such efforts have been crucial in revealing many transient meteor outbursts that would be missed in the old days and in refining the structures of known meteor showers.

Meteor astronomy, and our understanding of the solar system as a whole, will also benefit from the large, next-generation ground- and space-based telescopes. Surveys such as the Vera C. Rubin Observatory's Legacy Survey of Space and Time and NASA's upcoming Near-Earth Object Surveyor mission will map the solar system with unprecedented sensitivity, likely finding many meteor-shower parents in the process (*S&T:* June 2024, p. 34). Multi-purpose facilities such as the James Webb Space Telescope and the Atacama Large Millimeter/submillimeter Array will enable targeted observations of comets and asteroids with unparalleled sensitivity and spectral coverage. By combining knowledge on all fronts, we will deepen our understanding of comets and asteroids as well as the role that they play in the evolution of our solar system.

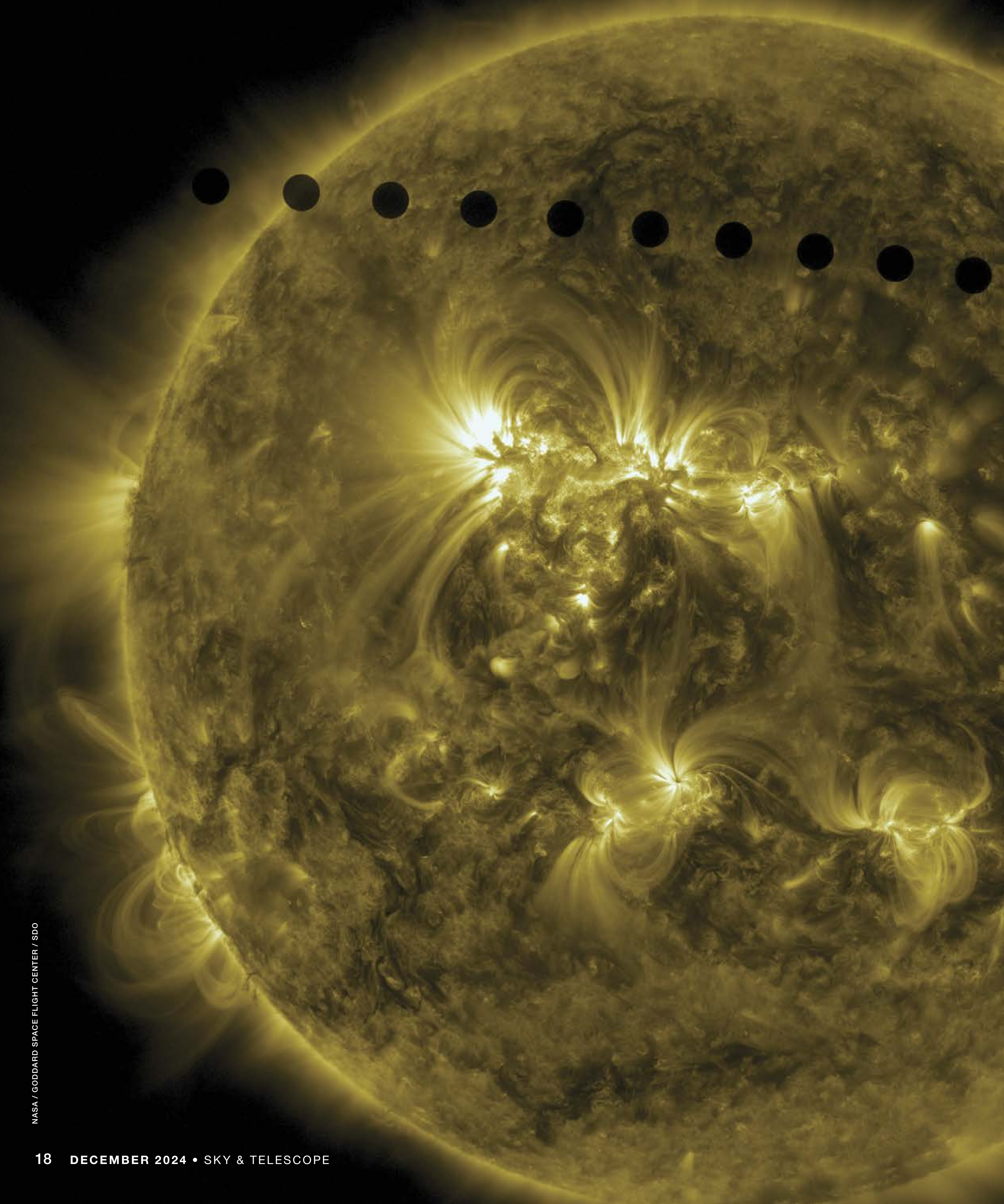
The advancement of planetary science and interplanetary exploration has taken meteor research out of our world, too. The impact hazard from meteoroids is a legitimate concern for human spaceflight and robotic spacecraft near and far. Research on this topic also provides valuable information about dust's distribution throughout the solar system.

In late 2014, for example, Comet C/2013 A1 Siding Spring flew close past Mars — whizzing only a third of the Earth-Moon distance away from the Red Planet. The flyby brought an intense meteor shower to the planet, an event that was well captured by a fleet of orbiters at Mars and told us a lot about the comet itself as well as the planet's atmosphere and magnetic environment.

More broadly, known and unknown meteoroid streams would bring meteor showers to any planets and moons with an atmosphere that intercept the meteoroids' orbits, although none of these has been directly observed yet elsewhere in the solar system. But we can expect that future orbiters, landers, rovers, and even human explorers will one day observe shooting stars on another planet or moon just like we do on Earth, and appreciate the rich information that they bring to us.

■ **QUANZHI YE** is a planetary astronomer at the University of Maryland and Boston University. He still enjoys going out stargazing when he is not doing his day (night) job.

 by William Sheehan



NASA / GODDARD SPACE FLIGHT CENTER / SDO

The 150th Anniversary of a Transit of Venus

A cast of impressively colorful characters attempted to nail down one of astronomy's most important yardsticks.

Transits of Venus are infrequent astronomical events, occurring in pairs eight years apart but separated by more than a century. Many readers will recall the most recent set, which took place in 2004 and 2012. You can think of Venus transits as mini eclipses, though the disk of the planet is obviously far too small to produce totality. In fact, when Venus passes in front of the Sun it spans just 58″, covering only 0.1% of the solar disk! And yet, transits have been historically important, because for well over a century they provided astronomers with their best chance to determine the distance of Earth to the Sun — the *astronomical unit*. Knowing the distance from Earth to the Sun is of course interesting as a mere matter of curiosity, but it also enters into calculations of the motions of the Moon and planets and serves as a crucial first rung on the cosmological distance ladder.

It was Edmund Halley who started the transit craze in 1716 when he suggested that timing the beginning and end of a Venus transit from two locations widely separated in latitude could allow astronomers to accurately measure the apparent angular shift in the planet's position. This in turn would lead to a value for the *solar parallax*, from which they could calculate the Sun's distance using trigonometry. Unfortunately, Halley died in 1742, and the next transits were not until 1761 and 1769. But his method inspired scientists to undertake grand expeditions to remote parts of the globe — most famously, Captain James Cook's voyage to Tahiti in 1769 (*S&T:* Mar. 2020, p. 58). The mass of data accumulated from the two 18th-century Venus transits took decades to analyze; Berlin Observatory director Johann Franz Encke finally completed the task in 1824. He derived a solar parallax of 8.5776 arcseconds, giving the distance to the Sun as 153,340,000 kilometers (95,280,000 miles). Although the result was more precise than previous determinations, it still fell short of expectations.

◀ **21ST-CENTURY TRANSIT** NASA's Solar Dynamics Observatory captured this composite image showing the most recent transit of Venus, which occurred on June 5–6, 2012. The spectacular level of detail presented illustrates how far science has advanced since the transit of December 9, 1874, when photography was in its infancy. What new advances will take place between now and the next Venus transit, on December 10–11, 2117?

The 19th Century Takes Up the Gauntlet

The next Venus transit was due on December 9, 1874. And so, 18th-century astronomers passed the torch to their 19th-century counterparts, who would be able to deploy an array of improved techniques and technology.

The 105 years between transits saw monumental political upheavals and the beginning of the Industrial Revolution, with its steam engines, spinning jennies, and locomotives. The adoption of precise standards of measurement, crucial to economic and military success, was emphasized as the distinguishing feature of science by the British physicist Lord Kelvin, who proclaimed, "When you can measure what you are speaking about, and express it in numbers, you know something about it."

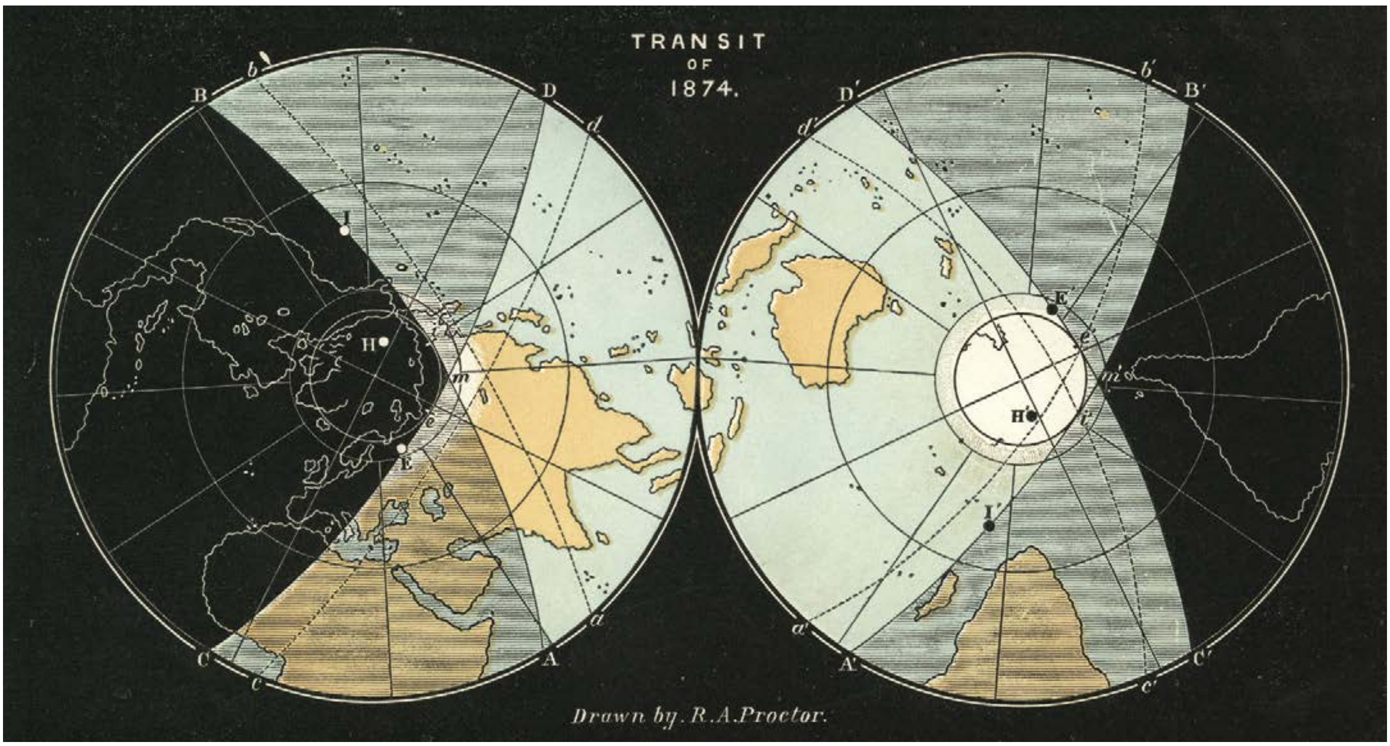
Astronomers shared this obsession, and nothing beckoned with greater urgency than precisely determining the astronomical unit. The application of Halley's method (including a refinement introduced by the French astronomer Joseph-Nicolas Delisle) was at the foundation of a vast enterprise to observe the transit of Venus.

In the 18th century, land travel was slow and sea travel unpredictable. In 1761, one transit observer, Jean-Baptiste Chappe d'Auteroche, took five months to travel from Paris to Tobolsk (Siberia) by land and arrived with little time to spare. He didn't return to France until 1763. In 1769, he needed eight months to make the journey from Paris to San José del Cabo in Baja, California (now Mexico), where he subsequently died in an outbreak of yellow fever. Only one member of his expedition managed to return home with their observations.

By 1874, however, it was possible to cross the Atlantic in less than eight days, in contrast to the 77 that Chappe required. The improvements in land travel due to the introduction of railroads was, if anything, even greater. The greater ease of movement meant that some 100 official expeditions set off to observe the December 9, 1874, transit, which was visible in its entirety across Japan, Southeast Asia, Indonesia, Australia, and New Zealand.

Governments helped sponsor overseas expeditions, and observatories and universities organized a few more. Of these, Great Britain, Russia, the United States, and Germany backed the largest number of expeditions, though Australian entities also organized many small parties, since the continent lay in the transit zone.

The 18th century also heralded the arrival of vastly improved astronomical instrumentation and techniques. Observers of the 18th-century transits had to make precise visual timings of the planet's disk making contact with the Sun's limb, using small telescopes often of imperfect optical quality. At the critical moments, various optical effects hampered precise timings. Most notorious was the aptly named, *black-drop effect*, which occurs as the disk of Venus and the edge of the Sun barely touch — the planet's silhouette distends like a drop of water about to drip from a faucet. The effect meant that even observers positioned side by side often disagreed on the precise moment of contact — intro-



ECLIPSE-MAPS.COM / PUBLIC DOMAIN

▲ **TRANSIT ZONE** As a Cambridge-trained mathematician who devoted his life to the popularization of astronomy, Richard A. Proctor published the standard works on the 19th-century transits of Venus in the English-speaking world. Proctor himself drew this aesthetically pleasing chart showing the circumstances of the 1874 transit, based on his own calculations.

ducing uncertainties that contributed to the inaccuracy of the results. But in 1874 astronomers not only had better telescopes, but they could also rehearse by viewing artificial transits. For example, French astronomers at the Paris Observatory aimed telescopes at a series of lamps and screens positioned in the window of a library in the nearby Luxembourg Gardens. Similarly, American astronomers set up their own transit simulation at a building near the U.S. Naval Observatory in Washington, DC.

More crucial was that astronomy now had a new weapon in its arsenal: photography. Visual observations were subjective, but the photographic plate was regarded as objective and not subject to the vagaries of what American astronomer Ormsby M. Mitchel called the "personality of the eye." Thus, the most serious efforts to observe the transit of 1874 employed photography, which would allow astronomers to leisurely measure the contact times after the fact.

Janssen and His Revolver Camera

The most innovative device deployed at the 1874 transit was the *revolver photographique*, invented by the French astronomer Pierre Jules César Janssen (1824–1907). Janssen's device produced a series of images, which could be shown in succession to make a primitive motion picture (preceding the famous "horse in motion" sequence captured by English photographer Eadweard Muybridge by four years). Janssen's "revolver camera" consisted of two slotted disks — a large spinning one with 12 slots and a smaller, fixed one with a single slot that formed a window that admitted only a small part of the solar image onto a photographic plate. The larger disk was advanced by a gear mechanism based on the one employed in the Colt revolver. The camera was designed to capture the "fortuitous moment" in which the contacts between Venus and the Sun's limb took place. Astronomers hoped that this new camera could defeat the uncertainties that plagued 18th-century observations.

Janssen was a wonderfully colorful figure. Lifelong suffering from a lame leg due to an accident at age eight plagued him, but he refused to allow his handicap to hold him back. Janssen devoted himself to scientific research and became an inveterate eclipse chaser. Among his many exploits, he observed the so-called King of Siam's eclipse of August 18, 1868, at Guntur, India, where he discovered (independently of Norman Lockyer of England) a spectroscopic method for observing solar prominences without the need for an eclipse. To observe the December 1870 total eclipse in Oran, Algeria, which occurred during the Siege of Paris, Janssen escaped from France in a balloon. However, despite his heroic efforts to get to the centerline, he was clouded out.

Since transits are really miniature eclipses, Janssen was excited about the forthcoming transit of Venus in 1874. Without knowing specifically where he would be setting up his instruments, Janssen and his team arrived in Japan after weathering a typhoon off the coast of Hong Kong. After stopping first at the port of Yokohama, they continued on to

▲ **HISTORY MADE HERE** *Top:* During the author's visit to Japan in 2004, he and a group of Japanese enthusiasts climbed Mount Konpira-yama near Nagasaki to find this small pyramid marking the location where Janssen's team observed the transit of Venus in 1874.

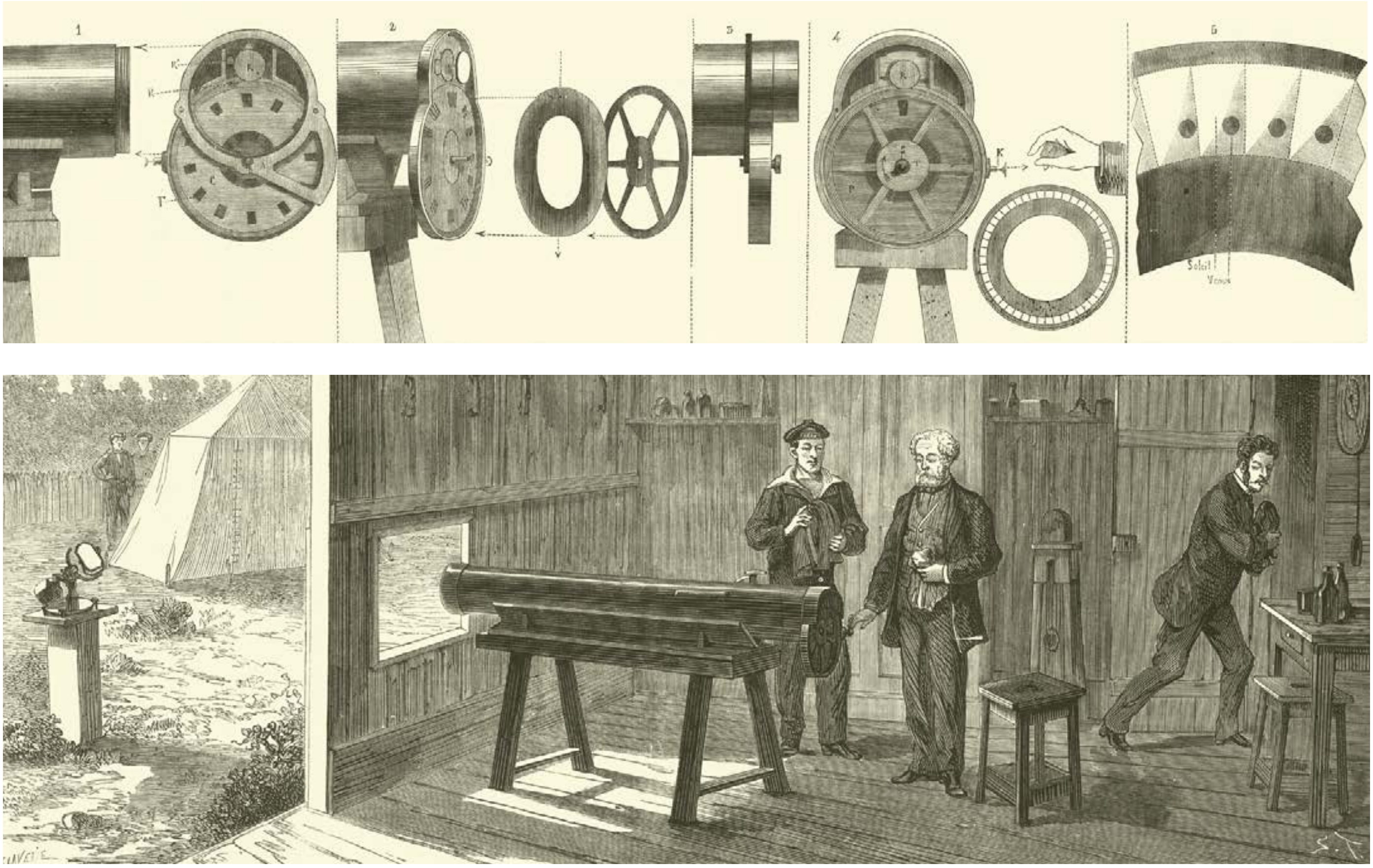
▲ **MADE FOR JAPAN** *Bottom:* In this portrait of the Janssen party upon their arrival at the Japanese port of Yokohama Bay, Janssen sits in the front middle, while the tube of a telescope is visible in the background along with the *revolver photographique*, on a table at far left.

MARKER PYRAMID: WILLIAM SHEEHAN; JANSSEN AND CREW: WIKIMEDIA COMMONS / PUBLIC DOMAIN

Nagasaki, where they established themselves on the mountain Konpira-yama — a magnificent setting with breathtaking views of the city below. As a precaution against bad weather, Janssen sent a detachment of observers to Kobe, more than 500 km away. As it turned out, the weather on transit day was perfect at both sites. The following day, Janssen telegraphed the president of the transit commission in Paris with the message:

> *10 December. Transit observed at Nagasaki and Kobe, interior contacts obtained. No ligaments* [i.e., black-drop effects]. *Photographed with revolver . . . Venus seen over Sun's corona before transit.*

American and British astronomers also mounted expedi-



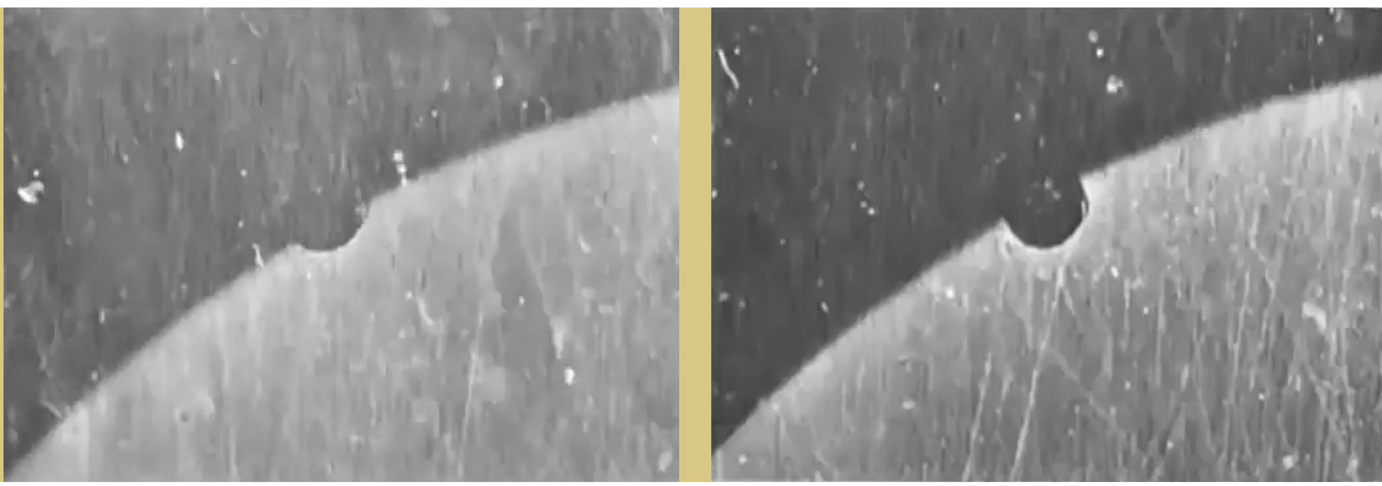
▲ **MOVING PICTURES** As shown in the top portion of this illustration, Janssen's *revolver photographique* consisted of two slotted disks, a large spinning one with 12 slots and a smaller fixed one with a single slot, which formed a window that admitted only a small part of the solar image onto a photographic plate. The larger disk was advanced by a gear mechanism based on that used in the Colt revolver. The lower panel illustrates how sunlight is directed to the device via a mirror placed outdoors.

▼ **BEST PICTURE** This sequence of frames was recorded with Janssen's *revolver photographique*. Each shows the silhouette of Venus as it contacts the limb of the Sun. The black-drop effect is evident in the fourth frame. The sequence can be viewed as a short movie at **https://is.gd/1874transit**. It deserves to be nominated as Best Picture of 1874.

tions to view the 1874 event. In the U.S., the Transit of Venus Commission sent eight official teams, including one to the Russian city of Vladivostok led by U.S. Naval Observatory astronomer Asaph Hall, soon to become famous for discovering the satellites of Mars. Others were dispatched to Japan, China, and New Zealand.

Reflecting its status as the world's greatest empire, Great Britain organized the largest number of observers under the directorship of George Biddell Airy, the redoubtable Astronomer Royal. He deployed expeditions to stations within five regions: Egypt, the Sandwich (Hawaiian) Islands, Rodrigues

JANSSEN'S REVOLVER CAMERA: LOOK AND LEARN; FRAMES FROM JANSSEN TRANSIT SEQUENCE: PUBLIC DOMAIN (4)



Island in the western Indian Ocean, New Zealand, and the Kerguelen Islands in the far southern Indian Ocean (formerly known as the Isles of Desolation, a name Captain Cook bestowed on them). Also, British astronomer James Ludovic Lindsay organized an expedition to Mauritius. It was reputed to be "the most completely equipped ever undertaken by a private individual in the interests of astronomy," in the words of the Scottish scientist George Forbes. The group's most noteworthy member was David Gill, whom Lindsay had previously hired to direct his private observatory at Dunecht in Aberdeenshire, Scotland.

▲ **PARADISE LOST** The first sighting of Venus against the Sun in 105 years was made by Captain George Lymon Tupman in Hawai'i. The deluge of telescopes and astronomers shown here was but one symptom of the arrival of European and American influence in the once-idyllic Kingdom. It would soon be overrun and lose its independence in 1893.

PUBLIC DOMAIN

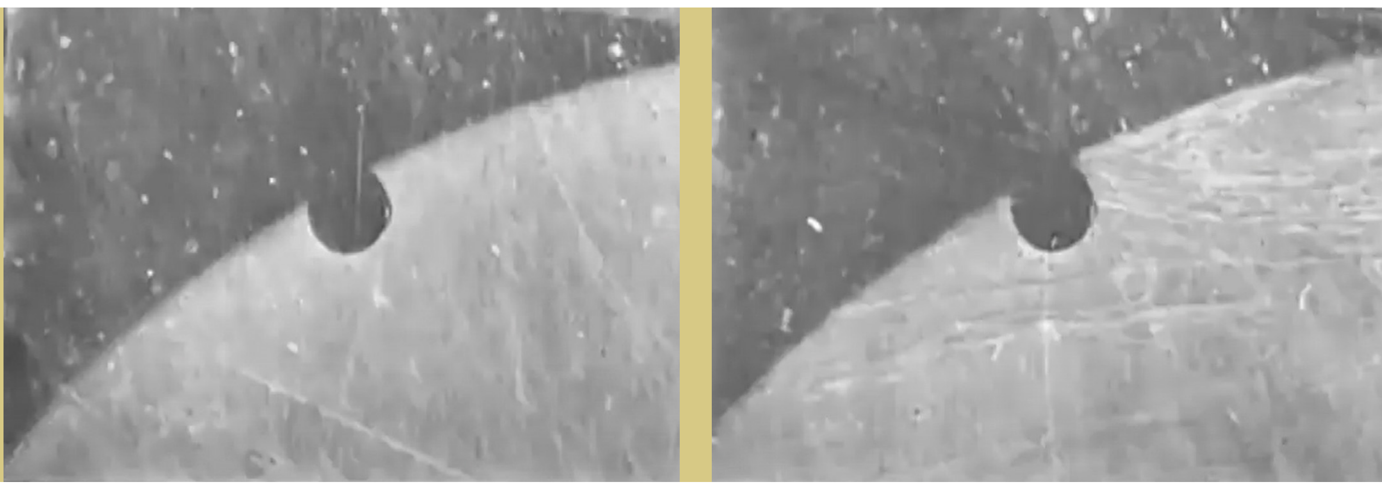
Peters Takes the Lead

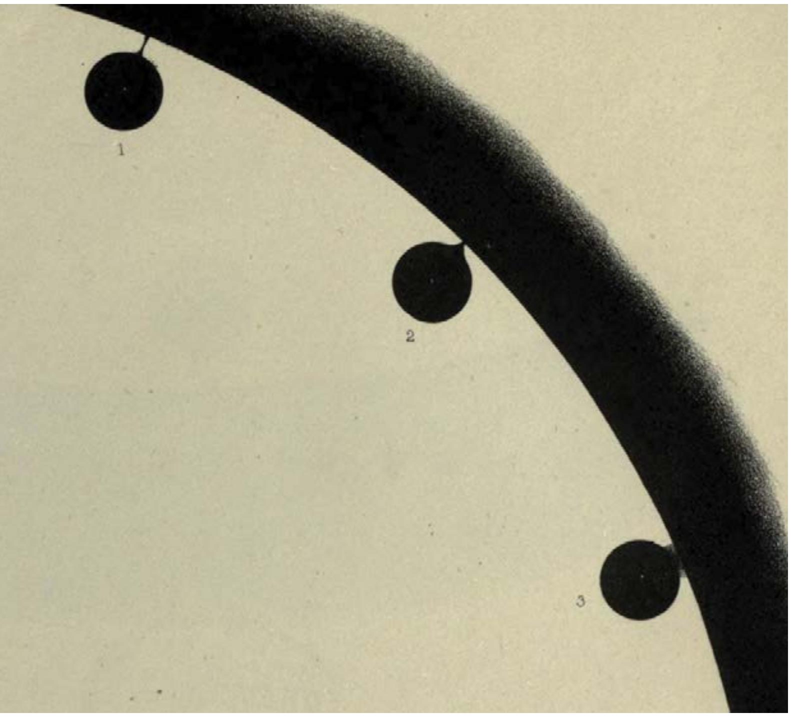
Perhaps the most fascinating observer of the 1874 transit was Christian Heinrich Friedrich Peters (1813–1890). Peters had already had an interesting career when, in the 1840s, he found himself in charge of planning a new observatory in Sicily during a particularly tumultuous time. In 1821, King of the Two Sicilies Ferdinand I (best remembered as the patron of Giuseppe Piazzi, who discovered Ceres, the first asteroid) had, with the aid of foreign troops, scrapped the constitution he had agreed to a year earlier, leaving Sicily to be governed by the police. During the revolutions that swept through Europe in 1848, Peters joined the revolt against the equally illiberal Ferdinand II (grandson of Ferdinand I), but it was quickly crushed, and reactionary forces regained control. Peters escaped to Constantinople after being abruptly relieved of his post at the observatory. Upon arrival, he had only enough money in his pockets to buy breakfast or a cigar. He chose the cigar.

In Constantinople, Peters became scientific advisor to Mustafa Reşid Pasha, Grand Vizier of Sultan Abdülmecid II and one-time Turkish ambassador to London and Paris. Peters, a remarkable linguist who was fluent in modern European languages as well as Greek, Latin, Hebrew, Arabic, Persian, and Turkish, conversed easily with Reşid. The Sultan had just acquired a fine, 11-inch refractor, and Reşid was inclined to put it at Peters' disposal. Unfortunately, according to a newspaper clipping from the time, Reşid's power and protection were insufficient to overcome anti-intellectual forces within the palace. In 1854, Peters' Turkish interlude ended with the outbreak of the Crimean War, and he fled once again, this time to America. Eventually he settled at Hamilton College in Clinton, New York, where he became the country's leading asteroid discoverer.

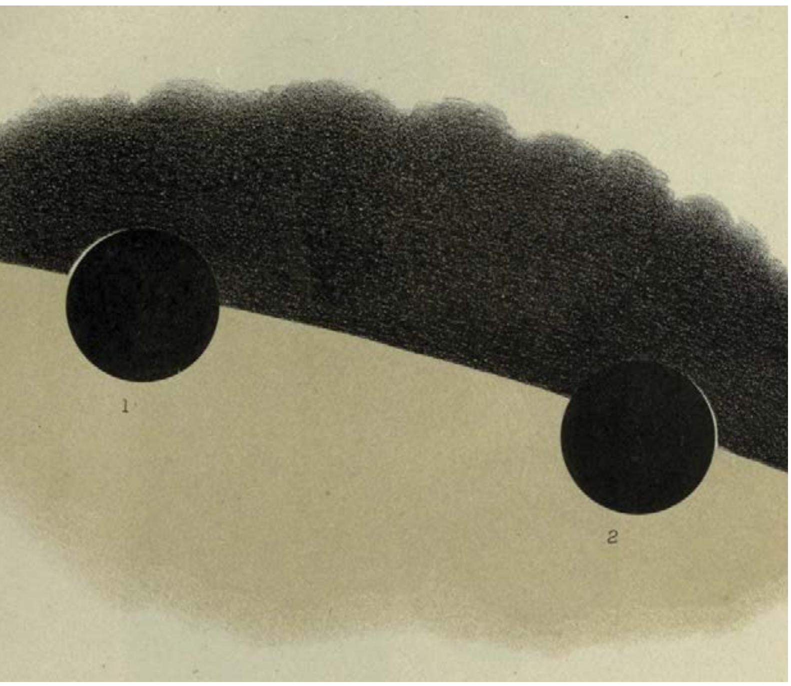
In 1874, Peters was appointed chief of the U.S. transit expedition to New Zealand. Before embarking on his long journey from San Francisco, Peters made sure that he was adequately provisioned. Thus, he wrote to the Lieutenant in charge of his transport on the U.S. man-of-war *Swatara*: "to do me the favor to buy on my account some 4 or 500 of your 'Maravillas' [cigars], and to stuff them in the outside boxes of the Equatorial, or Transit [instrument], where I think there might be plenty of room for a few cigar boxes?"

The *Swatara* first dropped off observers amid German and British teams at the Kerguelen Islands, and others at Hobart, Tasmania, before sailing to the port of Bluff, New Zealand. Seeking better weather prospects, Peters continued south through New Zealand, transporting telescopes and other supplies through valleys and across rivers, leading English parties





▲ **TRANSIT DOWN UNDER** This illustration from H. C. Russell's *Observations of the Transit of Venus, 9 December 1874; Made at Stations in New South Wales* shows the "black drop," as recorded by F. Allerding in Sydney, New South Wales, Australia, with a 3½-inch refractor stopped down to an effective aperture of 2 inches.



▲ **ATMOSPHERIC SIGHT** The brilliant arc of sunlight refracted by the atmosphere of Venus is recorded in these sketches by Captain A. Onslow, who observed the 1874 transit from Goulburn, in the Southern Tablelands of New South Wales, Australia, with a 3¾-inch, equatorially mounted refractor. (This drawing also appeared in H. C. Russell's book.)

to "sneer a little at us." At last, he set up his equipment in Queenstown, on the shores of glacial Lake Wakatipu and within sight of the mountains justly known as the Remarkables. (The site is now occupied by the Millennium Hotel with its Observatory restaurant.)

In the end, Peters' gallant efforts were vindicated. Most of New Zealand lay under heavy cloud on transit day, but on the high ground where he deployed his telescopes, he enjoyed short intervals of sunshine. He succeeded in timing the first and second contacts and exposing 59 photographic plates — a yield that exceeded the combined results of the rest of the New Zealand expeditions. One imagines he celebrated with a good cigar.

A Matter of Timings

Although the photographic results drew the greatest attention, visual observations also proved valuable. Perhaps due to improved optics, the black-drop effect did not figure as conspicuously this time as it did in 1761 and 1769. Nevertheless, the images on the photographic plates — from which so much was expected — proved to be no less subject to uncertainty than timings captured by eye.

Even the Janssen revolver, for all its promise, proved to be a bust. It produced diffuse, distorted images that were no more reliable than the best visual reports. Evidently this was in large part due to the blurring caused by Earth's ever-seething atmosphere. At an 1881 international conference in Paris to discuss results of the transit and to plan for the next one in 1882, Airy admitted that "the ardor of observers had been much cooled by the apparent general failure of the photographic principle."

Nonetheless, the slog of working out a new value of the astronomical unit began. Charles Edward Burton, an assistant at the Royal Greenwich Observatory, undertook the task of reducing the British data, including the disappointing photographic results. He applied himself to the painstaking task until his eyesight and health began to fail. George Lyon Tupman, who had organized the British expedition to observe the transit from the Sandwich Islands, took over. He described the heartbreak of the task:

> *When the negatives are placed under the microscope with an amplification of only 5 or 6 diameters, the limbs of both planet and Sun, even those which are pretty sharp to the unaided eye, become extremely indistinct, and the act of bisecting the limb with the wire or cross of the micrometer is mere guesswork.*

Not surprisingly, the solar parallaxes Tupman derived were very poor. Indeed, only by discarding the photographic values did the results show better mutual agreement than the visual timings made in the 18th century! The technological advances and new techniques of this bold new era ultimately made little difference.

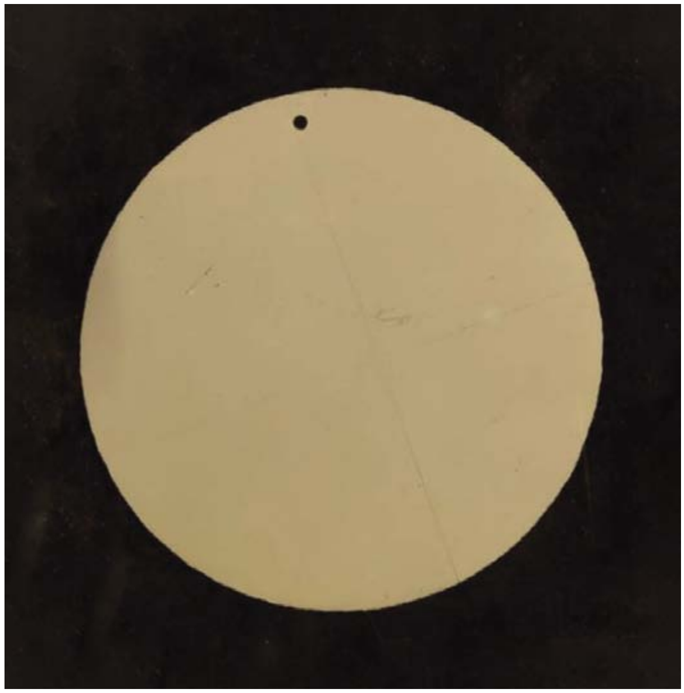
Meanwhile, it had become obvious that there were better methods for determining a value for the astronomical unit.

One involved measuring the position of Mars relative to the background stars. Gill, a member of one of Airy's expeditions who had first-hand experience with the shortcomings of the Venus-transit method, applied the Mars method and arrived at a value for the solar parallax of 8.780 arcseconds, for a mean Earth-Sun distance of 149,840,000 kilometers — only 0.2% different than the modern value.

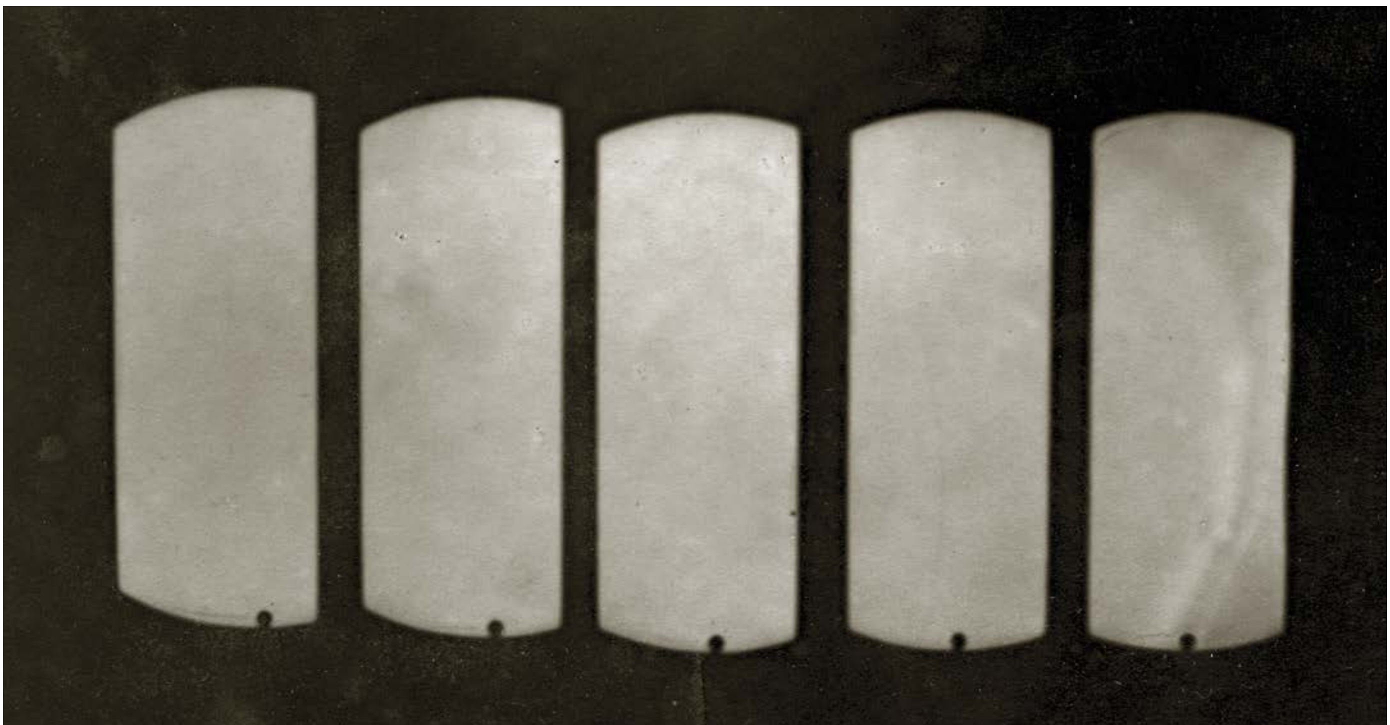
A new era had begun. The 1874 transit was now history, and though preparations were already underway to observe the 1882 event, the method had effectively been superseded forever. Indeed, astronomers today no longer treat the astronomical unit as a measured quantity but, rather, as a defined one. In 1976 the International Astronomical Union settled on a value of 149,597,870,700 meters "exactly."

Perhaps, the lasting legacy of 19th-century expeditions doesn't rest with the measurements they recorded or the images they worked so hard to acquire, but in the romance of a bygone era in which intrepid observers traveled the globe far and wide to incrementally advance humankind's understanding of the universe. For better or worse, that romance has now given way to precision.

■ Contributing Editor **WILLIAM SHEEHAN** co-authored (with the late John Westfall) *Transits of Venus*. He counts himself lucky to have seen Venus cross the Sun in 2004 and 2012 in perfect conditions. He concedes, however, the next transit, in 2117, may prove to be out of reach.



▲ **PIONEERING PICTURE** This photograph was taken on December 9, 1874, at Luxor, Egypt, by William de Wiveleslie Abney, a British astronomer, chemist, and photographer. He was the first to use a dry plate photographic emulsion (as opposed to the then-standard "wet plate" method) to photograph an astronomical event. In short order, dry-plate photography would become the norm.



DEVILISH DETAILS This series of images taken with Janssen's *revolver photographique* shows Venus encroaching on the Sun's limb. Since photography was supposed to be more objective than the human eye, astronomers hoped that Janssen's *revolver photographique* would be unaffected by the black-drop effect that made precise timings impossible during previous transits. Unfortunately, when examined under magnification, the images proved to be blurred and the black drop conspicuous.

DRY PLATE PHOTOGRAPHIC EMULSION: WIKIMEDIA COMMONS / PUBLIC DOMAIN; TRANSIT SEQUENCE: IMCCE / ESO

Galaxy-Hopping

Grab your biggest scope and aim north.

In my experience, many observers neglect the area of sky around the north celestial pole. Astronomers often select observing sites with an unobstructed view to the south — sacrificing the view to the north is usually considered an acceptable tradeoff. Anyone who uses a polar-aligned, fork-mounted Schmidt-Cassegrain or an equatorial mount understands how awkward it can be to navigate this region. So, it's understandable that the area around the pole is terra incognita to many observers. It's not, however, for lack of extragalactic targets. There are more than 4,000 cataloged galaxies within 10° of the north celestial pole and about 60 that are brighter than 15th magnitude. Eleven of these galaxies have NGC and another eight have IC designations. It's well worth the effort to visit the best and brightest of them.

While I primarily conducted my observations with my 18-inch Dobsonian, most of the targets discussed here should be detectable in 10-inch scopes under a reasonably dark sky. Unless otherwise noted, I used my usual galaxy-hopping eyepiece, a 12-mm Nagler with a Paracorr coma-corrector — a combination that yields 197× and a 25′ field of view in my 18-inch Dob.

Polarissima

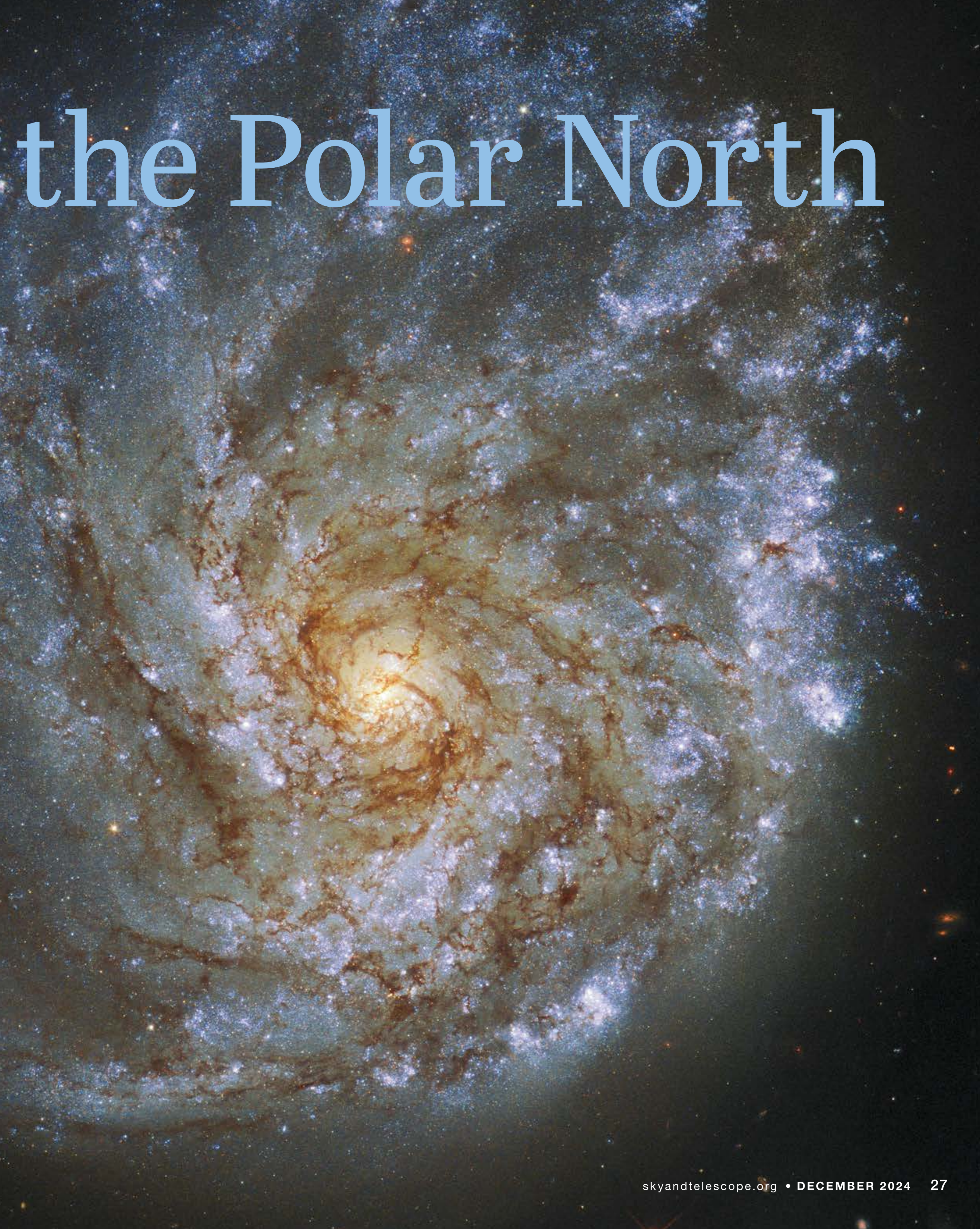
The logical place to start our tour is with **NGC 3172**, which earns distinction — and its popular moniker — by being the closest NGC object to the north celestial pole. Currently, it's slightly less than 1° from the pole. John Herschel, who discovered the object on October 4, 1831, named it Polarissima in recognition of its position — at the time, the object was a mere 4.5′ from the north celestial pole. A few years later he dubbed it Polarissima Borealis so as to differentiate it from Polarissima Australis, NGC 2573 (in Octans), which he also discovered.

Navigating so near to the pole can be a bit confusing — after all, from there, every direction is south. Even the most experienced observers can get disoriented, so it helps to widen your view a bit. Polarissima sits 1.5° from Polaris in the direction of 2nd-magnitude Epsilon (ε) Ursae Majoris, or Alioth, in the handle of the Big Dipper.

▶ **SUBJECT TO FORCES** NGC 2276 is a spectacular barred spiral galaxy some 120 million light-years away in Cepheus. It's part of the NGC 2300 group, and gravitational forces have distorted its shape. The Hubble Space Telescope acquired this image — the galaxy won't look like this in your eyepiece, but you can bear in mind its remarkable beauty when you observe it. North is at 1 o'clock here and up in all other images.

ESA / HUBBLE & NASA / P. SELL / ACKNOWLEDGEMENT: L. SHATZ

the Polar North



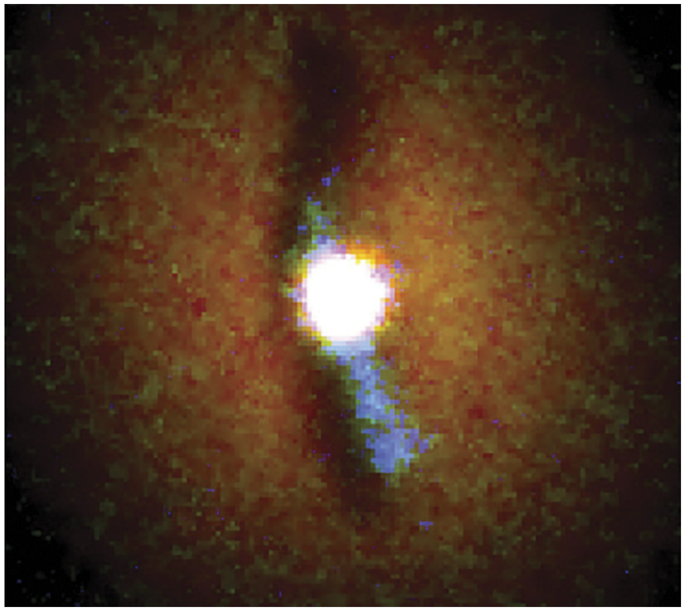
▲ **DIZZYING HEIGHTS** It can be tricky to orient oneself when observing around the north celestial pole. While this chart isn't meant to go deep — you can follow the author's galaxy- and star-hopping instructions to zoom in on targets — it is meant to give a general overview of the area around the pole.

In my 18-inch, 14th-magnitude NGC 3172 appears fairly faint, small, and round with only a slightly brighter core. There's a 12.6-magnitude star 1.5′ west-northwest of the center of the galaxy. NGC 3172 is quite challenging in my 10-inch: a barely detectable smudge.

Under the Little Dipper's Handle

The double star Epsilon Ursae Minoris (magnitude 4.2) in the Little Dipper's handle is a convenient jumping-off point for a pair of galaxies that William Herschel discovered on January 1, 1802. They mark his closest discoveries to the pole. So close in fact that it took the pair eight minutes to traverse the 4.5′ field of view of Herschel's standard eyepiece.

NGC 6251 is a giant elliptical and a bright radio source. An article that appeared in *Monthly Notices of the Royal Astronomical Society* in 1977 notes that its angular dimensions are "greater than those of any other radio galaxy in the northern sky," and, along with M87, it's also one of the first galaxies in



◀ **CLOSE NEIGHBORS** The elliptical galaxy NGC 6251 and the spiral NGC 6252 share the spotlight in this 15′ × 20′ image from the POSS survey. The pair are a mere 2.4′ apart.

▲ **LURKING SUPERMASSIVE BLACK HOLE** NGC 6251 harbors a supermassive black hole at its core, as do most galaxies — but it has the distinction of being one of the very first for which such a claim was made. The image above is a composite of visual and ultraviolet light — the visual picks up the dusty disk (dark band) surrounding the core of the galaxy, while the ultraviolet light (in blue) traces matter closer to the black hole.

which astronomers inferred the presence of a central supermassive black hole in 1979.

From Epsilon Ursae Minoris, move 40.4′ northwest to 13th-magnitude NGC 6251. At 140× in my 18-inch, the galaxy appears round with a bright, nearly stellar core. Neighboring, 14th-magnitude **NGC 6252**, 2.4′ to the north, appears smaller and without much variation in brightness across its surface. It's very slightly elongated east-northeast to west-southwest. My 30-inch Dob at 390× failed to reveal any additional features.

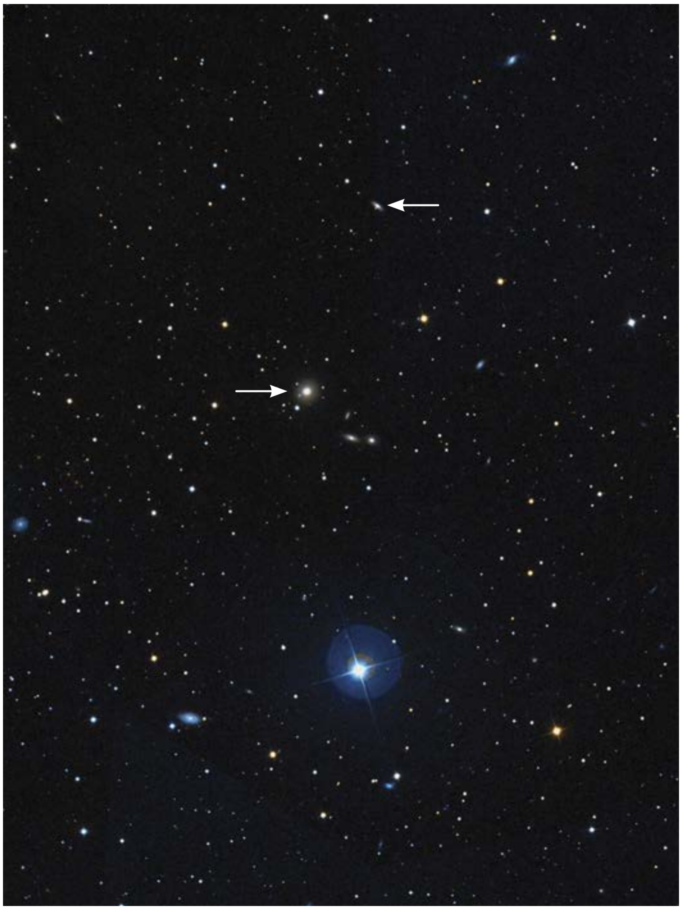
Slide 2.4° west of NGC 6251 to locate **IC 1143** — at magnitude 13.2 it's the brightest in a small group of elusive galaxies. It sits 11.7′ north of the 7th-magnitude star HD 140363. The view in a low-power eyepiece with a 1° field of view centered on IC 1143 will encompass the faint hints of eight or more ghostly galaxies of magnitude 15–16 hovering on the verge of detection. I really like the term "lumpy darkness" that observers use to describe such a field of vague objects. IC 1143 itself is round and rather faint with a brighter core. A 13th-magnitude star lies just southeast of the center of the galaxy.

The much fainter **IC 1139** (15th-magnitude) is another 8.5′ to the north-northwest. I found this galaxy to be rather challenging in my 18-inch, but with considerable concentration I could detect its faint glow and slightly elongated shape. The *Morphological Catalogue of Galaxies* misidentifies the 16th-magnitude galaxy MCG +14-07-019 as IC 1139. American astronomer Lewis Swift discovered both IC 1143 and IC 1139 on June 18, 1888. Swift, it should be noted, ranks among the top handful of observers — including William and John Herschel — in the number of visual finds attributed to him.

Look 1.5° northwest of IC 1143 to find a pair of interesting 13th-magnitude galaxies that never made it into the NGC or the IC. **UGC 9668**, also known as Markarian 839, is round with a brighter center. Some 5.6′ to its northwest is the nice edge-on spiral **UGC 9650**. Appearing a little brighter toward its center, the galaxy is elongated nearly north-south. This pleasing pair was surprisingly easy in my 18-inch.

About 10° from the north celestial pole, **NGC 5640** marks the outer boundary of our tour. Extending a line connecting Eta (η) and Zeta (ζ) Ursae Minoris (the top of the Little Dipper's bowl) northwest nearly twice the distance separating the stars will land you in its vicinity. The 15th-magnitude galaxy is a 44′ star-hop northwest of 6th-magnitude HD 129245. A triangle of 10th- and 11th-magnitude stars about 9′ to the east points west toward NGC 5640. In my 18-inch, it's very faint and appears small and round.

Some doubt lingers as to whether NGC 5640 is the object that William Herschel discovered on December 20, 1797. Another galaxy, PGC 51067, lies 7′ west, which actually appears a bit brighter and better matches Herschel's description of being "elongated near the parallel" (meaning extended in right ascension). There are errors in Herschel's recorded



▲ **STAR-HOP TO A PAIR** You can use 6.9-magnitude HD 140363 (bottom center) to star-hop to the 13th-magnitude elliptical IC 1143 (the smudge left of center, arrowed) and the 12th-magnitude spiral IC 1139 (above IC 1143). How many of the fainter (magnitudes 15 to 16) galaxies around this pair can you spot in your eyepiece?

POSS-II / STSCI / CALTECH / PALOMAR OBSERVATORY

position for the object, but the galaxy currently designated NGC 5640 is nearest to his position.

Extending the Little Dipper's Handle

Following the arc of the Little Dipper's handle another 3.2° from Polaris and into Cepheus, we find **NGC 1544**, a 13th-magnitude spiral that appears round with an almost stellar nucleus. A close pair of stars around magnitude 14.5 mark its northern edge. German astronomer Wilhelm Tempel discovered NGC 1544 in 1876 from Arcetri Observatory near Florence, Italy, with an 11-inch refractor. It's the most northerly object attributed to him and the second-closest NGC object to the north celestial pole.

Continue another 3.9° southeast to arrive at 12.9-magnitude **IC 442**. My 30-inch Dob at 390× shows the hint of a double nucleus in this small, round galaxy. There is no sign of that feature in my 18-inch, which reveals only a very slightly brighter center. British amateur astronomer William Denning discovered this galaxy using a 10-inch reflector on November 9, 1890.

From IC 442 turn north-northeast and slide 1.7° to reach **NGC 2268**, an 11.5-magnitude barred spiral elongated east-northeast to west-southwest. It appears fairly large and relatively bright with a brighter core and a faint outer halo. Observing from Marseille Observatory, French astronomer Alphonse Borrelly discovered NGC 2268 in 1871 using a 7.2-inch comet-seeker.

At around the same time and using the same telescope, Borrelly also came upon **NGC 2300**, which lies 1.4° north-northeast of NGC 2268, but he missed nearby **NGC 2276**, only 6.3′ to the west-northwest. It was German astronomer Friedrich August Winnecke who discovered NGC 2276 about five years later; he also independently noted NGC 2300. The pair are the brightest members of a small group of galaxies dominated by NGC 2300. There's strong evidence of interaction between members of this group — in fact, they're both listed in Halton Arp's *Atlas of Peculiar Galaxies*. The NGC 2300 group was the first in which an X-ray emitting *intergroup medium* was observed, thought to be related to, among other things, shocks driven by merger events. NGC 2276, in particular, contains several ultraluminous X-ray sources. I, however, couldn't detect any visible evidence of interaction at the eyepiece.

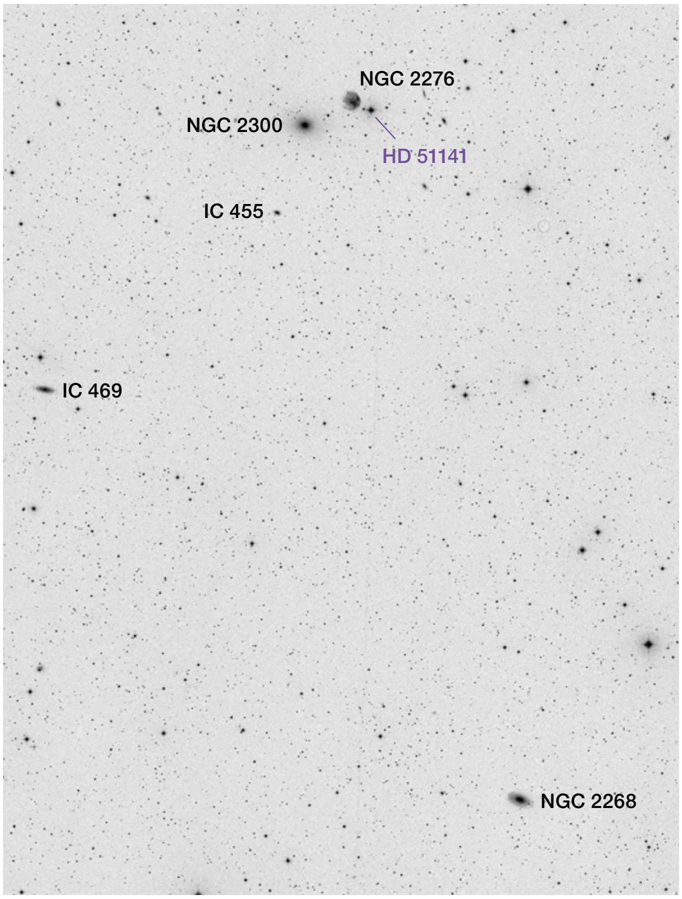
An article published in 2016 noted that the NGC 2300 group was "out of synch" with regard to stellar ages. Contrary to expectations, the core regions of the galaxies closer to the center of the group comprise younger stars than the spirals on the periphery, which have much older nuclei and bulges.

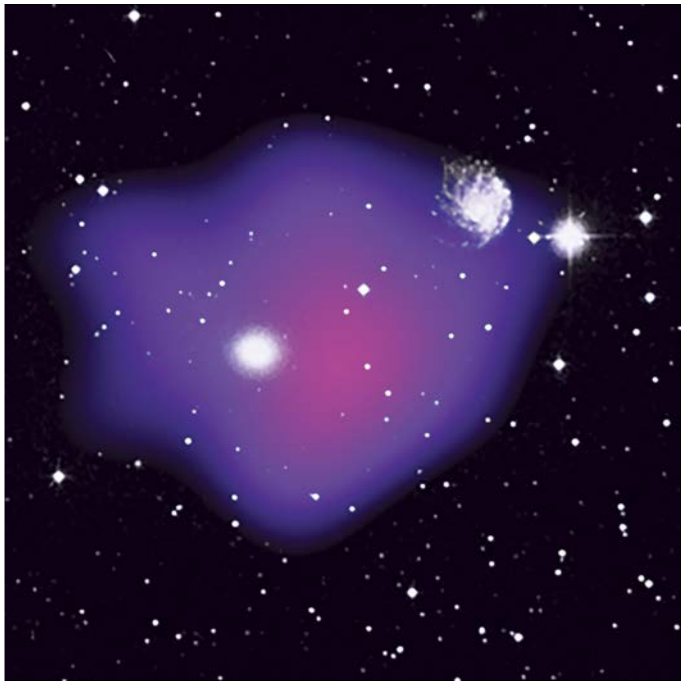
In my scope, 11.0-magnitude NGC 2300 appears oval with a bright core and a faint outer halo. NGC 2276 is an 11.4-magnitude, open-faced spiral of fairly low surface brightness, a sharply brighter core, and a mottled outer halo. An 8th-magnitude star (HD 51141) lies just 2.2′ to the southwest, where it tends to overwhelm the galaxy.

Historical Sources

The author has dipped into several online resources to dig up the chronologies and historical facts connected with the giants of visual observing. Below we list the webpages of astronomy historian Harold Corwin, visual observer extraordinaire and history sleuth Steve Gottlieb, and German astronomer and author Wolfgang Steinicke. If you're interested in the ins and outs of the discoveries, cataloging, misidentifications (and more!) of the NGC/IC objects, then these sites are for you:

http://haroldcorwin.net/ngcic/
https://is.gd/astronomy_mall
https://is.gd/steinicke_ngcic





◀ **LITTLE GROUP** NGC 2300 anchors a group of several galaxies. The interactions between the members have bent several galaxies out of shape, including NGC 2276, as shown on pages 26–27.

▲ **HOT GAS** This X-ray image obtained in 1992 with the German-led project ROSAT (Röntgensatellit) shows that the galaxies of the NGC 2300 group are embedded in a hot gas, which is a tracer of dark matter.

NGC 2300 GROUP IN VISUAL: POSS-II / STSCI / CALTECH / PALOMAR OBSERVATORY; NGC 2300 GROUP IN X-RAY: NASA

Sharing the 25′ field with the galaxy pair is **IC 455**, a small, 13th-magnitude lenticular that has a brighter core and appears slightly elongated almost east-west. Edward Emerson Barnard observed it in 1890 a month before Denning, but because he never reported the find it's Denning who receives credit in the *Index Catalogue*. It's interesting to contemplate that two great observers were observing the same area of sky at about the same time: Barnard with a 12-inch refractor at the Lick Observatory in California and Denning searching for comets with a 10-inch reflector in England. While Barnard was rather sensitive about the priority of his discoveries, he failed to report them on several occasions, a fact that Denning was critical of in later life.

Jump 43′ southeast of NGC 2300 to land on **IC 469**, which lies centered in a triangle of 9th- and 10th-magnitude stars. A 13th-magnitude barred spiral, it's elongated along its east-west axis and has a small, bright core. This is another of Denning's 1890 discoveries in the area.

Denning also discovered our next galaxy pair. **IC 499** and **IC 512** are separated by just 25.6′. But as they don't quite fit together in my preferred field of view, I can relate to the circumstance that led to him finding them some two weeks apart in August (IC 512) and September (IC 499) of 1890.

From IC 469, slide some 1.2° northeast into Camelopardalis to arrive at 12.5-magnitude IC 499, the closest IC object to the north celestial pole — you should spot it 1.2′ southwest of a 12th-magnitude star. An oval elongated almost east-west, I see the object as fairly faint with low surface brightness but with a brighter core. A 14th-magnitude star lies southwest of the center. Slew about 25′ southeast of IC 499 to arrive at 12.2-magnitude IC 512, which appears almost round with a very small brighter core. The halo has a rather blotchy appearance. Denning first took this object to be a comet and concluded it was a new nebula only after verifying that there was no movement over a prolonged observation.

Moving Farther Afield

For our next stop, begin back at NGC 2300 and drop 3.3° south to the 5th-magnitude variable star VZ Camelopardalis. **NGC 2336** is another 2.2° south of that marker and forms a triangle with 10th- and 11th-magnitude stars off its west side. Tempel discovered the 10th-magnitude galaxy in 1876 while observing at Arcetri Observatory. NGC 2336 is a giant spiral ring galaxy: A star-forming ring encircles the central bar — in fact, a 2018 journal article published in *Monthly Notices* identified 78 star-forming regions in the ring and spiral arms!

This fairly large galaxy is oriented nearly face-on and elongated north-south. It has a small, gradually brighter core with a strong central condensation. At 139×, the spiral arms show as an extended halo that appears dappled and brighter to the north. A 15th-magnitude star is just east of the core.

IC 467 is in the same field of view as NGC 2336, 20′ to the south-southeast. I needed averted vision to detect this 12.6-magnitude, low-surface-brightness galaxy. It appeared rather vague in my 18-inch — I could discern that it was elongated nearly east-west but couldn't extract any additional detail from its dim glow.

Moving 2.9° west of NGC 2336 and dropping a touch west-southwest, you'll find 13th-magnitude **IC 440** nested inside a triangle of 8th- and 9th-magnitude stars. In my 18-inch at 139×, IC 440 appears small and dim, with a faint, condensed core and lightly elongated in the northeast-southwest direction. There's a 16th-magnitude star positioned northwest of the core.

Two Last Stops

There are two more NGC galaxies within 10° of the north celestial pole. **NGC 1184**, one of William Herschel's Septem-

◀ **BEAUTIFUL BARRED GALAXY** Glorious NGC 2336 lies at a distance of 100 million light-years in Camelopardalis. This Hubble image highlights the younger, bluer stars and star-forming regions in the spiral arms as compared to the core of the galaxy that's dominated by older, redder stars.

▼ **TWO-FOR-ONE** NGC 2336 (at center) and IC 467 (below left) are only about 20′ apart, so you should be able to snag them both in the same field of view. Seventh-magnitude HD 54942 guards the pair from above.

NGC 2336: ESA / HUBBLE & NASA / V. ANTONIU; NGC 2336 AND FRIENDS: POSS-II / STSCI / CALTECH / PALOMAR OBSERVATORY ber 16, 1787, finds, is in Cepheus some 8.5° from Polaris in the direction of Alpha (α) Persei. If you imagine the brightest stars in Cepheus as a simple drawing of a house, the peak of the roof will point to the galaxy — it's about 10° from Gamma (γ) Cephei. NGC 1184 is a pleasing, 12.4-magnitude edge-on galaxy elongated roughly north-south. It has a stellar nucleus and a prominent central bulge that makes it appear a bit like a flying saucer. This is a nice example of a lenticular galaxy — lenticulars are thought to be former spirals that have depleted their star-forming gas.

Our final stop is **NGC 3057**. This is an appropriate finale since it's the last discovery that William Herschel reported in his third and final catalog in 1802. His object III-978, which became NGC 3057, was the 500th object in that third catalog. Although Herschel had logged an additional eight objects in his final two sweeps, they would not be published until they appeared in the *New General Catalogue*.

NGC 3057 is located 10° from Polaris along a line that traverses the body of the Great Bear and lands near the star Lambda (λ) Ursae Majoris (also known as Tania Borealis), which represents the bear's upraised rear foot. The 13th-magnitude galaxy is overall quite faint and mottled but is brighter toward its middle. A 13th-magnitude star lies to the south, about 1.4′ from the core.

Some of the greatest visual observers who ever lived have examined the area around the north celestial pole. Exploring the area in much the same way as they did enables us to share a commonality with the likes of the Herschels, Lewis Swift, and the other giants of those bygone eras. Although centuries divide us, we can still retrace their steps and experience some small measure of their wonder and thrill of discovery. I hope you'll allow yourself to enjoy the region's rich history and let it bring a new level of enthusiasm to your observing.

■ Contributing Editor **TED FORTE** enjoys galaxy-hopping from his home observatory outside of Sierra Vista, Arizona.

FURTHER READING: To learn about other galaxies around the north celestial pole, see Contributing Editor Steve Gottlieb's article in the February 2016 issue of *Sky & Telescope*.

Northerly Galaxies

Object	Type	Surface Brightness	Mag(v)	Size	RA	Dec.
NGC 3172	Spiral	13.7	14.1	1.0′ × 0.7′	11^h 47.2^m	+89° 06′
NGC 6251	Elliptical	13.7	12.6	1.8′ × 1.5′	16^h 32.5^m	+82° 32′
NGC 6252	Spiral	12.4	14.2	0.7′ × 0.3′	16^h 32.7^m	+82° 35′
IC 1143	Elliptical	13.1	13.2	0.9′ × 0.9′	15^h 30.9^m	+82° 27′
IC 1139	Spiral	12.4	14.9	0.6′ × 0.2′	15^h 29.4^m	+82° 35′
UGC 9668	Spiral	12.7	12.9	1.4′ × 0.7′	14^h 56.1^m	+83° 31′
UGC 9650	Spiral	12.8	13.5	1.5′ × 0.4′	14^h 53.8^m	+83° 35′
NGC 5640	Spiral	13.4	14.7	0.9′ × 0.4′	14^h 20.7^m	+80° 07′
NGC 1544	Spiral	13.3	13.3	1.3′ × 0.9′	05^h 02.6^m	+86° 13′
IC 442	Spiral	12.9	12.9	1.1′ × 1.1′	06^h 36.2^m	+82° 58′
NGC 2268	Barred spiral	13.4	11.5	2.7′ × 1.5′	07^h 14.3^m	+84° 23′
NGC 2300	Elliptical	12.8	11.0	2.8′ × 2.0′	07^h 32.3^m	+85° 43′
NGC 2276	Barred spiral	13.4	11.4	2.3′ × 1.9′	07^h 27.2^m	+85° 45′
IC 455	Lenticular	12.9	13.3	1.1′ × 0.7′	07^h 35.0^m	+85° 32′
IC 469	Barred spiral	13.3	12.6	2.2′ × 1.0′	07^h 56.0^m	+85° 10′
IC 499	Spiral	13.2	12.5	2.1′ × 1.1′	08^h 45.3^m	+85° 44′
IC 512	Spiral	13.0	12.2	1.8′ × 1.3′	09^h 03.8^m	+85° 30′
NGC 2336	Barred spiral	13.9	10.4	7.1′ × 3.9′	07^h 27.1^m	+80° 11′
IC 467	Barred spiral	14.0	12.6	3.2′ × 1.3′	07^h 30.3^m	+79° 52′
IC 440	Spiral	13.5	13.3	1.7′ × 0.9′	06^h 19.2^m	+80° 04′
NGC 1184	Lenticular	12.9	12.4	2.8′ × 0.6′	03^h 16.8^m	+80° 48′
NGC 3057	Barred spiral	14.0	13.0	2.2′ × 1.3′	10^h 05.7^m	+80° 17′

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.

UNDER CONSTRUCTION

The earliest exoplanet spectra from the James Webb Space Telescope are extraordinary — and challenging. Astronomers' toolkits need a major upgrade in order to interpret the data.

Luis Welbanks tingled with anticipation. It was July 2022, and his team had been eagerly waiting to see their data from the newly launched James Webb Space Telescope (*S&T:* Nov. 2022, p. 12).

For roughly eight hours, JWST had observed starlight as it filtered through the atmosphere encircling the distant gas giant WASP-39b, which lies about 700 light-years away. Astronomers often gather exoplanet data in this manner, relying on the host star to reveal the invisible: Although scientists typically cannot image the world directly, the alien air still leaves its mark by absorbing specific wavelengths of starlight that correspond to specific molecules in the exoplanet's atmosphere.

These so-called *transmission spectra* appear as nothing more than a series of wiggles and bumps. Yet they have the power to unlock crucial details — potentially even signs of life — on worlds that remain mostly invisible to our greatest telescopes. And JWST will give astronomers the best picture yet.

With so much at stake, it's no wonder that Welbanks (Arizona State University) was nervous. But the spectrum from WASP-39b did little to relieve his anxiety. As both observers and theorists gathered around a laptop with the new spectrum on its screen, their reactions played out in stark contrast. The observers beamed with happiness, overjoyed by the clarity of the spectrum and the details that quickly emerged. But the theorists, Welbanks included, whipped out their phones, worry lines on their faces.

A small bump was visible around 4 microns that Welbanks did not recognize. No theorist did. So he and his colleagues began frantically searching through database after database, trying to determine the source.

"The data were so great and the observers were so happy with it, but the modelers were freaking out a little," Welbanks says. "The journey for us had just begun."

It took several days (and half a year before any published results) to determine the source of the bump. It was sulfur dioxide. But the original computer models used to interpret the data didn't include the molecule — in part because the calculations didn't account for the myriad of chemical reactions that light from the planet's host star can drive in the upper atmosphere.

Now scientists understand that ultraviolet photons break up water molecules in WASP-39b's atmosphere, allowing the free hydrogen to interact with hydrogen sulfide and eventually create sulfur dioxide. But that answer was not obvious at first. In fact, the detection marked the first time sulfur dioxide was identified in any exoplanet atmosphere.

WASP-39b is just one example of the challenges that arise when scientists cross a frontier in our knowledge. No previous observatory has measured the subtle differences in so many individual wavelengths across the 3- to 5.5-micron infrared range to the precision necessary for compounds like sulfur dioxide to pop out in an exoplanet's transmission spectrum. "JWST revolutionized the field," Welbanks says. "But with better data, we need better models to explain these subtleties."

The problem is that astronomers can't simply pull up a complete list of all the spectral lines created in nature, compare it to the complex transmission spectrum they measured, and match up the lines. First, that master list is unknown. Second, the real spectral lines will change depending on the conditions in the alien atmosphere.

So astronomers create a series of models with every new dataset. Essentially, they run computer codes to build several synthetic planets and generate the predicted transmission spectrum of each hypothetical planet. They then compare those mockups to the actual one. The best match helps place constraints on the actual planet, allowing them to argue that the detected planet has a certain temperature, composition, or — the true holy grail — life.

But the models need work. Many, like the ones originally built for WASP-39b, lack crucial details about the planet's atmosphere, the star itself, and even the physics behind how light and matter interact. The difference between current models and reality is akin to the difference between a sketch and a photograph.

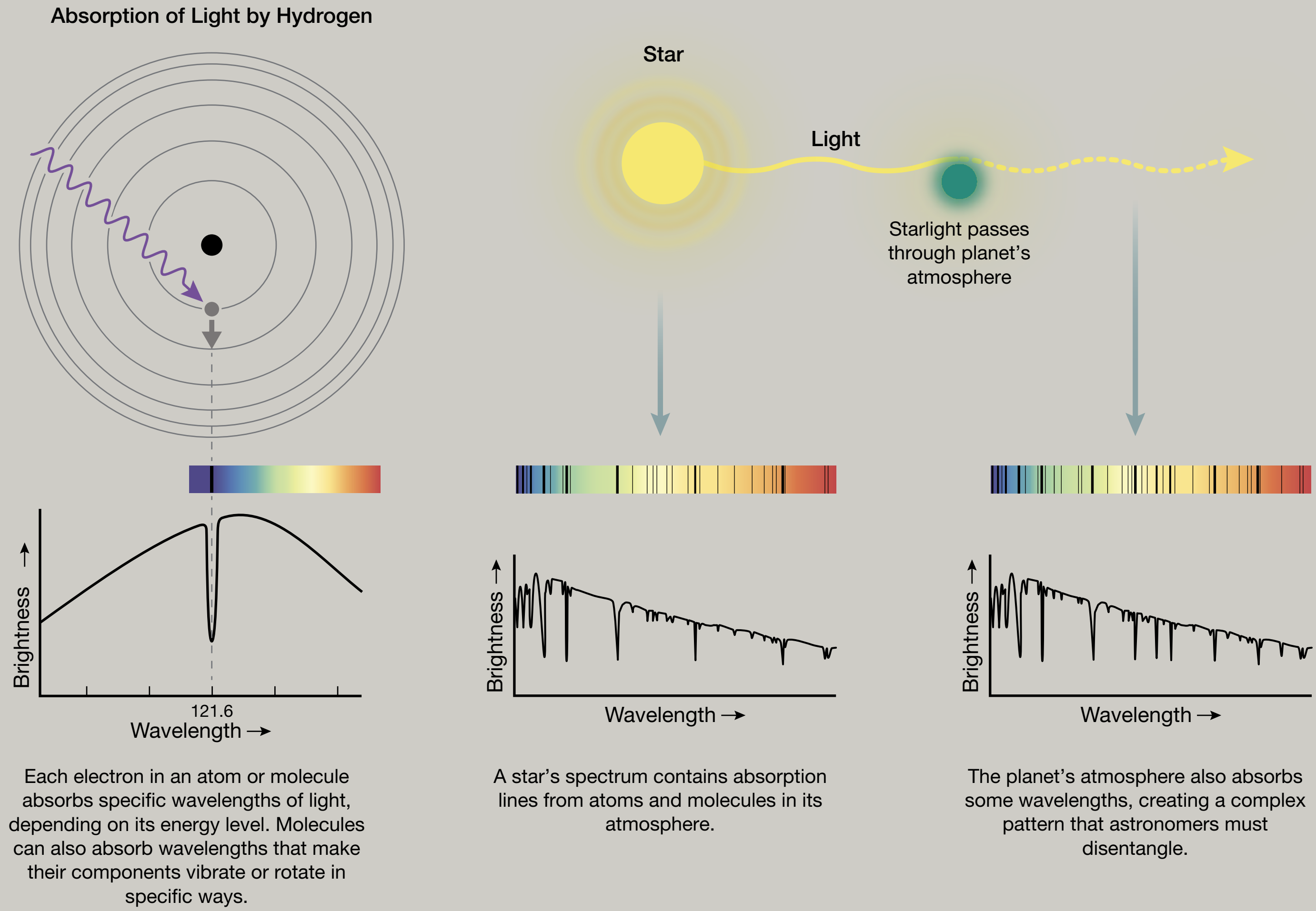
Luckily, theorists across the globe are already hard at work filling in the details of their planetary portraits.

A Huge Experiment

Welbanks has only recently finished analyzing the spectrum of WASP-39b. Through JWST's Early Release Science Program, he led a team of roughly 50 scientists in scrutinizing the planet with different methods. The goal was to provide astronomers with an instruction manual for how to handle future JWST observations.

But the results were alarming. Different astronomers, using different models, found wildly different answers for the properties of the exoplanet's atmosphere. "We had a

SAYOSTUDIO



▲ **TRANSMISSION SPECTRA** Astronomers can detect an exoplanet's atmosphere by identifying "extra" absorption lines in the host star's light, left as chemical fingerprints when the starlight passed through the planet's atmosphere. But correctly identifying the atmospheric composition and conditions responsible for those chemical fingerprints requires careful work.

BEATRIZ INGLESSIS / *S&T*, SOURCE: NASA / ESA / LEAH HUSTAK (STSCI)

$10 billion telescope giving us the best data on the planet," Welbanks says. "And even then, we were having challenges in explaining [the data] with our models."

So Welbanks and his colleagues began looking at every detail in the different calculations — from the smallest assumptions, like which units each team used, to the larger assumptions about the chemistry and physics at work in planetary atmospheres. The latter proved to be especially important.

When building these synthetic planets, astronomers have long taken shortcuts — assuming, for example, that the planet has the same composition and temperature everywhere. That is a far cry from reality.

But while astronomers would love to build the most complicated models physically plausible, they simply can't. Even the best computers can only do so much so fast. And scientists need to run millions of slightly different examples to find the best match. That means it would take ages to run the necessary calculations — literally: If theorists wanted to use a model that takes one month to compute a realistic spectrum, they would have had to start back in the last Ice Age to complete millions by today.

Moreover, a real transmission spectrum doesn't reveal all the details within a planet's atmosphere: It represents merely a passing shadow of a world that scientists cannot even see.

So scientists work hard to find the best balance, building models that are simple enough to run, yet complex enough to match the data. Now with JWST upping the complexity, that balance has been upset.

For example, when astronomers observe clouds in visible wavelengths — like those imaged by the Hubble Space Telescope — the clouds block all the light that hits them. It's like the clouds are a solid wall, presenting a blank surface that reveals little to nothing about its own composition while also hiding what lies below. "You don't see any more of the gas absorption, in the same way that you don't see any more blue sky on Earth," says Sarah Moran (University of Arizona).

But clouds are not an impenetrable wall in the mid-infrared wavelengths that JWST detects. In fact, it's just the opposite: Their molecules absorb starlight at these wavelengths, creating distinct spectral features that enable astronomers to deduce their composition.

Consider the gas giant known as WASP-17b, in a system some 1,300 light-years from us. When David Grant (University of Bristol, UK) and his colleagues inspected JWST's transmission spectrum of this world, they saw an absorption feature at 8.6 microns, which likely corresponds to pure quartz crystals swirling in the exoplanet's clouds.

Now that the data actually show absorption features from clouds themselves, scientists must learn how to identify these pieces of the crumbled wall. They need much more sophisticated calculations that incorporate absorption data from both a wide variety of different cloud compositions *and* from the molecules of the gas in the atmosphere, not just the latter. And the bricks they pull from the rubble will provide telling hints about the rest of the planet.

The flip side is that if astronomers model the clouds incorrectly, that error could propagate into other inferences about the planet — potentially leading to incorrect answers about the planet's temperature or the abundance of other atmospheric molecules.

Anna Lueber (Ludwig Maximilian University, Germany) and her colleagues recently demonstrated this idea by looking at WASP-39b with two different models — one that assumed clouds block all wavelengths of light by the same amount and one that assumed they did not. Her team found that for certain JWST data, the planet's estimated water abundance changed by an order of magnitude depending on which model the researchers used. For a hot Jupiter like WASP-39b, the amount of water vapor could affect important chemical processes in the atmosphere.

It's not the first time that astronomers have discovered that their planetary assumptions are lacking. Even something as simple as presuming that planets are spherical can cause trouble. A hot Jupiter — which orbits so close to its star that it's tidally locked, the same hemisphere perpetually facing the star — will have a dayside that is roughly 1000 kelvins hotter than its nightside, causing it to puff up and transform the planet into a world that looks more like an egg than a sphere.

In 2020, Ryan MacDonald (University of Michigan) and his colleagues found that if astronomers didn't account for this asymmetry, they would wildly underestimate the planet's temperature from the transmission spectrum, which by nature is a glimpse at the planet's day-night boundary. In some cases, the difference might amount to more than 1000K.

That actually explained a trend that MacDonald's team had noticed in many scientific papers, which described exoplanets as being much cooler than predicted. With updated models, astronomers can now not only accurately pinpoint that temperature but also better understand the circulation of the atmosphere, chemical reactions within the atmosphere, and even the chemistry of the clouds on these distant planets. Lueber's recent work on WASP-39b, for example, showed that the deduced amount of carbon dioxide changes by almost four orders of magnitude, depending on whether you assume that the atmosphere's temperature is constant or not.

Welbanks, too, has found that these factors dramatically impact their findings from WASP-39b. So do assumptions made about the star. Transmission spectra, after all, are obtained when a planet transits in front of its host star, so the spectra contain information about both the star and the planet. To obtain information on the planet alone, astronomers need to subtract the information that is coming from the star. But in order to do that, they need to correctly identify which parts of the spectrum are from the star. That means building not only an excellent planet model but also a reliable stellar model.

Take GJ 486b, a rocky planet orbiting close to a red dwarf star 26 light-years away. In 2023, astronomers used JWST to spy signs of water vapor in its spectrum. It would have marked the first time scientists had ever managed to discern an atmosphere on a rocky planet outside our solar system — and with water vapor to boot!

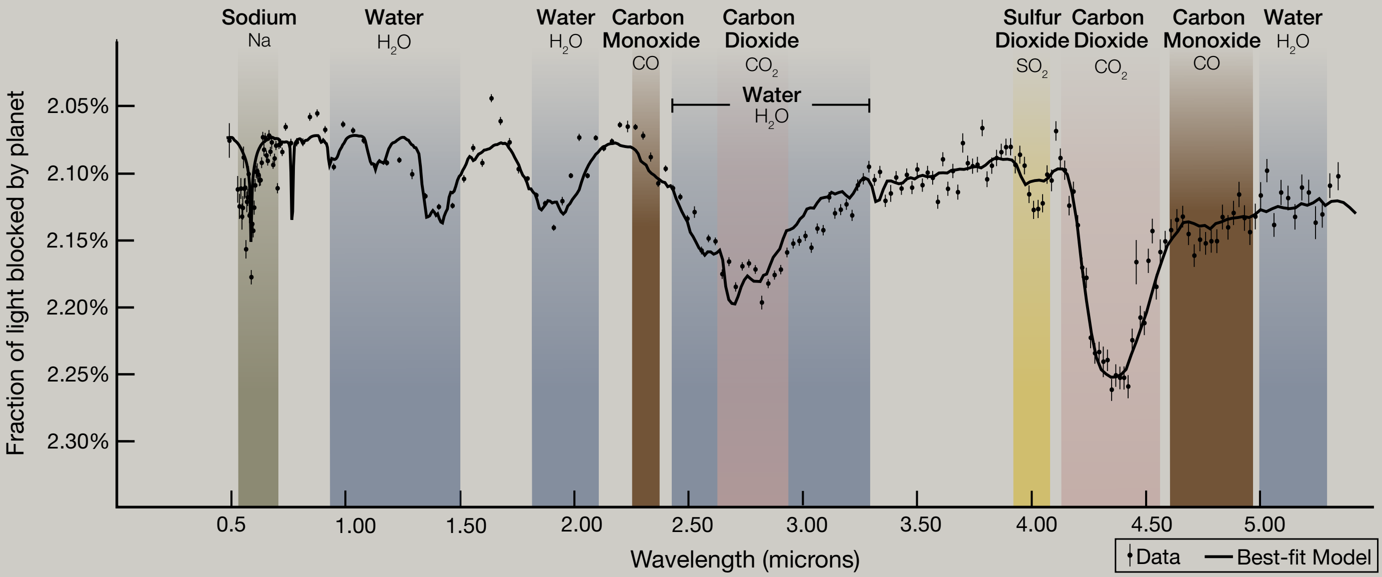
But an equally likely explanation for the water vapor is that it originated from the host star, not the planet. Red dwarfs are much smaller, dimmer, and cooler than our sun. That makes their star spots especially chilly — so much so that they can sustain the formation of water vapor. It's still unclear whether the water detected from the transmission spectrum originates in the planet's atmosphere or the star's.

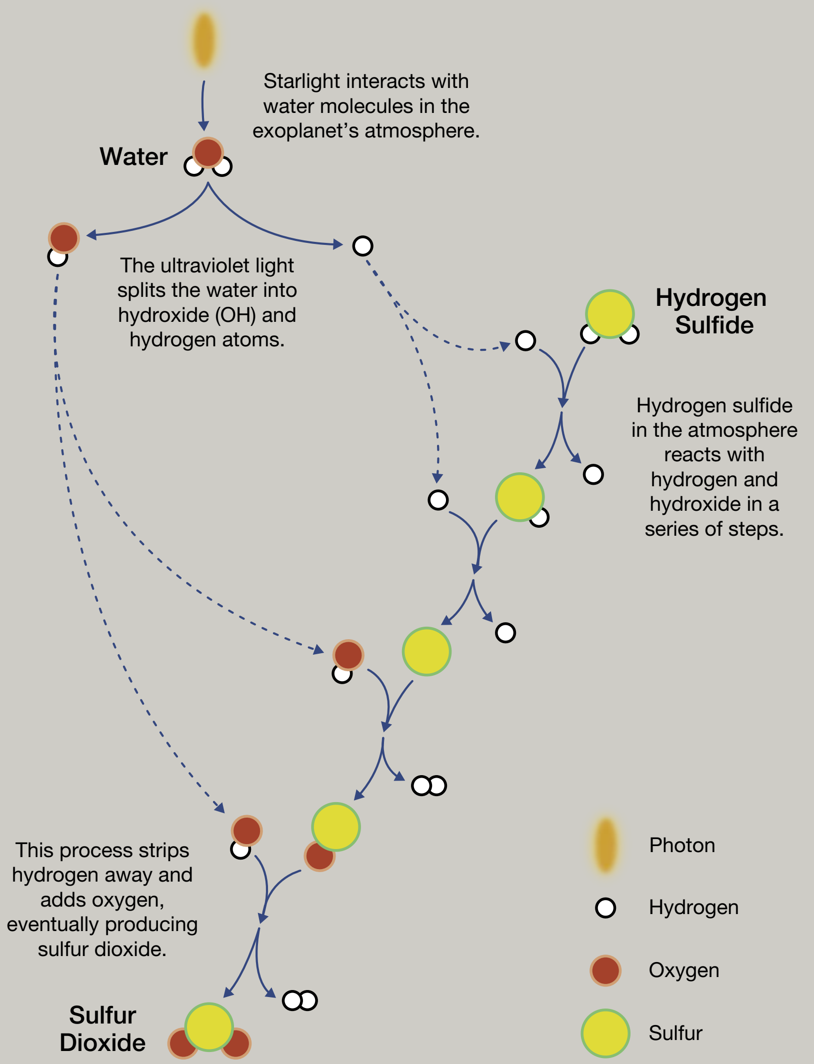
The answer — once again — relies on building better models.

A New Rosetta Stone

Underneath these issues is one very basic assumption: that astronomers understand how light and matter interact. *Opacity* is the measure of how easily photons pass through a material. They might pass straight through, be absorbed, or be reflected back, depending on how they interact with certain molecules within that material.

Consider a hydrogen atom, with a single proton in the nucleus and one electron orbiting the nucleus. The electron can absorb a photon and jump to a higher energy level, or it can emit a photon and drop to a lower energy level. Any undergraduate in a first-year physics lab has likely peeked at a hydrogen emission tube and jotted down the visible wavelengths associated with these transitions. In fact, such work underpins much of astronomical research, enabling scientists to deduce not only the compositions





▲ **UNEXPECTED WIGGLE** This first transmission spectrum from WASP-39b revealed the presence of several compounds in the gas giant's atmosphere, including sulfur dioxide — a detection that surprised theorists. (Note that researchers usually display these spectra mirror-flipped vertically, so that the absorption features are "bumps" instead of valleys; we have flipped all transmission spectra in this article to avoid confusing absorption features with emission ones.)

◀ **HOW WASP-39B MAKES SULFUR DIOXIDE** A series of steps transforms water and hydrogen sulfide in the planet's atmosphere into the molecule sulfur dioxide.

WASP-39B'S SPECTRUM: NASA / ESA / CSA / JOSEPH OLMSTED (STSCI), ADAPTED BY BEATRIZ INGLESSIS / S&T; CREATION OF SULFUR DIOXIDE: BEATRIZ INGLESSIS / S&T, SOURCE: NASA / JPL-CALTECH / ROBERT HURT of exoplanet atmospheres but also spinning galaxies, stellar nurseries, and even the earliest structures of the universe.

But in reality, it is not so simple. The spectral lines can change shape depending on the temperature of the gas and even the surrounding molecules. Moreover, not all molecules have been studied extensively.

To date, most of the research has been Earth-centric, meaning that scientists have mapped molecules common on Earth and at temperatures we normally encounter. But these same molecules act differently at temperatures of thousands of degrees, like those found within the atmospheres of hot Jupiters. Here, electrons are more likely to jump between energy levels, and the molecules are more likely to rotate and vibrate in different ways, creating more complex spectra. Water, for example, might have 320,000 transitions at room temperature, but it has roughly 5 billion at high temperatures.

Needless to say, it is challenging to map the absorption spectrum for every possible atom and molecule at every possible temperature.

To make matters more difficult, it is hard to recreate these conditions in the lab. Some of the gases, like phosphine — which was recently detected in Venus's atmosphere — are both poisonous and explosive at high temperatures. "You cannot find many people who would want to do experiments like that," says Iouli Gordon (Center for Astrophysics, Harvard & Smithsonian).

So scientists often have to rely on theoretical calculations to determine how molecules absorb light in different environments. But those calculations need new generations of computing facilities and can take impossibly long to run. Right now, scientists are trying to balance the two, using some lab data to provide key results that inform computational work (*S&T:* May 2021, p. 34).

Scientists also worry about how a molecule's spectrum will shift when it's surrounded by other, different molecules. Water, for example, has been mapped extensively on Earth — that is, in a nitrogen-dominated atmosphere. But if it is surrounded by hydrogen instead, like in a hot Jupiter, it will behave slightly differently. And so if astronomers try to interpret a water feature using data derived on Earth, their understanding will be inexact.

"It would almost be like using a Rosetta Stone with modern Greek instead of ancient Greek," says Julien de Wit (Massachusetts Institute of Technology). "We'd get some things right. But some other things would be slightly off. That's the issue with the opacity challenge."

De Wit, Gordon, and their colleagues recently analyzed synthetic data (similar to what JWST will see) with different spectral-line lists built using different methods. They found that the derived planetary properties — such as composition — could change by an order of magnitude for some planets, depending on their assumptions. Welbanks and his team encountered a similar challenge in analyzing WASP-39b's spectrum.

To accurately gauge these planets, scientists need accurate opacity models.

Enter HITRAN (High-resolution Transmission Molecular Absorption Database), a repository of both experimentally derived and calculated lists for a wide variety of different molecules. Originally built by the U.S. Air Force in the 1960s, the database initially included only seven molecules. It is now managed by the Center for Astrophysics and has expanded to include dozens of molecules in variant forms, including gases that are not necessarily present in the terrestrial atmosphere. Gordon, the current director of the HITRAN project, is working hard to ensure that expansion continues — acting as a liaison between the exoplanet community and the theorists who can provide new, improved spectra.

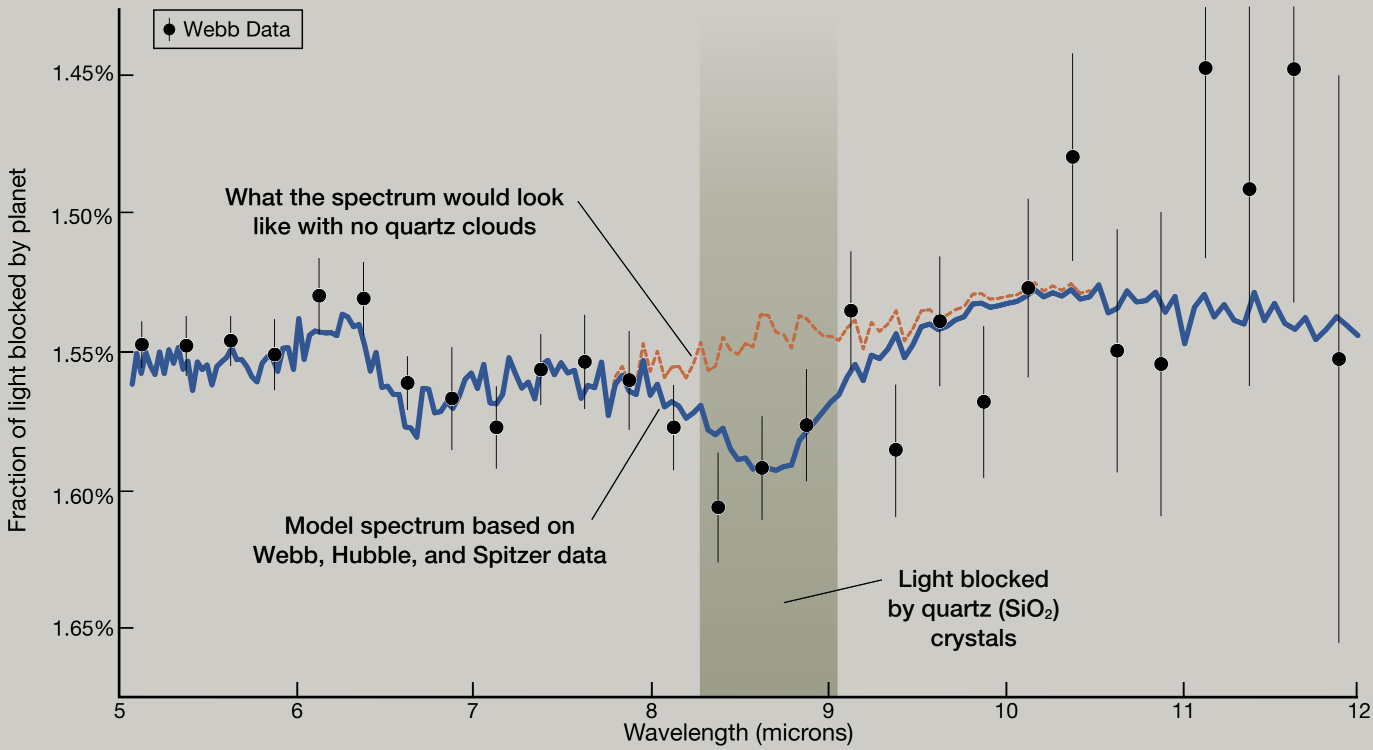
The database will inform a wide array of applications. Climate prediction models for Earth utilize HITRAN. So does work in the medical field. One research group even used it to determine the best glass shape from which to drink champagne and beer.

A World Made of Cheese

The worst-case scenario is that, due to model assumptions, astronomers may reach an egregious conclusion. "If we're not careful, it is a matter of time before someone puts out a press release that says, 'Astronomers Find that the Moon Is Made out of Cheese,'" Welbanks says. This result could happen if astronomers tried to compare the composition of the Moon with a cheese model and a sponge model. "Both models are wrong — but when we only have those two models, and we compare only those two models, one of them is going to win by definition."

That, of course, is an extreme case. But it does demonstrate how scientists might argue a planet has life because that is the best match to the data, only to be woefully wrong.

Despite the obstacles, many theorists are optimistic. "These are challenges, but also opportunities," de Wit says. "As we're forced to improve our models of each of these components — stellar models, opacity models, planetary models — we are going to gain new insights. We'll get access to new physics, not only when we do the theoretical work, but also when we compare the theoretical work to the data that we get access to with James Webb. It's a new frontier."



▲ **QUARTZ CLOUDS** Astronomers mix and match different compounds in their models to determine which is responsible for the features they see in exoplanet spectra. For WASP-17b, they realized quartz clouds in the planet's atmosphere would explain the starlight absorbed at 8.6 microns.

Some findings might even cross into different fields. The last edition of HITRAN, for example, included carbon disulfide thanks to work that was funded by the National Institutes of Health, because those with an enhanced amount of carbon disulfide in their breath might have kidney problems or schizophrenia. But once it was added to the HITRAN database, astronomers included it in their models and detected it within Venus's atmosphere.

The HITRAN collaboration will only continue to improve its database, adding more and more alien molecules. It also has a high-temperature version, called HITEMP. And other projects are just getting off the ground. A new research venture that brings together experts in exoplanets and stellar activity at institutions across the U.S. and Europe, for example, is working toward overcoming any contamination from host stars, particularly red dwarfs. Although research on planets like GJ 486b has been unable to differentiate findings between the star and the planet, theorists suspect that they will find a solution soon.

"I don't see any real showstoppers," says Alexander Shapiro (Max Planck Institute for Solar System Research, Germany). "I think we have all the tools in hand."

Those tools include the takeaways from the work on WASP-39b by Welbanks and his team, such as a list of the potential pitfalls. Overall, the team found that scientists need to not only focus on the opacity, cloud, and stellar assumptions but also build models to higher resolution — an order of magnitude higher than the resolutions required for working with Hubble data — to move us from a sketch toward a realistic portrait of exoplanet atmospheres.

But to do that within the confines of limited computing power and funding, astronomers will need to prioritize their assumptions. "We know we are always incomplete," Welbanks says. "Our observations and models are but a projection of reality. So ideally, we want to give an answer but have a reliable estimate of our uncertainty." Then, astronomers can tackle those uncertainties one at a time, choosing whether to focus first on the star, the clouds, or something else.

Many argue that these problems demonstrate the incredible advancements brought by JWST. The fact that these models now need to account for the 3D characteristics of the exoplanets, even details of the clouds themselves, shows that the data are actually telling us what these worlds look like — even if we can't see them.

"We're genuinely learning a lot about what these guys are really like," MacDonald says. "It's a great place to be in, where we're actually doing real science now on planets that are hundreds of light-years away."

■ Contributing Editor **SHANNON HALL** is a freelance science journalist who spent more than 20 nights observing exoplanet atmospheres for her master's degree.

NASA / ESA / CSA / RALF CRAWFORD (STSCI), DAVID GRANT (UNIV. OF BRISTOL), HANNAH R. WAKEFORD (UNIV. OF BRISTOL), NIKOLE LEWIS (CORNELL UNIV.), ADAPTED BY BEATRIZ INGLESSIS / *S&T*

SKY AT A GLANCE
December 2024

4 DUSK: Face south-southwest to take in the graceful sight of the waxing crescent Moon about 2½° below left of Venus. The view will become more dramatic as twilight deepens. Turn to page 46 for more on this and other events listed here.

7 EVENING: The Moon, one day shy of first quarter, hangs some 4° lower right of Saturn in the southwest. Watch as the pair sinks toward the west-southwestern horizon.

7 ALL NIGHT: Jupiter arrives at opposition (go to page 60). This month mighty Jove blazes in Taurus midway between Aldebaran and Elnath, or Beta (β) Tauri.

12 EVENING: Algol shines at minimum brightness for roughly two hours centered at 10:08 p.m. PST (see page 50).

13 EVENING: In the southeast, the waxing gibbous Moon gleams a bit less than 5° left of the Pleiades star cluster in Taurus. Jupiter shines lower left.

13–14 ALL NIGHT: The Geminid meteor shower is expected to peak. However, the almost-full Moon will severely hamper viewing.

15 EVENING: Algol shines at minimum brightness for roughly two hours centered at 9:58 p.m. EST (6:58 p.m. PST).

16 EVENING: The Moon, one day past full, forms a neat triangle with Castor and Pollux, Gemini's bright lights. It sits about 5° right of the stars above the eastern horizon.

17 EVENING: Face east to see the waning gibbous Moon perched a bit more than 1½° above ruddy Mars. Viewers in northern Alaska and northernmost Canada will see the Moon eclipse the planet.

18 EVENING: Algol shines at minimum brightness for roughly two hours centered at 6:47 p.m. EST.

19 EVENING: The Moon shepherds Regulus as they rise in the east-northeast. The waning gibbous is about 2° upper left of the star.

21 THE LONGEST NIGHT OF THE YEAR in the Northern Hemisphere. Winter begins at the solstice at 4:21 a.m. EST (1:21 a.m. PST).

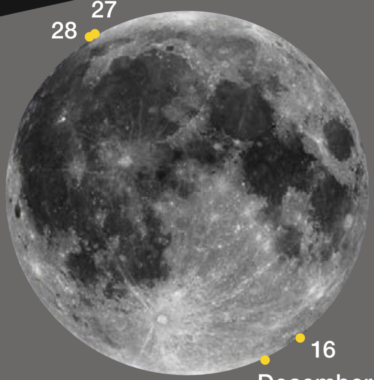
24 DAWN: Look south-southeast to see the waning crescent Moon a bit more than 3° upper right of Spica, Virgo's lucida. Catch this sight before the rising Sun washes it away.

28 DAWN: A lovely sight will greet early risers. In the southeast, a thin lunar crescent will be just ½° right of Antares, the Scorpion's heart, while tiny Mercury shines a bit farther left of the pair.

—DIANA HANNIKAINEN

▲ The aurorae grace the skies above Nuuksio, outside Helsinki, in southern Finland.
MARKUS HOTAKAINEN

DECEMBER 2024 OBSERVING
Lunar Almanac
Northern Hemisphere Sky Chart



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

MOON PHASES

SUN	MON	TUE	WED	THU	FRI	SAT
1	2	3	4	5	6	7
8	9	10	11	12	13	14
15	16	17	18	19	20	21
22	23	24	25	26	27	28
29	30	31				

NEW MOON
December 1
06:21 UT

FIRST QUARTER
December 8
15:27 UT

FULL MOON
December 15
09:02 UT

LAST QUARTER
December 22
22:18 UT

NEW MOON
December 30
22:27 UT

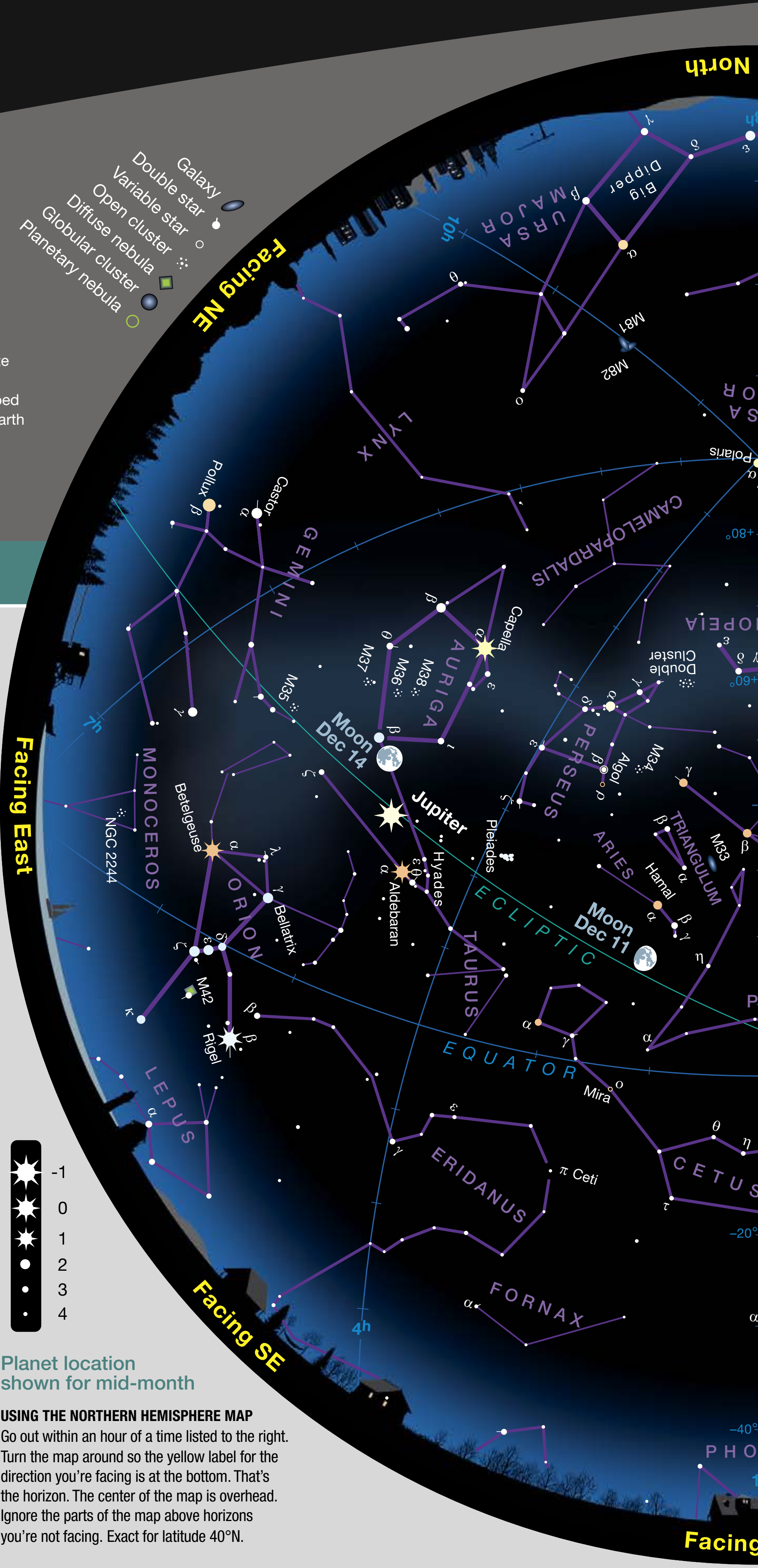
DISTANCES

Perigee 365,361 km	December 12, 13^h UT Diameter 32′ 43″
Apogee 404,485 km	December 24, 07^h UT Diameter 29′ 32″

FAVORABLE LIBRATIONS

- Helmholtz Crater — December 14
- Pontécoulant H Crater — December 16
- Pythagoras Crater — December 27
- Cleostratus Crater — December 28

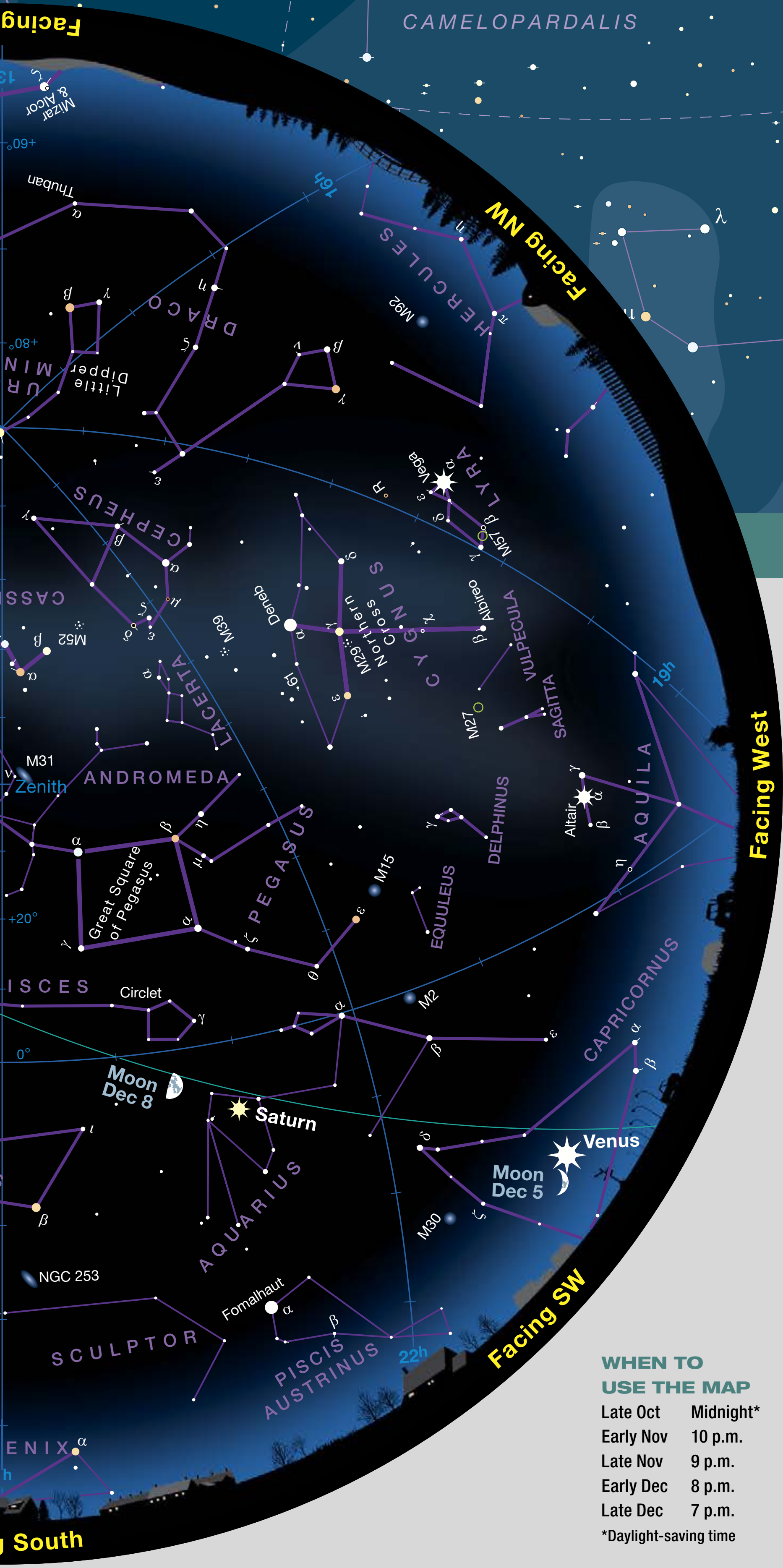
Galaxy
Double star
Variable star
Open cluster
Diffuse nebula
Globular cluster
Planetary nebula

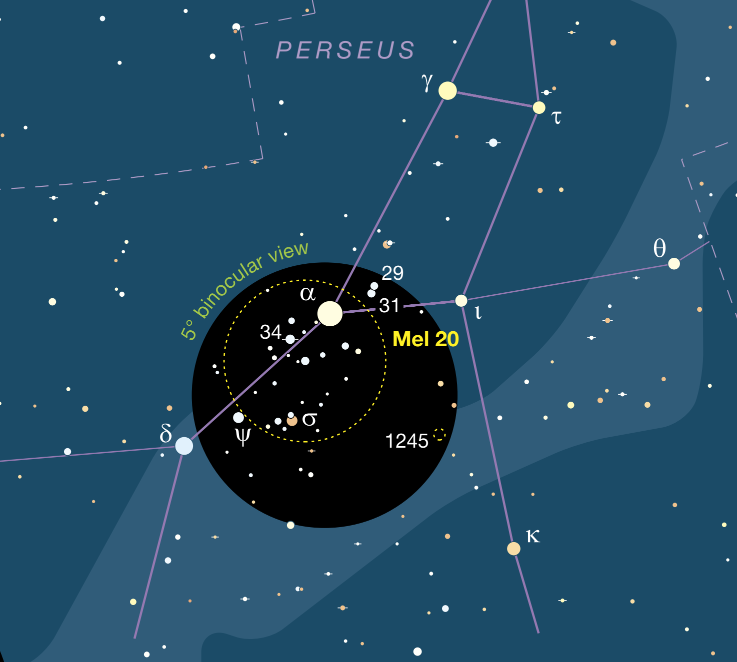


-1
0
1
2
3
4

Planet location shown for mid-month

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





Binocular Highlight by Mathew Wedel

Heroes Across Time

Confession time: When I realized that I'd only ever briefly mentioned the open cluster **Melotte 20**, also known as the Alpha (α) Persei Association, I literally slapped my forehead. One of the crown jewels of the northern sky, and somehow across all these years I hadn't covered it. But then, what a phenomenal way to close out the year.

The Alpha Persei Association is the biggest and brightest deep-sky object in the constellation Perseus, the Hero. The collection of stars sprawls across roughly 3°, nestled between 29 and 31 Persei in the northwest to Delta (δ) Persei in the southeast. It also lies in the hazy band of the Milky Way, and photometric studies have revealed an even larger, older star stream lurking beyond.

The association's size and internal complexity make it one of the best binocular targets in the entire sky. Here you'll find suns from magnitude 1.8 (Alpha Persei) down to the limit of whatever instrument you're using, nice binocular doubles, and chains and loops of stars that draw the eye effortlessly through space. In particular, look for a long, lazy S shape that runs northwest-to-southeast through 29, Alpha, and 34 Persei, bends back northwest in a ragged line of 5th- and 6th-magnitude stars, then drops southeast again in a steadily brightening arc through Sigma (σ) and Psi (ψ) Persei. Within that expanse, the teardrop-shaped gaggle of stars trailing southeast from Sigma Persei reminds me of a whale surfacing in a starry sea.

Finally, look for the 8th-magnitude open cluster NGC 1245, about 3° southwest of Alpha Persei. At roughly 10,000 light-years away, NGC 1245 lies more than 17 times farther from us than the Alpha Persei Association — a hero from another age, perhaps.

■ **MATT WEDEL** could spend a whole observing session just exploring Melotte 20 — and has!

WHEN TO USE THE MAP

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

*Daylight-saving time

DECEMBER 2024 OBSERVING

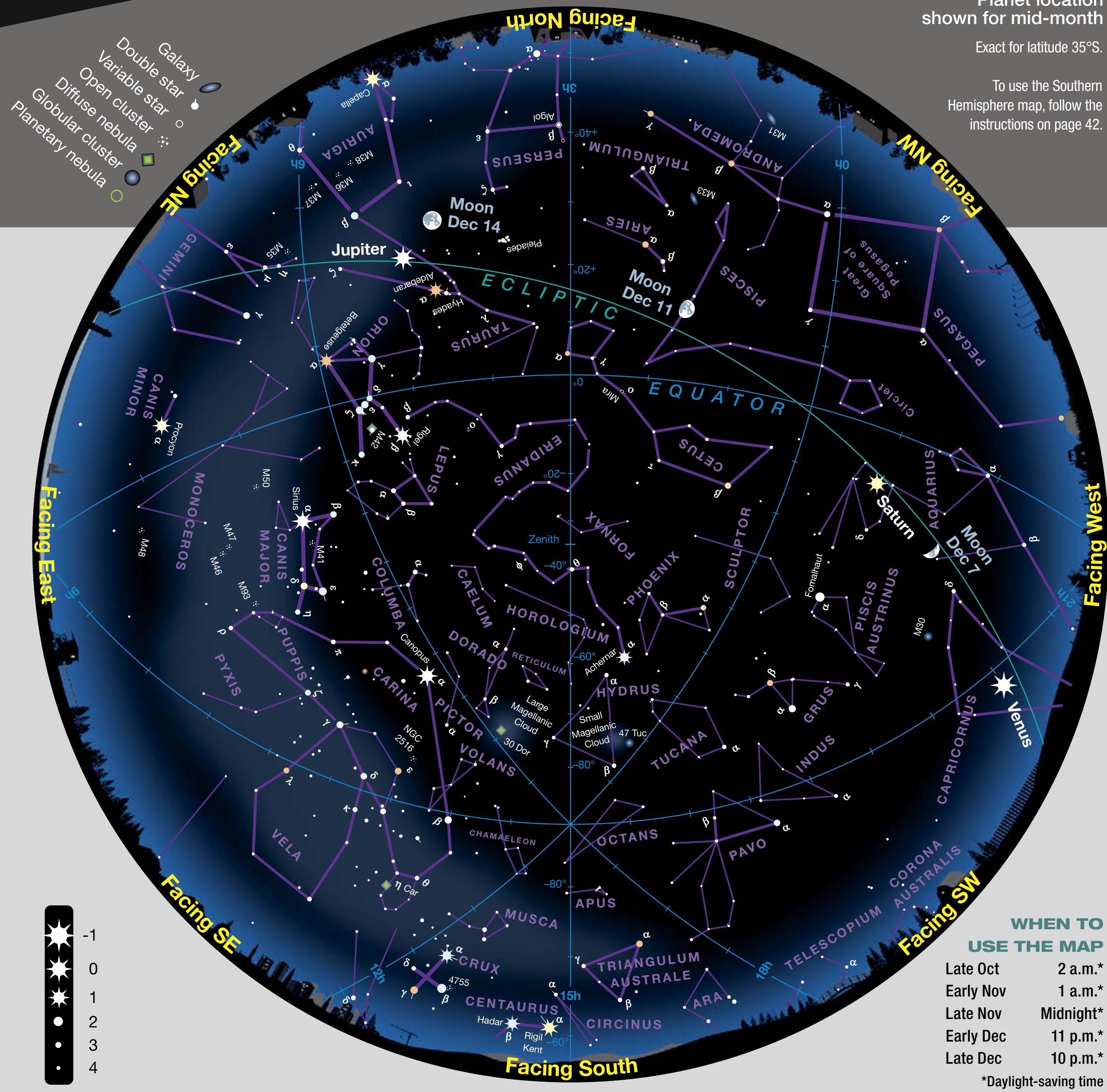
Southern Hemisphere Sky Chart

by Jonathan Nally

Planet location shown for mid-month

Exact for latitude 35°S.

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



WHEN TO USE THE MAP

Late Oct	2 a.m.*
Early Nov	1 a.m.*
Late Nov	Midnight*
Early Dec	11 p.m.*
Late Dec	10 p.m.*

*Daylight-saving time

THE CONSTELLATION **Eridanus**, the River, is a long, sprawling line that flows from the celestial equator west of Orion all the way south, spanning some 58° of declination. One of Ptolemy's creations from the 2nd-century BC, it is one of today's 88 officially recognized constellations.

Marking the River's southern end is the sky's 9th-brightest star, +0.5-magnitude Achernar — an Arabic name that means, appropriately, "the river's end." Since southerly skies were out of reach to the early Greek astronomers, Eridanus originally terminated at the star we know today as Theta (θ) Eridani or Acamar — a name that also means "the river's end." In Renaissance times, when explorers started discovering southern skies, they extended the constellation and named its bright, southernmost star Achernar. ■

A Shapeshifting Asterism

The Circlet of Pisces changes form depending on how you look at it.

Pisces, the Fishes, comprises three significant parts: a Northern Fish near Beta (β) Andromedae, a Western Fish beneath the Great Square of Pegasus, and a long, V-shaped ribbon or cord joining them by their tails. The constellation is faint. Its brightest stars are around 4th-magnitude; nevertheless, the Western Fish is a popular target for naked-eye stargazers. It includes an *asterism* (a familiar pattern of stars) known as the Circlet of Pisces — a curiosity unto itself, as sources vary on which stars represent it.

In one popular tale from Roman mythology, the two Fishes represent Venus, goddess of love, and her son Cupid. One day, mother and son were walking along the banks of the Euphrates River, when they encountered Typhon, a fearsome giant with 100 snake heads. To avoid the wrath of this terrible monster, Venus grabbed Cupid, jumped into the river, and changed both of them into fishes. To commemorate their escape, Minerva, goddess of wisdom, placed them among the stars.

When I survey books dating from 1860 and later, I find many references to a "circlet" of stars in the heavens. But instead of referring to Pisces, the term is applied to Corona Borealis, the Northern Crown. It's in William Tyler Olcott's 1907 *A Field Book of the Stars* that I first find mention of the Pisces asterism. "The Circlet," Olcott wrote, "is a very striking group forming a pentagon."

Olcott's pentagon refers to the Circlet's five brightest stars: Iota (ι), Theta (θ), Gamma (γ), Kappa (κ), and Lambda (λ). When seen under a dark sky, these stars do appear as a sharply defined pentagon. All we need to do is add 5.1-magnitude 7 Piscium to the mix and the pentagon rounds out into a circle. What's more, 7 Piscium shines only about 0.2 magnitude fainter than Kappa, the dimmest member of the pentagon.

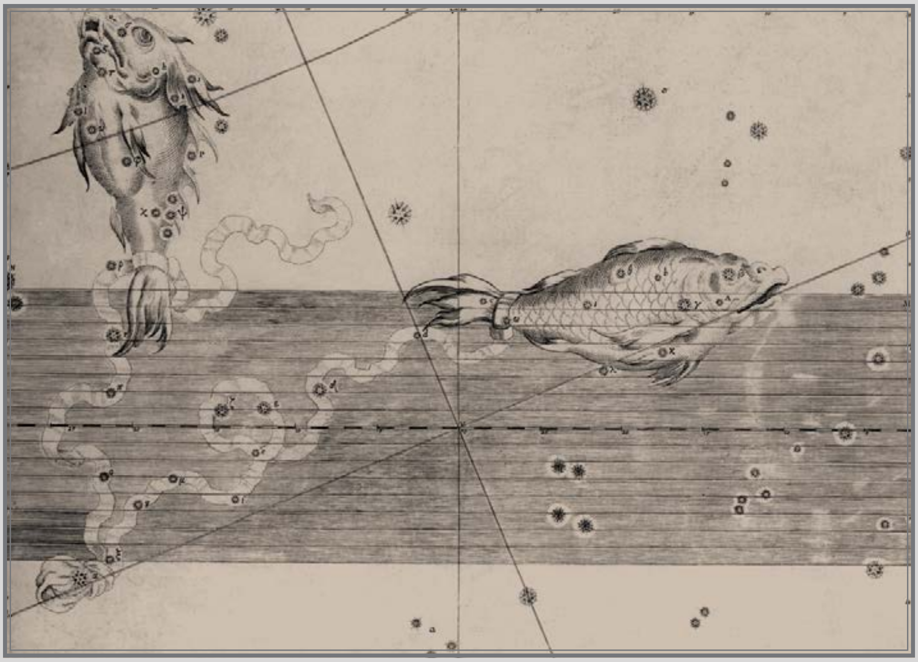
Although Johann Bayer plotted the stars of the Circlet in his 1603 *Uranometria*, he didn't refer to the asterism by that name. As you can see in the illustration below, Bayer's round of stars includes 7 Piscium, which he labels as "b". Olcott also plotted the star in his drawing of the Circlet, inadvertently transforming his "pentagon" into a hexagon. Some later celestial cartographers not only included 7 Piscium in depictions of the Circlet but also added variable star TX (19) Piscium. Olcott was aware of TX, writing that optical aid will reveal "two faint stars in addition [7 and TX], making the figure seven-sided or elliptical in form."

In fact, under a dark sky, TX can be monitored without optical aid through its entire cycle of variability, which ranges from magnitude 4.9 to 5.5 over a period of about 224 days. When it's at its brightest, TX rivals Kappa and 7 Piscium, adding breadth to the Circlet.

TX Piscium is a fascinating star in its own right. A luminous red giant in the final stages of evolution, it has more sooty carbon in its atmosphere than oxygen, lending it a rich red color. It's one of the reddest stars visible to the unaided eye, though binoculars are required to appreciate its scarlet hue.

Returning to our original tale, if you're wondering about the cord connecting the two Pisces fishes, sadly its mythological significance has been lost to time. It can be (and has been) imagined as a cord tying Venus and Cupid together so that they wouldn't lose each other among the reeds in the dark waters of the Euphrates.

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



▲ This illustration from Johann Bayer's 1603 *Uranometria* star atlas depicts the Western Fish of Pisces. Although he doesn't identify the Circlet, Bayer labeled the asterism's five principal stars and includes 7 Piscium, which he labels as "b."

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

A Month of Near Misses

The Moon passes close to several stars and planets this month.

WEDNESDAY, DECEMBER 4

The **Moon** has a busy month that includes no fewer than four naked-eye occultations. Unfortunately, they're out of reach for most readers. But that's not to say there aren't any interesting conjunctions — there are plenty of those, too, starting with this evening's pairing of the waxing crescent Moon and **Venus**, the brilliant Evening Star.

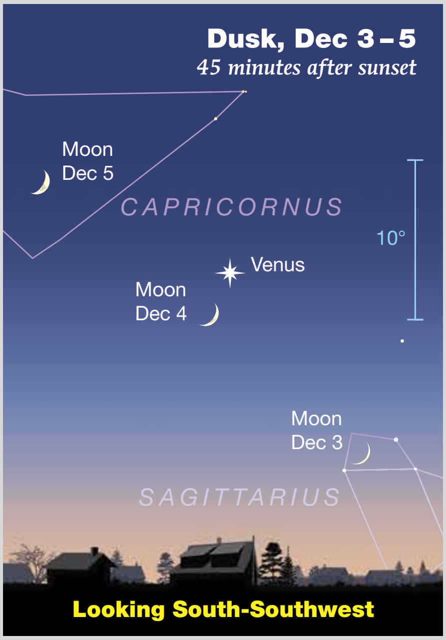
Hovering above the southwestern horizon as twilight fades, the duo is separated by just a bit more than 2½°. The Moon is a mere 3½ days old, which means earthshine is readily visible. Indeed, that's one reason you might want to use your binoculars to view the event — the extra magnification binos provide makes the ghostly "dark" portion of the lunar disk even easier to see. Venus-and-Moon meetings are essentially monthly events — and the closer the encounter, the better. Of the four conjunctions remaining in Venus's current evening apparition (including this one), only February's is closer. That's a pretty good reason to brave the cold and take in the sight.

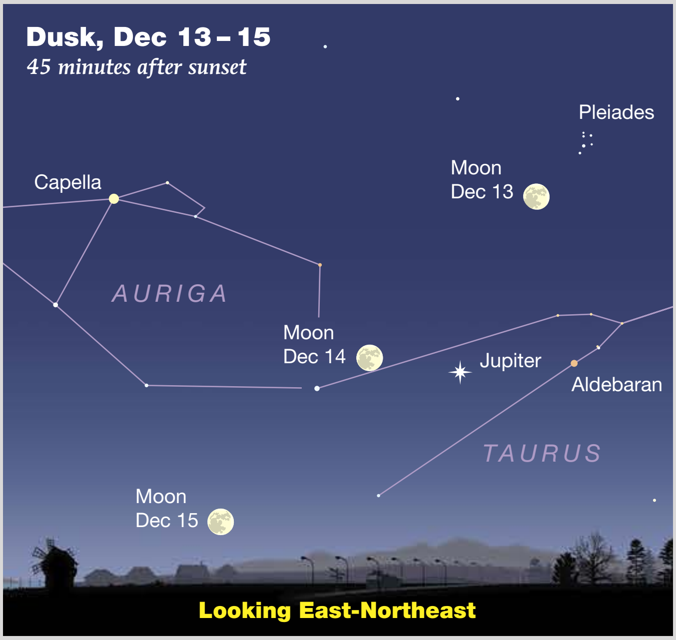
SATURDAY, DECEMBER 7

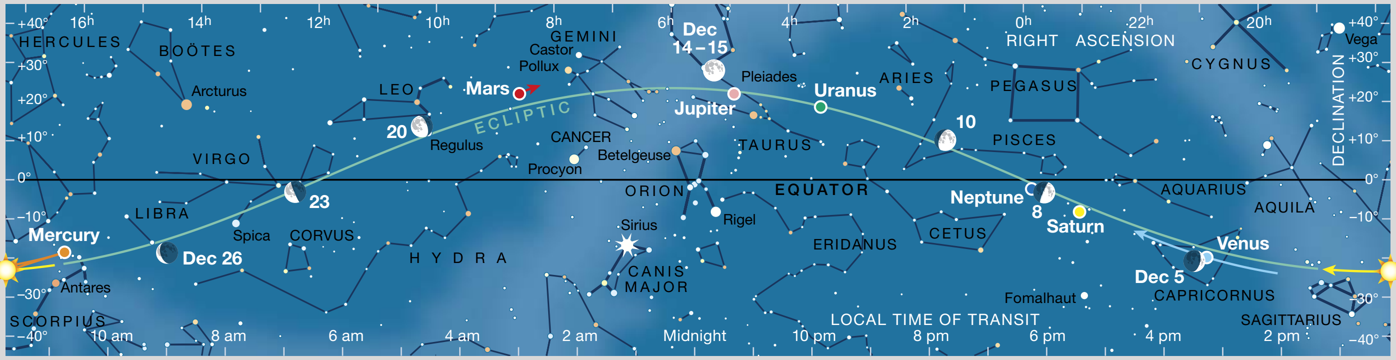
We have two late-evening events to enjoy today. First, the **Moon** and **Saturn** meet up. Since the waxing lunar crescent is still drifting toward the planet, the later you look, the closer they'll appear. Obviously, the two are setting, so if you wait too long, they'll be out of sight. The Moon approaches to within about 3° of the Ringed Planet. Binoculars will nicely frame the scene and give an enhanced view. You won't be able to see the famed rings, but if you look closely, you can notice that Saturn does appear slightly "out of round" at binocular magnification. This is one of the four occultations I mentioned earlier, but you'd have to be out in the Pacific to see it — it occurs after the Moon and Saturn are below the horizon as seen from our side of Earth.

Our second event actually unfolds slowly enough that you could look a night or two earlier or later and see essentially the same thing. That event is **Mars** sitting roughly 2° from the center of the **Beehive Cluster**, M44, in Cancer. Tonight, the Red Planet ceases its eastward motion and, after briefly pausing, starts to drift westward in what astronomers refer to as *retrograde motion*. In fact, this change in direction is an optical illusion created by our shifting perspective as Earth catches up to Mars as they orbit the Sun together. On February 24, 2025, Mars reaches the western extremity of its retrograde loop and resumes eastward ("direct") motion. Halfway between today and

▶ These scenes are drawn for near the middle of North America (latitude 40° north, longitude 90° west). European observers should move each Moon symbol a quarter of the way toward the one for the previous date; in the Far East, move the Moon halfway. The blue 10° scale bar is about the width of your fist at arm's length. For clarity, the Moon is shown three times its actual apparent size.





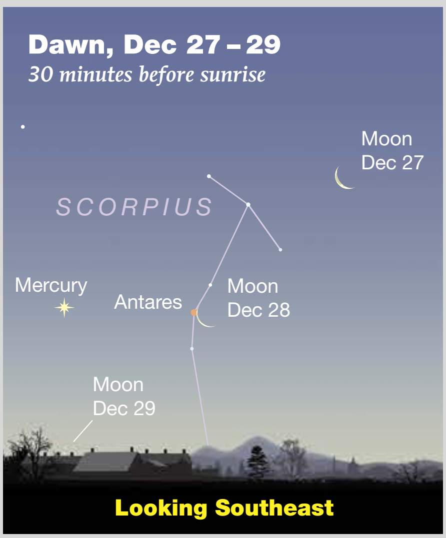


▲ The Sun and planets are positioned for mid-December; the colored arrows show the motion of each during the month. The Moon is plotted for evening dates in the Americas when it's waxing (right side illuminated) or full, and for morning dates when it's waning (left side illuminated). "Local time of transit"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

that February date, Mars reaches opposition (on January 16th, at 3h UT), when it's at its biggest and brightest for the current apparition.

SATURDAY, DECEMBER 14

Late this evening, look high overhead to catch a nifty, three-piece alignment. Strung out in a line are **Aldebaran** (the brightest star in Taurus, the Bull), **Jupiter**, and the full **Moon**. The alignment is most perfect shortly after 11 p.m. EST, though the Moon moves slowly enough that you don't need to be terribly exact here. Jupiter is about 7° from Aldebaran, and the Moon is a little more than 7½° from Jupiter. Nice. Regular readers of this column may recall the October installment in which I noted that when the full Moon appears near an outer planet, that planet must be near opposition. And so it is this time — Jupiter



reached opposition on December 8th, less than a week ago. When the Moon swings by the planet next month, it will be a 90%-illuminated waxing gibbous.

If you continue to watch as the night of the 14th transitions into the morning of the 15th, you'll see the Moon approach to within just 25′ (roughly one Moon diameter) of 1.7-magnitude **Beta (β) Tauri**. The gap between the star and the northern edge of the lunar disk is at its minimum at around 3 a.m. (on the 15th) EST. Binoculars are very helpful for this conjunction, as the overwhelming glare from the Moon makes seeing the star a bit tricky.

WEDNESDAY, DECEMBER 18

The month's closest conjunction occurs in the predawn hours today. That's when the waning gibbous **Moon** glides just north of ruddy **Mars**. They rise near each other on the evening of the 17th and remain close all night. But it's at around 4:36 a.m. EST that they're at their very closest and separated by about 17′ as seen from mid-northern latitudes, though the exact amount depends on your location. The farther north you are, the smaller the gap. For example, from Edmonton, Alberta, less than 12′ separates the Red Planet from the Moon's southern limb. And from the high Arctic and Greenland, the conjunction becomes an occultation.

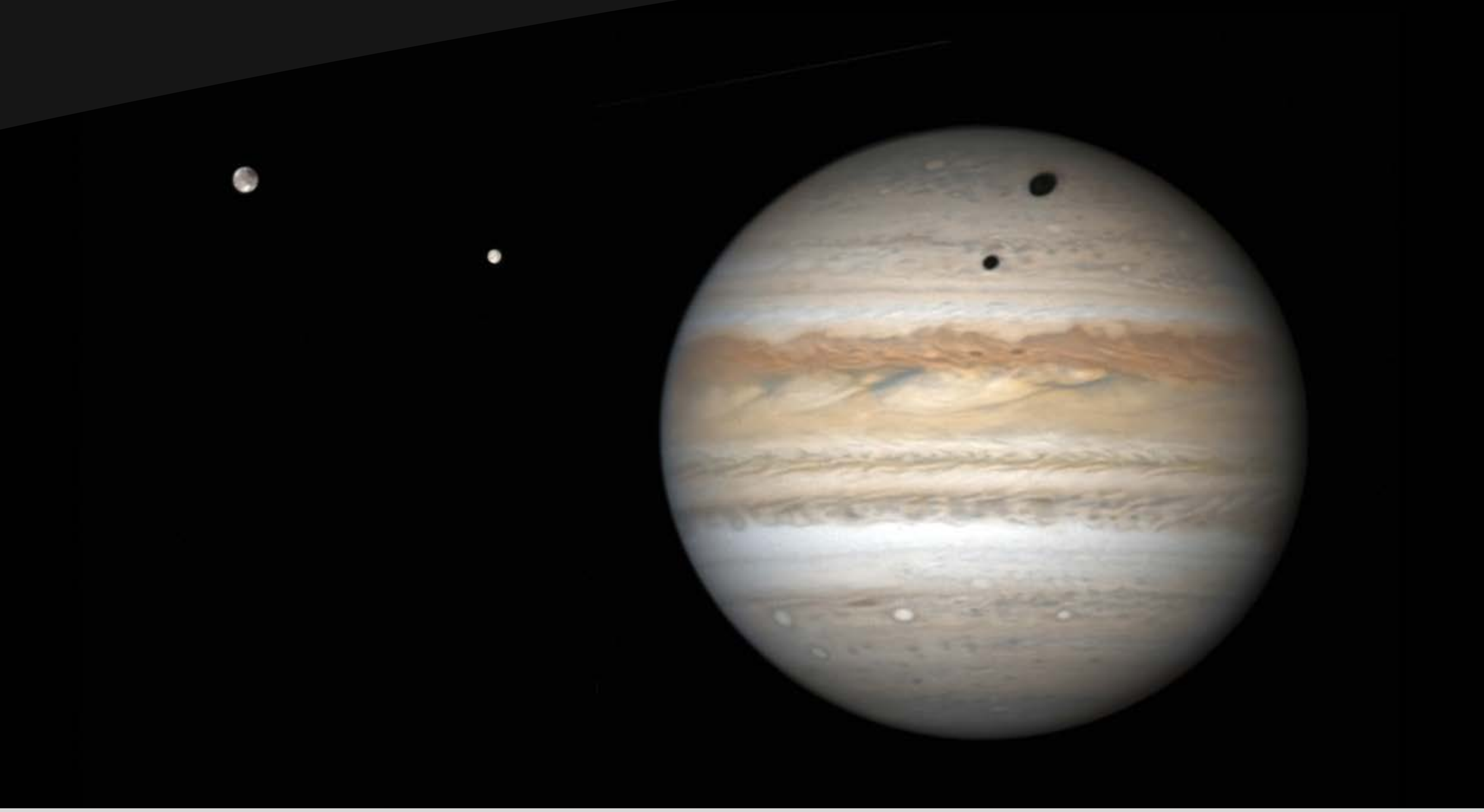
Despite the glare from an 89%-illuminated Moon, you'll have no trouble seeing Mars. It's less than a month away from opposition and its closest approach to Earth, so it shines gamely tonight at magnitude –0.9 — just a half magnitude shy of its peak brightness for this apparition. This is another of those events that binoculars don't help you *see* so much as *appreciate*. The optical boost enhances the color contrast between peachy-orange Mars and the stark, silvery-gray of the lunar surface.

SATURDAY, DECEMBER 28

Our final highlight for the month is a dawn double-feature. First, look to the southeast to catch the 6%-illuminated waning crescent **Moon** a mere 45′ right of 1st-magnitude Antares, in **Scorpius**. This is another one of December's "occultation elsewhere" conjunctions — observers in Polynesia and the southern half of South America are the ones in the right spot this time.

Our second feature is the chance to sight **Mercury** during its best dawn apparition of 2024. The innermost planet is a bit more than 8° left of Antares. Mercury reached its greatest elongation (22° west of the Sun) on the 25th (at 3h UT) and achieves an altitude of 11° above the east-southeastern horizon half an hour before sunrise, where the little world shines at magnitude –0.4. If mornings aren't your thing, you'll get another shot at sighting Mercury during the peak of its dusk apparition in March.

■ Consulting Editor **GARY SERONIK** has been fascinated by the comings and goings of the planets since he was a child.



See Jupiter Big and Bright

It's opposition time once again for the solar system's most dynamic planet.

Jupiter stands before the northern summit of the ecliptic this month, roughly 1° shy of its maximum northerly declination. When it reaches opposition on December 7th, it will shine from Taurus at magnitude −2.8. Believe it or not, that's bright enough to cast faint shadows.

In October 2023, just before the previous opposition on November 3rd, I attempted to see my shadow by Jupiter-light when the planet gleamed in the eastern sky. With averted vision I could barely discern my shape projected on a white garage door as I swayed from side to side — in low light, motion helps to reveal things dimly perceived. As the photo on the facing page shows, my DSLR camera clearly recorded its own silhouette by Jovian light in a 30-second exposure at ISO 8000.

For observers at mid-northern latitudes, Jupiter crosses the meridian far above the muck that clings to the horizon. That places the planet in relatively steady skies, making the current apparition one of the best for pushing your observing skills to the limit to uncover delicate details in the planet's churning cloudtops. You can even try to discern mottled albedo features on Jupiter's largest moon, Ganymede. At 1.8″ across, it's only 0.6″ smaller than Neptune's disk when that planet reaches opposition, as it did last September.

There are also lots of easy sights. Low magnification and a small scope are all you need to enjoy the dance of the Galilean satellites (see page 78) as they weave their way around the planet night after night during the month. Jupiter's north pole is tipped earthward 2.9° at opposition. As a result, Callisto, the outermost of the four bright moons, passes approximately 5″ north or south of the Jovian disk instead of crossing its face. You can view these cherry-on-top (and bottom) passes occurring on December 4th at around 2 a.m. EST (south of Jupiter); on December 12th 4 a.m. PST (north); and on December 28th 9:30 p.m. EST (north). The other three Galilean moons will undergo their usual entertaining

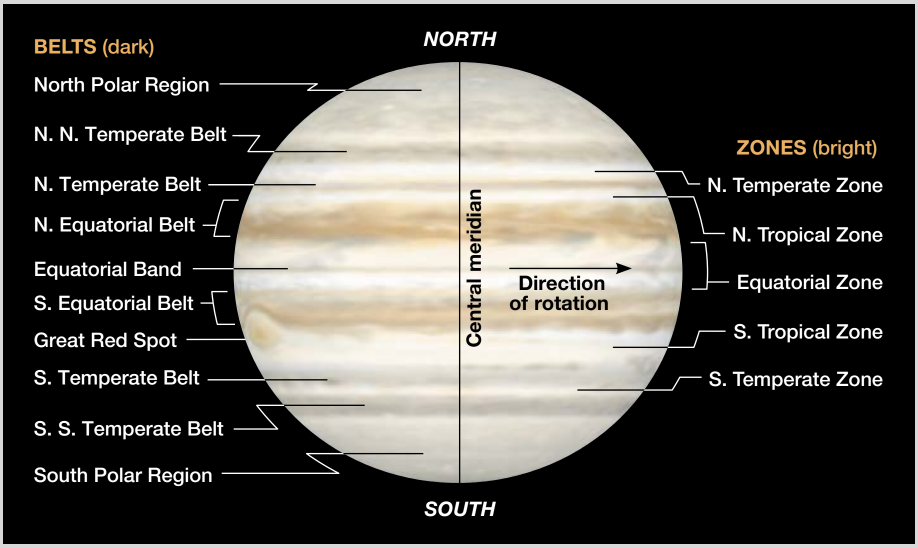
▲ This March 25, 2019, photo by UK planetary imager Damian Peach shows Ganymede (left) and Europa casting their shadows on the clouds of Jupiter's northern hemisphere during a double-shadow transit. Ganymede, the larger moon, casts the bigger shadow. While not rare, shadow transits allow us to see from a distance what our own Moon does during a total solar eclipse.

assortment of events listed on the table appearing on page 51.

This month, observers in the Americas also get treated to a pair of double-shadow transits, in which the shadows of two moons simultaneously land on Jupiter's cloudtops. Both instances involve Ganymede and Io, with Ganymede's shadow being the larger of the two. The first occurs on December 23rd, when Io's shadow joins Ganymede's at 2:47 a.m. EST and lasts until Ganymede's shadow exits the Jovian disk a little more than an hour later, at 3:51 a.m. The second event happens on the morning of the 30th and is best viewed from the western U.S. and western Canada. Both shadows dot the disk from 2:37 a.m. to 3:54 a.m. PST. A 4-inch telescope with a magnification of around 100× or greater guarantees success as long as the seeing conditions are steady. On each occasion, the moons precede their shadows across the Jovian disk. See if you can spot them, too!

Want to dig deeper? Observers with 10-inch or larger telescopes can seek out the irregular-shaped moon Himalia, which was discovered photographically in 1904. At about 170 kilometers (106 miles) across, it's the sixth-largest Jovian satellite and the brightest outer moon. Himalia has an orbital period of 248 days and stands nearly 1° away from Jupiter at greatest elongation. At Jovian opposition it shines faintly at magnitude 14.7, which makes it challenging to find when it's near Jupiter's glare. Try in early December when the moon lies relatively far to the southeast of the planet, or in early February 2025 when it's near greatest western elongation. Use your favorite charting software to pin down the satellite's precise location amongst the stars. Since Himalia moves around 20″ per hour (roughly half a Jupiter diameter) in December, its shifting position will betray its nature in a just few hours.

Jupiter's belts and zones merit frequent telescopic inspection. Since the planet rotates in a little less than 10 hours, if you observe the Jovian disk at the same time on successive dates, you'll see the entire planet in just a few nights.



Start with the prominent North and South Equatorial Belts (NEB and SEB) that stripe the planet and enclose the bright Equatorial Zone (EZ). In smaller scopes the belts may look gray. But in an 8-inch or larger instrument with magnifications of 250× or higher, not only will the lush textures of the belts become apparent, but so will their distinctly rusty hues. Extending from the south side of the NEB into the EZ you'll occasionally notice curved, bluish-gray wisps of clouds called *festoons*. Next easiest to see after the equatorial belts — at least in recent years — has been the South Temperate Belt (STB), which is located just south of the southern edge of the SEB.

▲ Light from Jupiter created this silhouette of the author's camera and tripod projected on his garage door last October when the planet was near opposition.

The planet's best-known feature is the Great Red Spot (GRS). It's easiest to view when it transits Jupiter's central meridian. (Up-to-date transit times are listed on pages 50 and 51.) The gradually shrinking spot has become more challenging to observe in the past few years. However, planetary photographer Damian Peach found that the GRS actually measured slightly larger in a July 2024 image compared to last year's appearance. While that may be true, when I observed the feature with my 10-inch Dob in so-so seeing in early August, the pink-colored oval required careful concentration to see.

In a recent item entitled "The Origin of Jupiter's Red Spot," published in the June 2024 *Geophysical Research Letters*, Agustín Sánchez-Lavega and his colleagues indicate that the GRS we see now may be distinct from the large, dark spot first observed by Cassini in 1665. Their research suggests the GRS may be a more recent weather system first observed in 1831. You can read the complete article at **arxiv.org/pdf/2406.13222**.

Color filters can be effective for pulling out details on Jupiter. A blue filter, such as the Wratten #80A, improves the contrast of the GRS and other red features, while a green #58 will help enhance cloud-belt contrast. Filters are also effective in reducing the planet's glare. Give them a try and enjoy the Jupiter show!

JUPITER DIAGRAM: S&T; SHADOW IMAGE: BOB KING

Saturnian Moon Mergers

LIKE ITS FAMOUS RINGS, many of Saturn's bright moons are found near the planet's equatorial plane. The rings have narrowed considerably this year, making it fun to see Titan, Rhea, Tethys, and Dione cycle back and forth from one side of the planet to the other in near-linear fashion. Since we view their orbits practically edge-on, the moons occasionally make close passes to one another, almost appearing to merge along our line of sight.

Watching these pairings through a telescope gives us an appreciation for the dynamism of the Saturnian system. It's a kick to see the satellites slowly approach and depart in an hour or less. And who can deny the pleasure of seeing how close two moons can get before we can't resolve them anymore?

In December there are seven close pairings. I've listed them here along with the approximate times specified for the regions in which the events are best observed. On December 3rd at 8:52 p.m. PST, Dione is 3.2″ north of Tethys; on the 13th at 5:59 p.m. EST, Titan is 7.3″ north of Rhea; on the 18th at 8:09 p.m. PST, Enceladus is 3.8″ north of Dione; on the 19th at 6:27 p.m. EST, Dione is 5.7″ north of Tethys; on the 21st at 6:39 p.m. EST, Tethys is 1.4″ north of Dione; on the 25th at 7:37 p.m. CST, Tethys is 0.4″ north of Enceladus; and on the 29th at 7:05 p.m. PST, Enceladus is 3.4″ north of Dione.

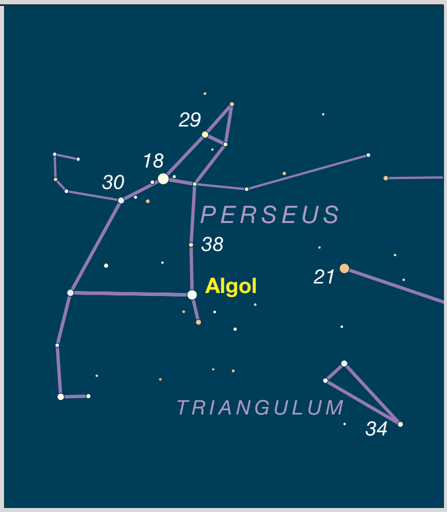
For the closest pairings, use the highest magnification that seeing conditions will allow. Take the time as well to get a sharp focus by first aiming at the edges of Saturn's rings.

You can also monitor the motions of Saturn's five brightest moons by using our interactive app, presented on the Tools page at **skyandtelescope.org**. Even a small telescope will show Titan.

Minima of Algol

Nov.	UT	Dec.	UT
3	2:42	1	18:52
5	23:31	4	15:41
8	20:20	7	12:30
11	17:09	10	9:19
14	13:58	13	6:08
17	10:47	16	2:58
20	7:36	18	23:47
23	4:25	21	20:36
26	1:14	24	17:25
28	22:03	27	14:14
		30	11:04

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



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

Action at Jupiter

DECEMBER IS OPPOSITION month for Jupiter as it hits that mark on the 7th at 21h UT. For many observers, opposition marks the start of the prime, evening Jupiter observing season as the planet rises at sunset and crosses the meridian at local midnight. The planet is currently in Taurus and far north along the ecliptic. On opposition night for observers at mid-northern latitudes, Jupiter is more than 30° above the horizon from roughly 7:30 p.m. to 4:30 a.m. local time. Jupiter gleams at magnitude –2.8 and offers telescope users a disk spanning a generous 48.2″. Turn to page 48 for more on observing this wonderfully dynamic, feature-rich planet.

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

Features on Jupiter appear closer to the central meridian than to the limb for 50 minutes before and after transiting. Here are the times, in Universal Time, when the Great Red Spot should cross Jupiter's central meridian. The dates, also in UT, are in bold. (Eastern Standard Time is UT minus 5 hours.)

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

December 1: 1:21, 11:17, 21:13;

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

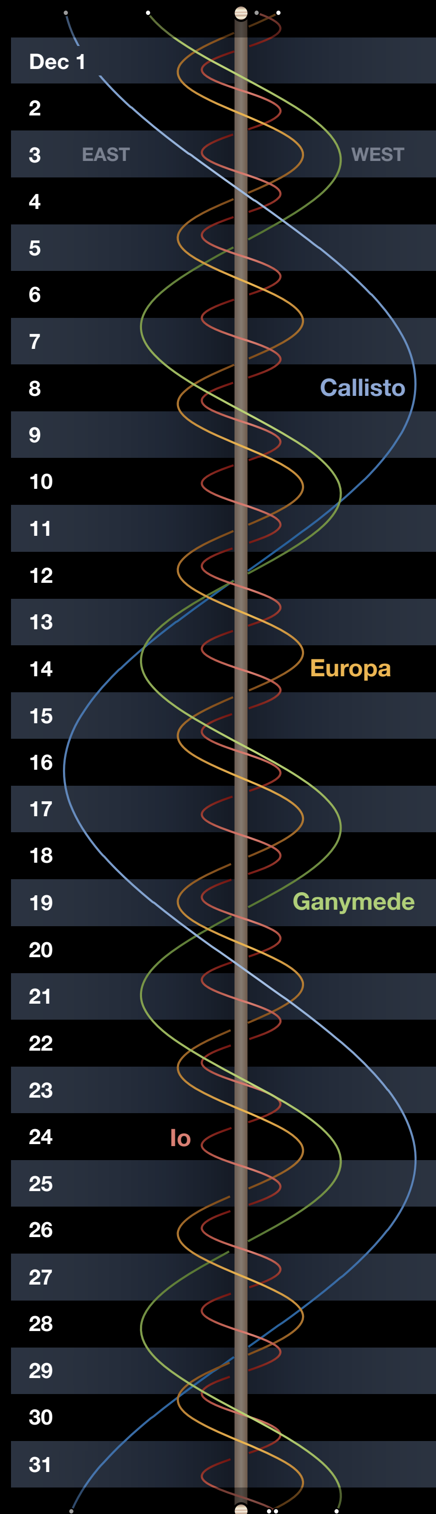
These times assume that the spot will be centered at System II longitude 66° on December 1st. If the Red Spot has moved elsewhere, it will transit $1\frac{2}{3}$ minutes earlier for each degree less than 66° and $1\frac{2}{3}$ minutes later for each degree more than 66°.

Phenomena of Jupiter's Moons, December 2024

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

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

Jupiter's Moons



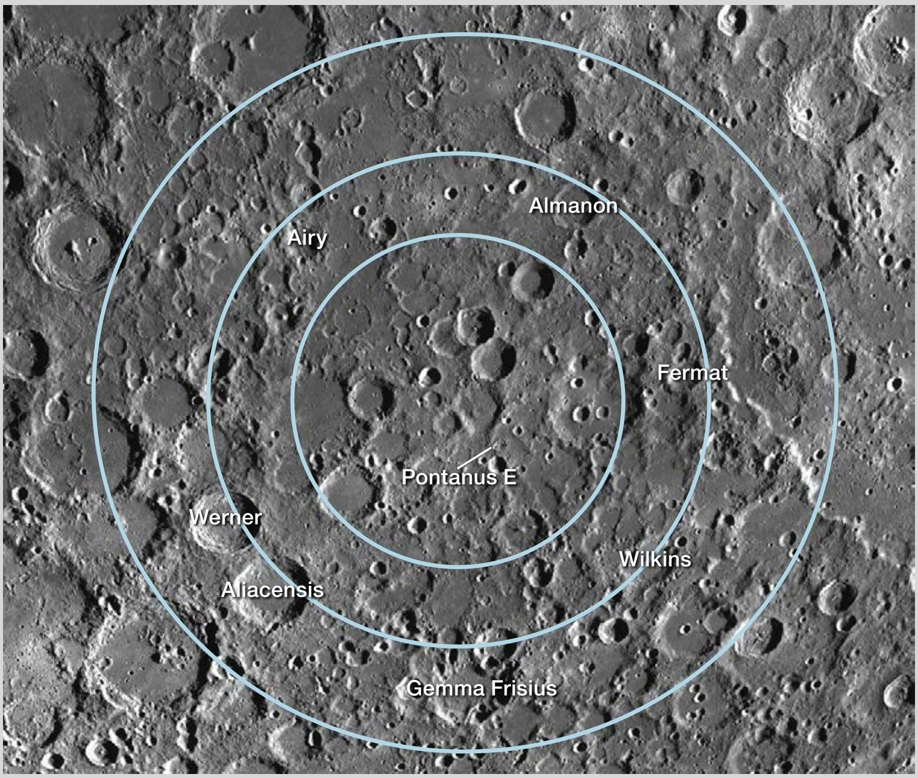
The wavy lines represent Jupiter's four big satellites. The central vertical band is Jupiter itself. Each gray or black horizontal band is one day, from 0^h (upper edge of band) to 24^h UT (GMT). UT dates are at left. Slide a paper's edge down to your date and time, and read across to see the satellites'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

The Werner-Airy Enigma

Does this lunar region contain a forgotten basin?

All parts of the lunar surface have a history, but if there are no grand craters, towering mountains, or curving rilles, that history is more challenging to discern. One such place stretches about 500 kilometers west from the northwestern extent of **Rupes Altai** scarp and nearly to Mare Nubium. This area I'm writing about is made up of neither smooth maria nor heavily cratered highlands but instead contains about a dozen large, flat-floored craters and smaller, partially rimmed, and degraded craters with light-hued, smooth material within and between the craters. What is the history of this unusual area?

More than 50 years ago, pioneer lunar astronomer Ralph Baldwin noticed that portions of this area are relatively bland and suggested that it could be the remains of an ancient, highly degraded impact basin. As the image below shows, a circle that encloses much of the area is roughly traceable clockwise from **Almanon** through **Fermat** and **Wilkins** to **Gemma Frisius** at its southern extent. It then continues northwest through **Aliacensis** and **Werner** on the west, past **Airy** to the northeast, and back to Almanon. Although this putative Werner-Airy Basin had been included in various lists of possible impact basins, most scientists discount it, for several reasons. It isn't topographically lower than its environs, it has few (if any) remnants of a rim, and NASA's GRAIL mission failed to detect any gravitational anomalies within its proposed borders — all typical basin features. However, China's recent Geologic Map of the Moon (*S&T:* Aug. 2023, p. 52) accepts the Werner-Airy feature as a basin, with rings bearing diameters of 350, 515, and 765 km. These rings are difficult to identify visually.



▲ The area above is sometimes designated as the Werner-Airy Basin. The location of the area's three concentric rings comes from the Chinese Academy of Sciences Geologic Map of the Moon.

The most common characteristic of the Werner-Airy area is its widespread patches of smooth plains. During the 1960s, such plains were commonly interpreted as old volcanic materials different from the dark, basaltic lavas making up the maria. Then in 1972 the Apollo 16 spacecraft landed just north of the Werner-Airy Basin and collected samples. But as astronaut Ken Mattingly immediately recognized, the rocks they found were not volcanic but comprised of fractured and pulverized material. Mattingly's comment was: "Well, it's back to the drawing boards, or wherever geologists go" to come up with a better theory.

Due to the Apollo 16 results, all bright, smooth lunar plains are considered fluidized ejecta from the formation of basins and large craters. And probably almost all are, but two features in the Werner-Airy Basin create a bit of uncertainty. Within the inner ring of the putative basin is **Pontanus E**, a 13-km-wide, concentric crater. Slightly more than 100 concentric craters are found on the Moon, and the majority are on or very near maria. The inner-donut-ridge of a concentric crater is thought to form by the intrusion of magma through faults beneath the crater, uplifting a ring around the floor. The existence of Pontanus E implies that magma was once under the middle of this region.

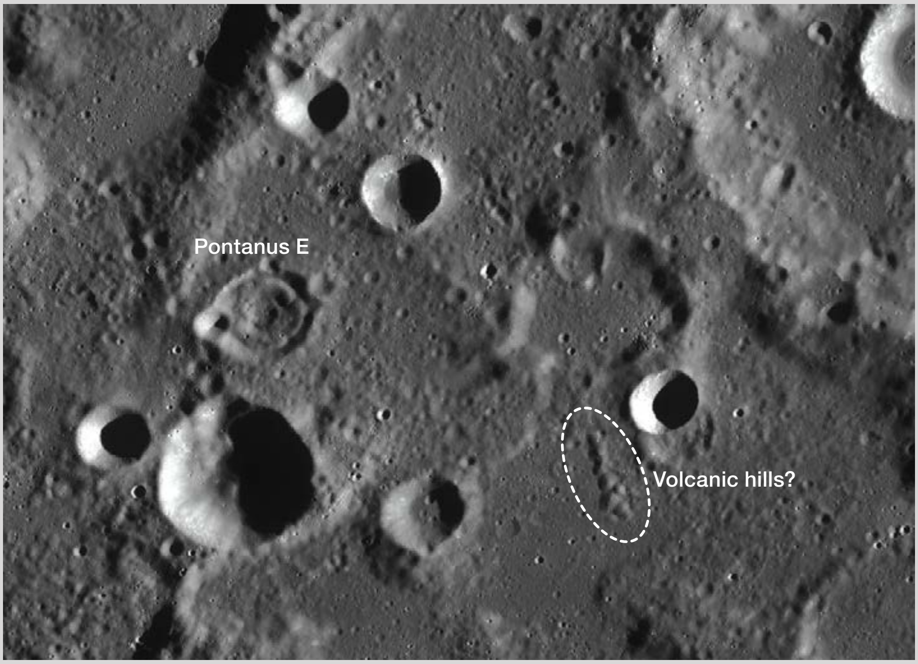
Some 50 km southeast of Pontanus E are 8 small hills about 2-3 km wide in a 12-km straight line. They are smaller and steeper-sloped than volcanic mare domes. Any one of the hills could be random topography, but being adjacent to one another and in a straight line strongly suggests that they formed by pockets of magma that erupted through a fault onto the surface. However, the features aren't dark, nor do they have compositions like mare basalts. If they are volcanic features, for some reason they have a different composition from mare lavas, or they have been blanketed by highlands ejecta.

Other than a small number of silica-rich volcanic features, such as the Gruithuisen domes, there are very few lunar magmas different from mare basalts. Thus, the concentric crater and line of hills are suggestive of unusual volcanism. However, the existence of the concentric crater and line of hills supports the interpretation that the Werner-Airy Basin could be real, because basins deeply fracture the lunar crust and provide conduits for subsurface magmas to reach the surface.

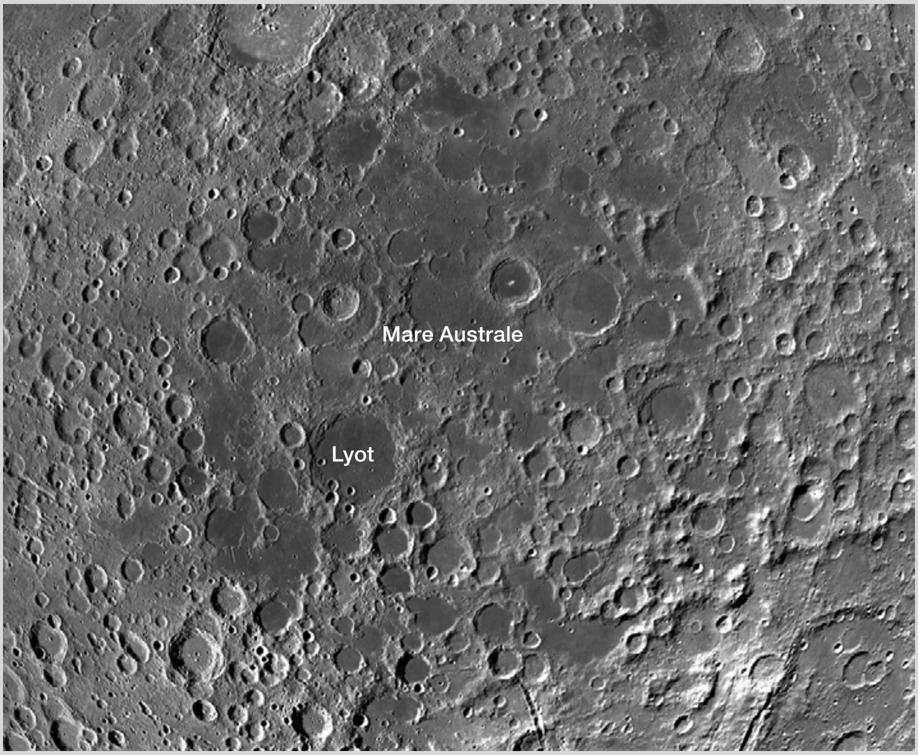
Look closely at the Werner-Airy area. It's vaguely definable, with smooth plains and more degraded craters than the surrounding terrain. Its history is clearly different. Its large size and circular shape are consistent with it being the remnant of an ancient, highly eroded basin. In fact, Chinese astronomers list it as the second oldest basin, after the 2,400-km-diameter South Pole-Aitken Basin. However, recent studies have demonstrated that every recognizable impact basin has a gravity anomaly due to the upward flow of the lunar mantle beneath. If Werner-Airy is a basin, it may have formed so early in lunar history that the Moon's thin crust wasn't strong enough to retain the topographic and gravitational anomalies of the basin, and it isostatically adjusted to erase its excavated depression and mountainous rim.

Another area quite similar to Werner-Airy is **Mare Australe** at the Moon's southeast limb. Australe is a roughly 1,000-km, near-circular, rimless, non-depressed area with smooth plains located within and between large craters. But the smooth plains are dark mare lavas, not light plains. The northern portion of Australe has a gravity anomaly and is considered a basin. But the southern portion, like Werner-Airy, has no anomaly and isn't regarded as such. And yet, somehow, deep conduits brought significant mare lavas to flood the region's craters and the spaces between them.

The Werner-Airy area has a past we don't yet understand, which is an intriguing mystery deserving detailed investigation.



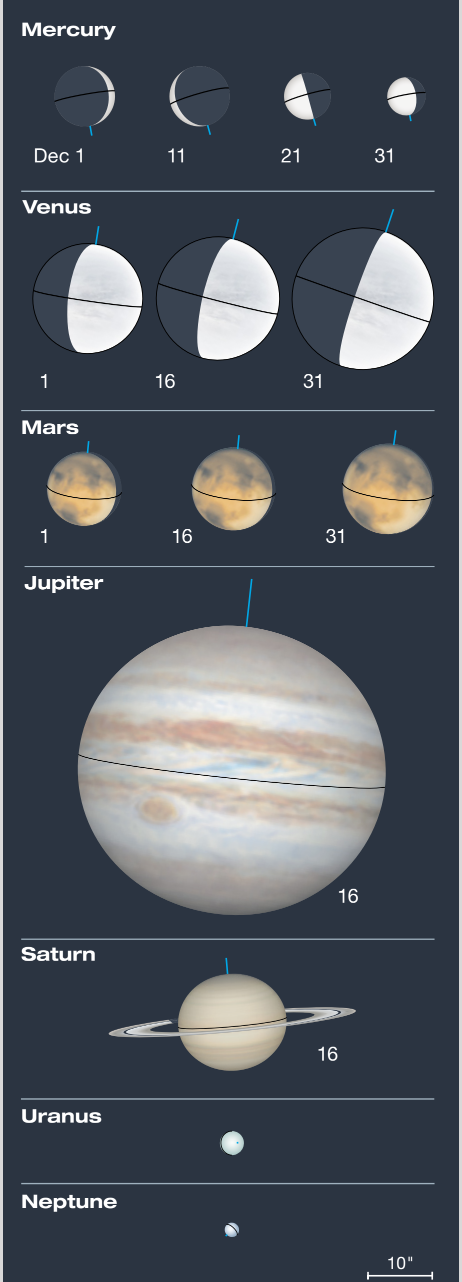
▲ The chain of hills southeast of Pontanus E (lower right) likely has a volcanic origin.



▲ With the exception of its dark maria, Mare Australe resembles the putative Werner-Airy Basin.

■ Contributing Editor **CHUCK WOOD** enjoys deciphering visual clues that hint at the history of the Moon's formation.

PLANET VISIBILITY (40°N, naked-eye, approximate) **Mercury** visible at dawn from the 13th • **Venus** visible at dusk all month • **Mars** rises in the evening and visible to dawn • **Jupiter** visible from dusk to dawn • **Saturn** transits during evening twilight and sets before midnight.



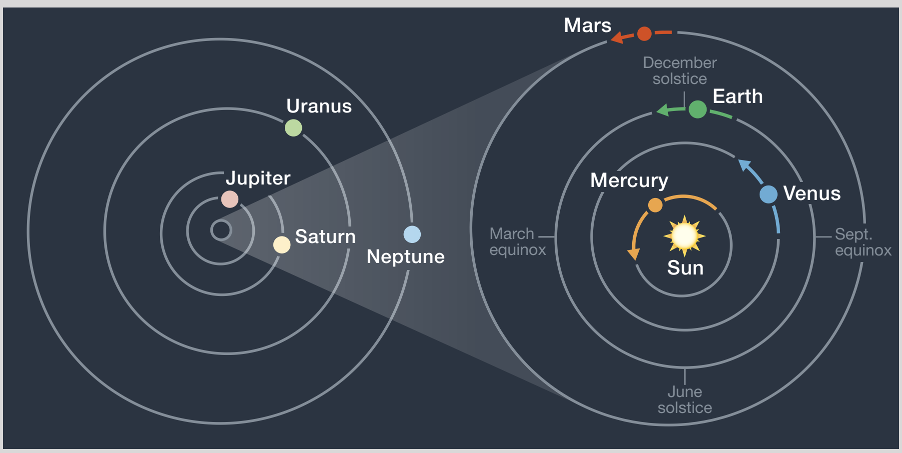
December Sun & Planets

	Date	Right Ascension	Declination	Elongation	Magnitude	Diameter	Illumination	Distance
Sun	1	$16^h 28.9^m$	–21° 47′	—	–26.8	32′ 26″	—	0.986
	31	$18^h 41.1^m$	–23° 06′	—	–26.8	32′ 32″	—	0.983
Mercury	1	$17^h 17.4^m$	–23° 23′	11° Ev	+2.1	9.4″	10%	0.715
	11	$16^h 27.5^m$	–19° 09′	11° Mo	+2.1	9.4″	10%	0.717
	21	$16^h 26.5^m$	–19° 07′	21° Mo	–0.3	7.3″	51%	0.925
	31	$17^h 09.4^m$	–21° 40′	21° Mo	–0.4	5.9″	76%	1.131
Venus	1	$19^h 38.4^m$	–23° 59′	43° Ev	–4.2	17.1″	68%	0.974
	11	$20^h 27.5^m$	–21° 32′	45° Ev	–4.3	18.5″	64%	0.903
	21	$21^h 13.5^m$	–18° 11′	46° Ev	–4.4	20.1″	60%	0.831
	31	$21^h 56.2^m$	–14° 08′	47° Ev	–4.5	22.0″	56%	0.758
Mars	1	$8^h 34.5^m$	+21° 21′	123° Mo	–0.5	11.6″	93%	0.806
	16	$8^h 33.9^m$	+22° 05′	139° Mo	–0.8	13.0″	96%	0.718
	31	$8^h 20.3^m$	+23° 31′	157° Mo	–1.2	14.2″	99%	0.659
Jupiter	1	$5^h 03.1^m$	+22° 06′	172° Mo	–2.8	48.2″	100%	4.094
	31	$4^h 46.5^m$	+21° 45′	154° Ev	–2.7	47.1″	100%	4.183
Saturn	1	$22^h 58.8^m$	–8° 45′	94° Ev	+1.0	17.4″	100%	9.527
	31	$23^h 04.5^m$	–8° 05′	65° Ev	+1.1	16.6″	100%	10.010
Uranus	16	$3^h 25.8^m$	+18° 28′	150° Ev	+5.6	3.8″	100%	18.701
Neptune	16	$23^h 50.3^m$	–2° 28′	93° Ev	+7.9	2.3″	100%	29.833

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

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

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



Holiday Gadgets for Astrophotographers

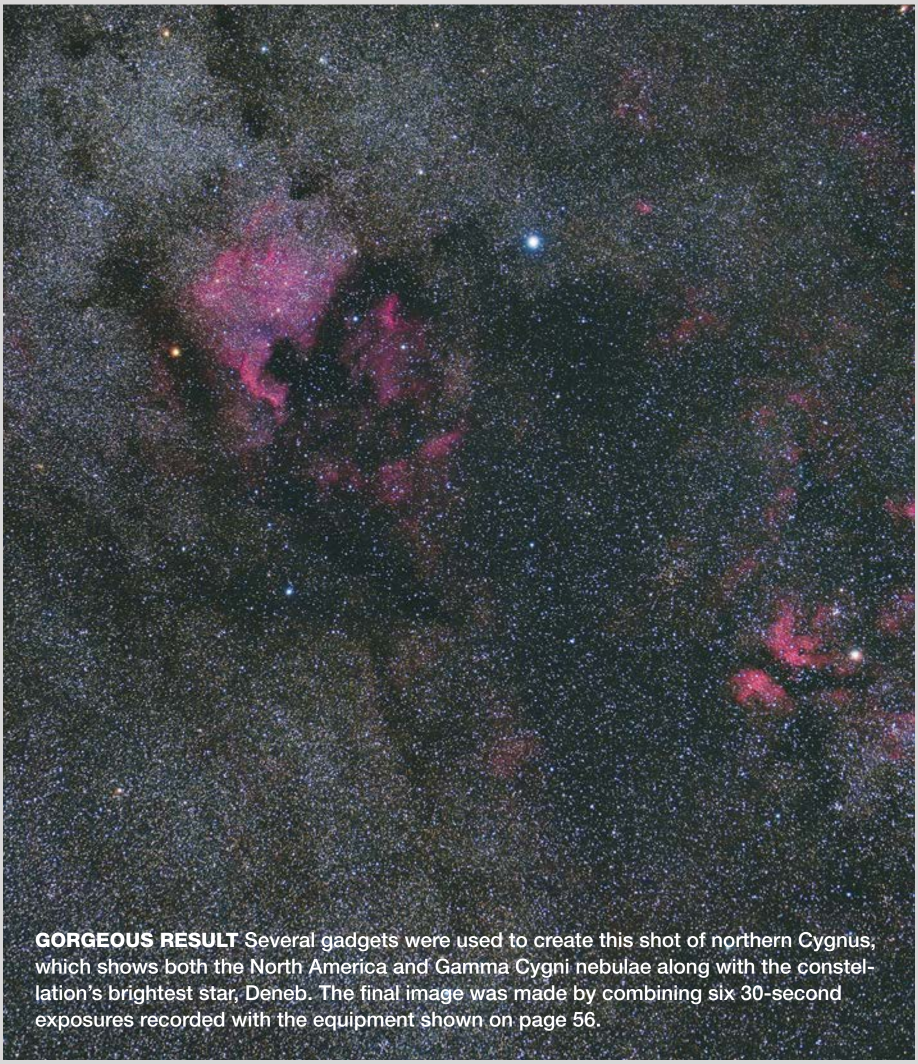
Get your credit card warmed up — it's goodie-buying season!

It's that time of year. You know what I mean. Wherever you are, you're probably shopping . . . or at least thinking about it. It might be a gift for others. It might be a gift for yourself. It might just be the fact that everything is on sale and you're being bombarded by non-stop advertising, but it's hard to deny it's shopping season. In light of that, this month we thought it'd be fun to put together a small gift guide for the aspiring (or even, experienced) astrophotographer.

So, here we go!

Going Steady

Aside from a camera, a good **tripod** is the most useful piece of astrophotography gear you can own. And yet, it's often the most underestimated in terms of importance. Sure, a handheld smartphone can capture and stack short exposures, but nothing beats the quality jump that you get when you can extend the exposure time, by at least a little bit.



GORGEOUS RESULT Several gadgets were used to create this shot of northern Cygnus, which shows both the North America and Gamma Cygni nebulae along with the constellation's brightest star, Deneb. The final image was made by combining six 30-second exposures recorded with the equipment shown on page 56.

ALL IMAGES COURTESY OF THE AUTHOR

Even an inexpensive tripod will do an infinitely better job of steadying your camera than you can by hand alone. Like many things in life, however, you get what you pay for. Most low-end models don't move smoothly from one position to another — the tripod head shifts in frustrating fits and starts. Or perhaps, after you've taken the time to carefully frame up the view, the backlash shifts the camera off target when you tighten the lock knobs down. You end up playing that game where you intentionally overshoot your target so that when the camera settles into place, it's aimed close to where you want it.

Weight can also be a factor — especially if you travel with your gear. A carbon-fiber tripod is very light but tends to be more expensive than models made with more conventional materials.

Sometime in the last epoch (when camera stores were still a "thing"), I was surprised to find that top photographers often buy tripods and tripod heads separately — similar to how advanced amateur astronomers often purchase an optical tube assembly (aka a telescope) and mount separately. Doing so makes it easier to mix and match to ensure you get exactly what you need.

If your budget allows it, I'd advise spending upwards of $100 for a good tripod and perhaps a similar amount for either a quality ball-head or 3-way pan/tilt head. Read online reviews and maybe reach out on photographic forums for recommendations.

For the Smartphone Set

While a tripod is an essential piece of gear if you have a DSLR or mirrorless camera, it's also extremely useful if you mainly photograph with your smartphone. To do so, you'll need a **smartphone tripod adapter**. This gadget lets you attach your phone to a regular tripod to allow for long-exposure nightscape shots. I'd also recommend a small **Bluetooth remote** to trigger your phone's camera remotely without having to touch (and thus, shake) the device. These work with both Apple and Android devices, and with many third-party photo apps as well. Shop around — it's possible to get a tripod, adapter, and Bluetooth remote bundled together for very little money.

Another great gadget is a **smartphone telescope adapter**, which helps correctly position your phone's camera lens with your telescope's eyepiece so you can harness the magnifying power of your scope. Deep-sky astrophotography done this way is challenging, but quick snapshots of the Moon and planets are pretty easy. You can even capture sunspots if your telescope is equipped with a safe solar filter. At outreach events, I use a smartphone adapter to let visitors take their own close-up photos of the Moon — it's a huge hit. There are several models from numerous manufacturers to choose from. A basic unit starts at around $20.

Easy Automation

If you already have a tripod and interchangeable-lens camera, the next gadget on your wish list should be a **remote shutter release**. Most cameras have a socket to accommodate one of these. A remote shutter release allows you to start an exposure without touching

◄ **DREAM TEAM** The rig portrayed here consists of a Canon EOS Ra DSLR camera, 70-to-200-mm f/2.8 zoom lens, and Sky-Watcher Star Adventurer GTi portable multipurpose mount. A top-of-the-line star tracker like this one isn't inexpensive, but it's still airline-portable and can even support a small telescope. This collection of gear is capable of producing a wide range of stunning results, including the astrophoto shown on the previous page.

the camera. For most camera models, you also have the option of a wireless remote, but with these you're typically restricted to the longest exposure time your camera will do on its own. If you want to expose for longer than 30 seconds (the maximum for most cameras), you need to put the camera in Bulb mode and lock the shutter-release button for the duration of the exposure, however long you wish it to be.

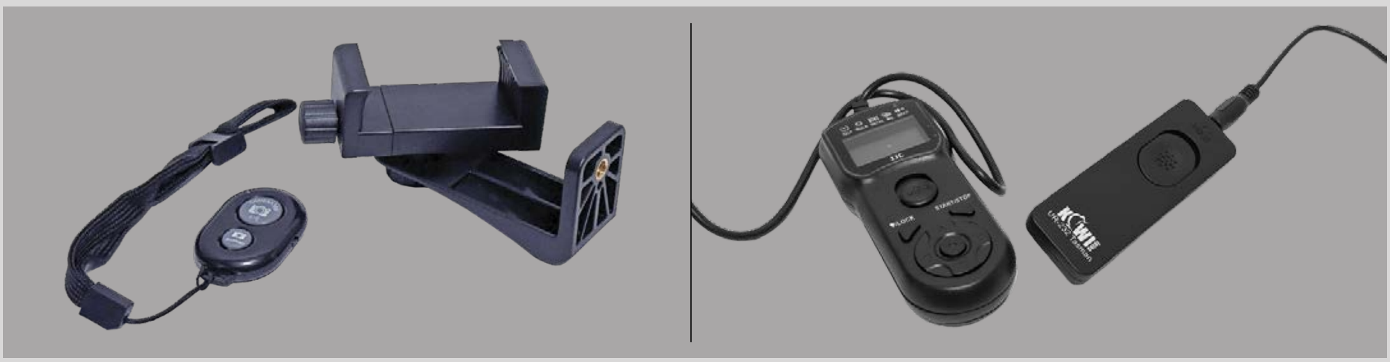
Even more useful is an **intervalometer**. Yes, it's true than many cameras allow you to use an intervalometer app on your mobile device, but a proper external intervalometer is much more versatile. For example, if you want to do a star-trail sequence that requires 120 one-minute exposures, you'd have to stay within range of your camera and leave the app running in the foreground for two hours!

An intervalometer is a handy, self-contained programmable timer that automates the process of capturing multiple exposures. You can set the exposure length, the number of shots, and even program in a delay between exposures if you like.

Once the device is up and running your sequence of shots, you can walk away and do some observing while the intervalometer happily keeps your camera clicking away. They're great for star trails (*S&T:* Aug. 2024, p. 55), capturing multiple sub-frames of a given target, and for time-lapse videos. An intervalometer can even replace your standard remote shutter release. In fact, unless you're really determined to keep things as simple as possible, I can't imagine why you wouldn't just get an intervalometer instead.

You'll have to be sure to purchase an intervelometer designed to work specifically with your make and model of camera. However, "off brand" units are available and generally cost far less than those made by the camera manufacturers themselves. Expect to pay in the

▼ **SMART SOLUTIONS** *Left:* You can mount your smartphone on a tripod with a simple, low-cost adapter bracket. This unit came bundled with a Bluetooth camera shutter remote (left of the bracket) that works with both Apple and Android devices. **JIGGLE-FREE SHOOTING** *Right:* Either an intervalometer (device at left) or a simple, locking shutter release (right) is an essential accessory for any nightscape photographer. The intervalometer allows you to set up an automated exposure sequence, while the shutter release facilitates single, long exposures with your camera in Bulb mode.



neighborhood of $25 for a wired model and double that for a wireless one.

Star Tracking

Deep-sky astrophotographers know that a polar-aligned equatorial mount is a necessity for avoiding star trails in long-exposure photos. But the large and heavy equatorial mount that your telescope rides on is usually overkill for just a camera and a lens. Thankfully, there are many smaller and more portable options. A battery-powered **star tracker** will keep stars from trailing in long exposures. How long an exposure you can do depends only on your sky conditions, the accuracy of your polar alignment, the quality of your star tracker, and the focal length of your lens. Nothing beats going deep and long when it comes to night-sky shots. Take several one-minute or so exposures (using your brand-new intervalometer) and align and stack them together to create a low-noise image with deep details.

Star trackers are ideal for the traveling astrophotographer as well. Most units can easily go in carry-on luggage or a backpack. You can hike to a remote location, set up your camera, tripod, and star-tracker, and shoot to your heart's content — at least until the batteries die.

Once again, there are several models to choose from, and you can pay around $200 and up, depending on the model and what accessories are included.

LUNAR PRIZE Close-up shots of the Moon using the afocal method (aiming your smartphone camera lens at the eyepiece of your telescope) can produce surprisingly satisfying results, as this photo shows. The key is positioning your smartphone correctly over the eyepiece — something a device such as the Celestron NexYZ 3-Axis Universal Smartphone Adapter used for this image makes easy.

Classy Glass

For the big spenders out there, one of the most impactful investments you can make is a **fast lens** for your camera. When we say "fast" what we mean is a lens that lets in a lot of precious light relative to its focal length. And more light means shorter exposures and cleaner images. If you're a nightscape photographer struggling with your camera's f/3.5 kit lens, an f/2.8 upgrade will revolutionize your efforts. But the ultimate is an f/1.4 wide-angle lens, which makes capturing the night environment about as easy as it gets.

Typically, such a lens will let you capture the Milky Way in stunning detail with only a 10-second exposure — short enough to avoid star trails even with a camera mounted only on a tripod. Such an optic makes constellation shots and panoramas a cakewalk.

Of course, premium optics come at a premium price, so you want to be sure you get full value for your money. I usually won't buy a lens without trying it first — an approach I highly recommend. Go to **lensrentals.com** and see if they have the model you're interested in. I rented my latest fast lens through them and took advantage of their "Keeper Test Drive" program, which allowed me to simply buy the lens instead of returning it — the rental fee went toward the purchase price.

Buying brand-new photographic gear is a lot like buying an automobile — as soon as you pay for it, it starts to depreciate. But that's also why used equipment can be a good buy. A well-cared-for lens can perform just like new, but at significant savings. Shop around.

Hobby Happy Holidays

Every time I complain about astrophotography being an expensive hobby, I just remember my friends who are into golfing, boating, or jet skiing. Now *those* are expensive hobbies! Keep your budget in mind and weigh the benefits against the costs of any new gadget purchase. Some of the items listed here can be pretty inexpensive — and sometimes "cheap and inferior" gear is far better than no gear at all. Consider the kinds of astrophotography you like to do — or aspire to do — and let that guide your buying decisions. If you do that, you're more likely to end up with something you'll actually use.

Just don't max out your credit card!

■ Contributing Editor **RICHARD S. WRIGHT, JR.** loves the dopamine rush he gets from astrophotography. But when the weather is poor, he gets his dopamine by shopping instead.

Slashes in the Sky

Spend some time on winter nights observing flat galaxies.

▲ **THIN STREAKS** The delicate flat galaxy FGC 2379 lies in the shadow of NGC 7241. Some flat galaxies not only appear exactly edge-on but also lack any pronounced bulge. They look as if the sky had been slashed with a fine scalpel.

Being able to see complex features, such as spiral arms in galaxies, is a rare skill. However, we are hardwired to detect straight edges. Our eyes are drawn to them when we point our telescopes at "flat" galaxies. But even the famous edge-on Splinter Galaxy, NGC 5907, still shows something of a bright bulge in the middle, so you might be wondering: Are there any galaxies that are truly flat? Yes! In fact, the *Flat Galaxies Catalogue* (FGC) lists more than 4,000 of these marvels, enough for a lifetime of exploration.

While studying collective motions of galaxies in the nearby universe, Russian astronomer Igor Karachentsev discovered a relationship between a galaxy's optical and radio properties that could be used to derive its distance independently of redshift. He published his findings in 1989 in the *Astronomical Journal*. The relationship was the most precise for edge-on galaxies whose length on photographic plates was at least seven times their width — in other words, *flat galaxies*. In 1993, Karachentsev and his colleagues compiled a catalog hoping it would serve as a source of targets professional astronomers could use for measurements that would yield a wealth of cosmographical information. Within a decade, however, amateur astronomers started to dip into the catalog to pursue its brightest members as observing targets.

As one might expect reading this column, "bright" is a relative term when it comes to the *Flat Galaxies Catalogue*. Few of its members exceed magnitude 14 — the aforementioned Splinter Galaxy, which is cataloged as FGC 1875, is one of the brightest at magnitude 10.3. To get a taste of the more typical flat galaxies in the December sky, set up the biggest scope you have under a dark sky and sample the starter course below.

Flat Galaxies

Catalog entry	UGC designation	Surface Brightness	Mag(v)	Size	RA	Dec.
FGC 2070	UGC 10561	13.7	14.3	2.3′ × 0.3′	$16^h\ 46.6^m$	+62° 49′
FGC 2250	UGC 11435	13.5	14.2	2.0′ × 0.3′	$19^h\ 23.8^m$	+55° 59′
FGC 2255	UGC 11455	14.4	14.3	2.6′ × 0.5′	$19^h\ 30.0^m$	+72° 07′
FGC 2360	UGC 11893	14.7	15.4	2.1′ × 0.3′	$22^h\ 04.1^m$	+33° 56′
FGC 2385	UGC 11994	13.5	14.0	2.3′ × 0.3′	$22^h\ 20.9^m$	+33° 18′
FGC 2379	UGC 11964	13.1	14.3	1.9′ × 0.2′	$22^h\ 15.5^m$	+19° 13′

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.

NGC 2379: GARY IMM; ALL SKETCHES BY IVAN MALY; ALL DSS IMAGES: POSS-II / STSCI / CALTECH / PALOMAR OBSERVATORY

In Draco's Coils: FGC 2070, FGC 2250, FGC 2255

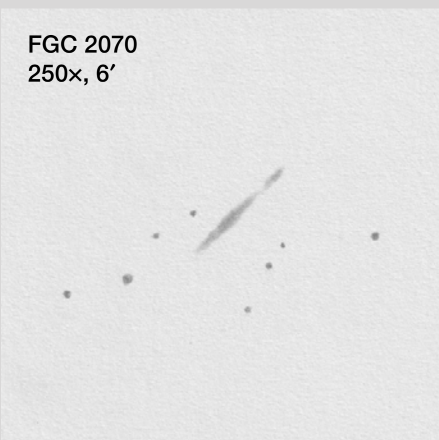
Look some ¾° southeast about halfway along the line connecting the 3rd-magnitude stars Eta (η) and Zeta (ζ) Draconis to find **FGC 2070**, a beautiful, little, 14.3-magnitude edge-on galaxy that deep images show is bisected by a dust lane. Even on an exceptional night with steady seeing conditions, I was unable to detect the dark lane in the Buffalo Astronomical Association's 20-inch telescope, the instrument I used for all the observations included here. The galaxy appeared as a long and asymmetric slash through the sky background, flanked by two rows of stars as portrayed in my sketch below. (All sketches represent the view through the 20-inch telescope and with north up.) The westernmost of these stars is visual magnitude 16.9, which indicates the depth of view that our skies afforded that night.

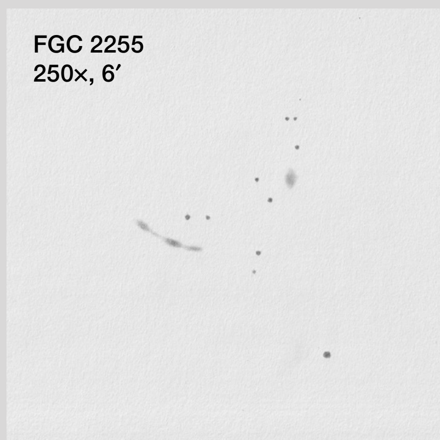
When observing flat galaxies, I find myself using somewhat lower magnifications than I usually employ on challenging targets. In the best view at 250×, FGC 2070 displayed no distinct core and tapered smoothly to its pointed ends, only to continue after a gap with a visually separated star cloud to the northwest. Deep images show this feature to be a bend in the spiral arm. That's right: If you look for subtle clues, you can detect spiral structure in an ultra-thin galaxy 270 million light-years away!

Moving through our sampler in increasing right ascension, we next come to 14.2-magnitude **FGC 2250**. It's in Draco, but you'll find it most easily by pointing 2¾° north-northwest of Kappa (κ) Cygni, which marks the left wingtip of the Swan. The reported major-to-minor axis ratios for this galaxy run as low as 5.9 (a bit below Karachentsev's seven-times cut-off), so this is one of the galaxies in the catalog that's not exactly edge-on. However, classified as a late-type spiral, it lacks a pronounced bulge in photos. In the 20-inch, I could see a small core that was no brighter than the rest of the galaxy, a shallow arc attached to it on the north side and running west, and a fainter, sharply curved arm on the eastern end.

A diamond arrangement of four stars lay to the galaxy's west, with the easternmost star at magnitude 16. In g-band images, whose spectral sensitivity is similar to our dark-adapted vision, the arms are clumpy, as is typical of late-type spirals, with loosely wound arms. Try increasing the magnification under very dark skies to see if it will show this fine structure to you.

To arrive at our next target, move north to 3.9-magnitude Epsilon (ε) Draconis and from there another 2⅓° northeast to find 14.3-magnitude **FGC 2255**. Images reveal a fine needle with a fainter splinter of light separated by a dark lane. Visually at 250×, I see something more like a string of objects that stretch east to west. The brightest of these is at the position of the galaxy's core. The thin feature shown in my sketch below connects to the core from the west, corresponding to the arm that curves around that end of the galaxy. On the eastern end, a droplet of light seemingly dangled, barely connected to the core. This is the opposite arm, which in photos is separated by the dark gap. The visual appearance also captures the curvature of the galaxy's southern edge — the three light patches seem to be strung along a shallow arc. When going for these features, test the depth of your view by looking for the dim companion to the 14.5-magnitude star directly north of the galaxy's core: It glows feebly at magnitude 16.4.





In Pegasus: FGC 2360, FGC 2385, FGC 2379

Karachentsev didn't include the famous dusty edge-on galaxy NGC 891 in the *Flat Galaxies Catalogue*, even though it has a major-to-minor axes ratio of 7. But to see its virtual twin, which is much farther from us than NGC 891, scan some 3° north-northwest of 4th-magnitude Eta Pegasi. **FGC 2360** (magnitude 15.4) lies exactly edge-on and has a bright — though flat — core and is bisected by an equatorial dust lane in photographs. At a magnification of 150×, I saw the nucleus as nonstellar, and the galaxy's core appeared boxy. Sharp-edged extensions stretch to the east and west, tapering gradually. The compact galaxy PGC 67957 hung in the eyepiece field some 4′ to the northwest. I couldn't detect any trace of FGC 2360's equatorial dust band (which is 2″ across) that night. Make sure you search for this feature when seeing conditions are steady.

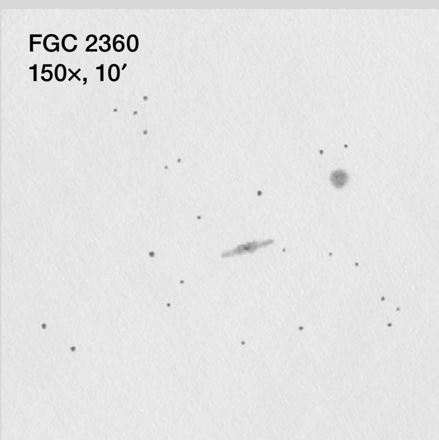
Return to Eta Pegasi and slew 2¼° east to arrive at **FGC 2385**, which you should see less than 2′ southwest of 9.6-magnitude TYC 2737-1324-1. Visually, the 14.0-magnitude galaxy stretches from a field star on its eastern end, first broadening to a modest core then tapering again. Continue scanning with averted vision along the same line until you detect another patch of light, tenuously connected to the core. In photographs, this is the counterpart to the peripheral disk that extends past the star on the opposite end. Visually, I could only see the farthest extent of the galaxy in the western direction, likely due to the interference with the light of the embedded star. Trace the outermost reaches of the galaxy to the east and see how far you can go.

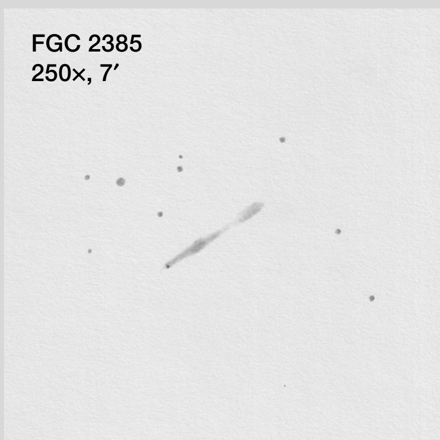
To round off our tour, drop south past the front legs of Pegasus and scan a bit less than 6½° south-southeast to find **FGC 2379** — the galaxy is only 4′ west of 12.6-magnitude NGC 7241. While the NGC object itself is strongly inclined to our line of sight, FGC 2379 has a major-to-minor axes ratio of 13! This makes it the flattest galaxy in our list. Here, however, we come to the limit of what we can see in the eyepiece. At least I did. The minor axis is a mere 12″ long, and the galaxy's magnitude is 14.3 — this feeble light is spread out over nearly 2′ along the length of the major axis. What this amounts to in terms of contrast perception (which defines resolution in visual observing) is that I could only detect the central portion of the galaxy. And it appeared much thicker than its tabulated dimensions. Try to see this flat galaxy as a *flat* galaxy — it will test you, your telescope, and your sky.

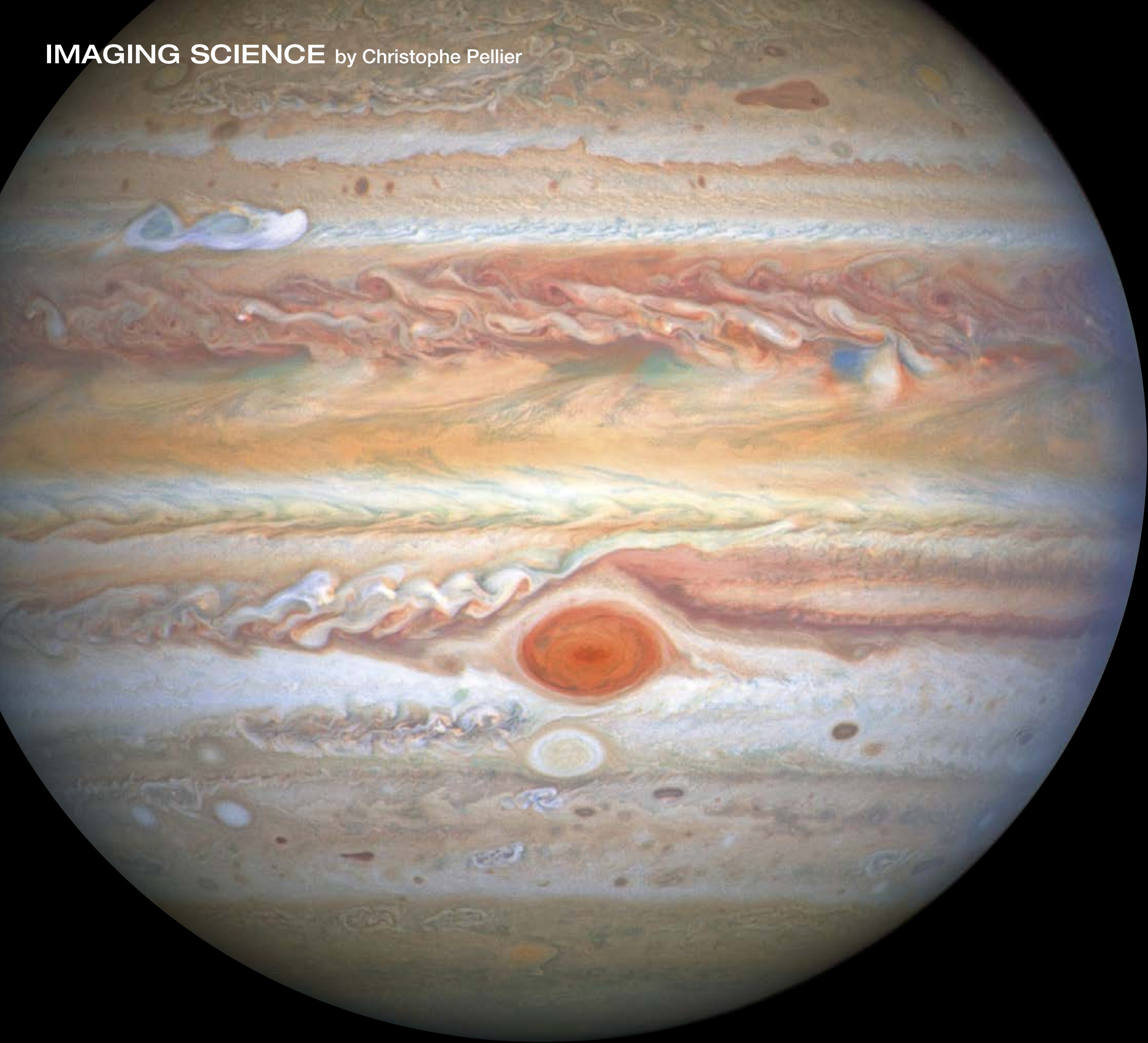
Has the sampler been appetizing? Wondering what's beyond? The Astronomical League has assembled a list of a couple hundred flat galaxies that are perhaps the most accessible to amateurs — you'll find the table at **https://is.gd/AL_flat_galaxies**. (Al Lamperti, whose name you might recognize as the author of, among other things, several Going Deep columns, is the program coordinator.) The book *Observing Flat Galaxies* by Alvin Huey will guide you through another fine selection. And in 1999, Karachentsev and his colleagues published a revised version of their catalog that you'll find in electronic format at **https://is.gd/FGC_1999**.

Whichever way you choose to go about it, happy hunting!

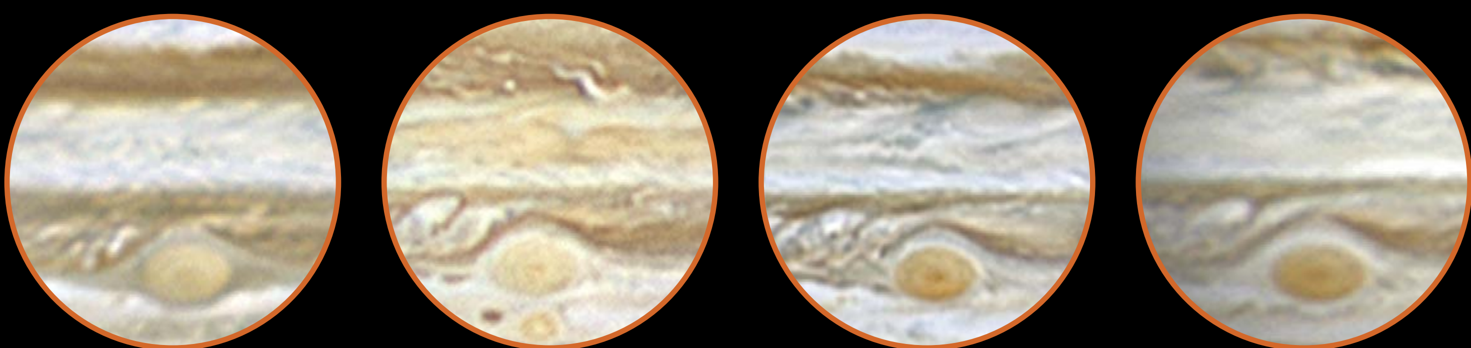
IVAN MALY is a fixture at his astronomy club in upstate New York. His website is at **www.deepskyblog.net**.







Planetary Photometry:



2011 2012 2013 2014

Color as Information

How to get more science out of your solar system images.

Amateur astronomers have long been the primary resource for monitoring the planets. Typically, we enjoy taking color images of the planets with the primary goal of resolving fine details. These pretty pictures help us follow dust storms on Mars as they develop, turbulence in the upper clouds of Venus, or upheavals in the atmospheres of the outer giant planets. Amateurs' contributions are especially valuable because professional astronomers have neither the equipment nor the resources to focus on the major planets for extended periods (unless a spacecraft is visiting one of them).

But there's more to color images than just pretty pictures — they contain valuable information about ongoing phenomena in the atmospheres of the bodies within the solar system. It's difficult to monitor subtle changes visually at the eyepiece and in photographs, but through the use of photometric filters, imagers can expand the amount of useful data they record, which can enrich our understanding of our neighboring worlds. Here's how to do it.

Photometry and Color

Photometry allows us to improve our understanding of celestial objects by analyzing the intensity of light we receive from them in different wavelengths.

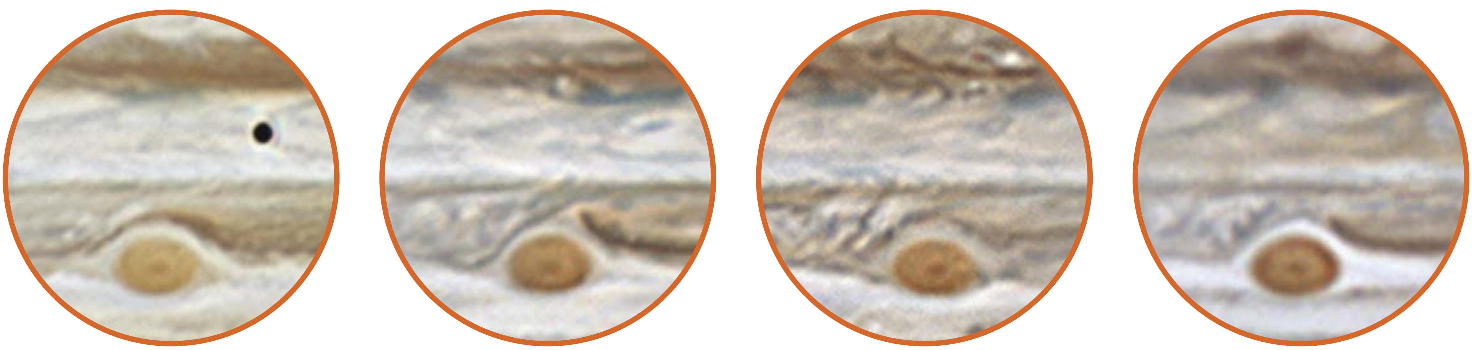
In planetary science, the key to measuring color is its *albedo* — the amount of sunlight a surface reflects. This measurement is typically expressed as a percentage, or on a scale from 0 (having no reflection) to 1 (perfect reflection). Albedo explains why objects have color. For example, a blue object displays a higher albedo in blue than in green, and even more so with respect to red wavelengths. This is readily apparent if you compare the color channels of an image in a graphics program such as *Adobe Photoshop*. Accurately measuring the differences in albedo requires a change in one's approach to planetary imaging.

An excellent visual manifestation of albedo changes is the evolution of the color of Jupiter's Great Red Spot (GRS). From 2014 to 2020, the GRS reddened noticeably, with the deepest color occurring in the 2018 apparition. Experienced amateurs active before 2000 will certainly remember when the GRS was a pale, pink feature hardly visible at the eyepiece. Observers often only detected it due to the presence of its bright, whitish Red Spot Hollow, which the storm draws from the South Tropical Zone.

Changes in the brightness and color of the GRS are fairly obvious, but other planetary phenomena may only be detected through photometry. For example, using photometric measurements scientists find that the albedo of the planet Venus at ultraviolet (UV) wavelengths can double in a matter of a few years. The highest value of 40% albedo occurred in 2006 then slowly decreased for six years, reaching a low of 20% in 2012 before the trend reversed. This is a significant change yet would hardly be discernible when comparing images from the two periods — the only way to detect this is to measure the intensity of the light reflected from the planet through photometry.

Photometric Technique

So, how do you perform photometric measurements of the planets? The method I prefer is *differential photometry*, as described by the American Association of Variable Star Observers (AAVSO) at **https://is.gd/photometryguide**. This technique compares the measured intensity of the targeted planet to that of known reference stars across multiple wavelengths.



2015 2016 2017 2018

▼ **VARIABLE PLANET** These images show Jupiter's central region between 2011 and 2018. Each year, the planet displays striking variation in the colors of its belts and zones, and the Great Red Spot's brightness and hue change noticeably. But how can we measure such variations?

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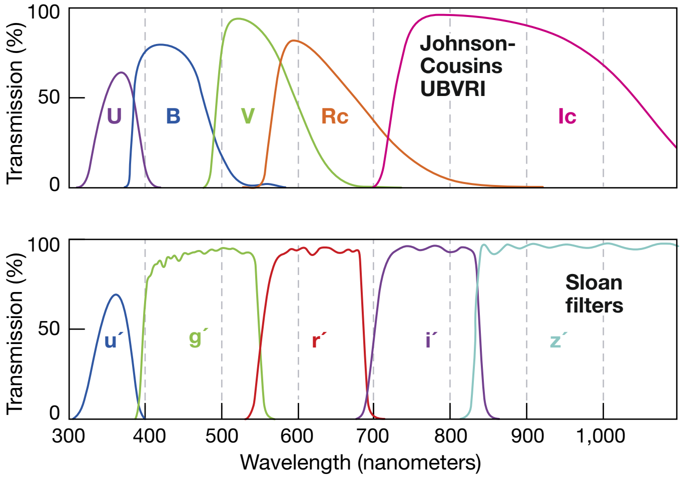
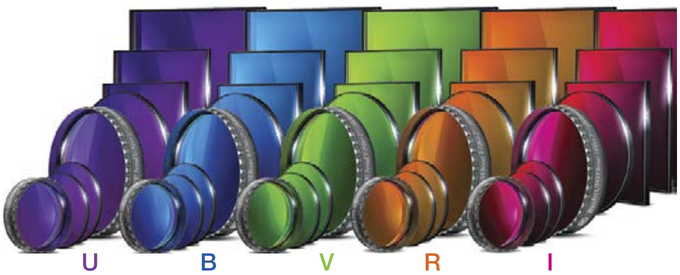




▲ **PHOTOMETRIC FILTERS** Of the two primary types of photometric filters in use today, the Johnson-Cousins UBVRI system offers the best color separation for planetary imagers.

For example, if Uranus is measured having the same intensity in the B band as that of a nearby 6th-magnitude star, then we can conclude that Uranus's magnitude in that band is also 6. But it's more complicated than that — corrections are needed, because your optical system never exactly matches that of the reference system, and because our atmosphere affects the intensity of objects at different wavelengths and altitudes.

The photometric filters (known as a *photometric system*) that I use are the Johnson-Cousins U, B, V, Rc, and Ic, with a few filters from the Sloan system (the z' band as well as the associated Y band offered by certain manufacturers). In addition, I often image Jupiter through the non-photometric wavelength of methane, the CH_4 absorption band at 890 nanometers, as it penetrates deeper within the planet's atmosphere (which is particularly important when studying the gas giant).

These days, the Sloan system has superseded the Johnson-Cousins one as the standard for stellar photometric measurements. I find the Sloan filters less suited to studying the planets, though, particularly because the Sloan g' band passes both the green and blue wavelengths.

Several manufacturers offer photometric filters as well as methane filters, including the Andover Corporation (**andovercorp.com**), Asahi Spectra (**asahi-spectra.com**), Baader Planetarium (**baader-planetarium.com**), Chroma (**chroma.com**), and Optolong (**optolong.com**). Note that some offer a variation of the Johnson-Cousins filters called Johnson/Bessel, or simply Bessel.

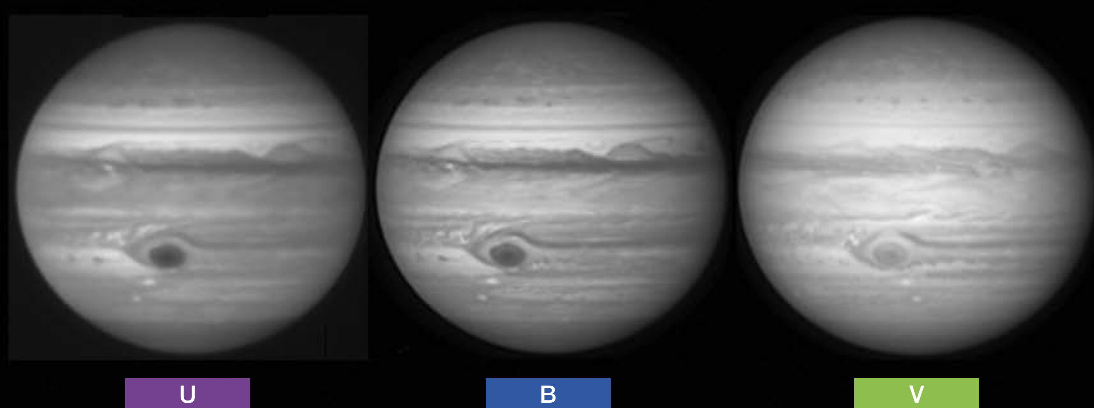
Performing photometry on planetary images is challenging, because the comparison star should be captured in the same field as the target, using the same gain setting. Planets rarely pass near suitable comparison stars, especially at the high magnification necessary to resolve individual features on their surfaces or cloudtops — I compromise by observing known reference stars at the same elevation as the planet in the same general area of the sky. The accuracy of these measurements isn't as high as with true differential photometry, but I achieve a level of precision on the order of a few hundredths of a magnitude, which is sufficient for this work. Observing more than one comparison star and averaging the results increases my accuracy.

For Jupiter, I've also occasionally used the Galilean moons as photometric references. This may seem unorthodox, since the moons aren't steady sources of light like known comparison stars. But if you know the magnitude of one moon, it's fairly easy to determine Jupiter's magnitude, particularly since both bodies can be recorded in a single field — which is exactly how differential photometry should be performed.

As for the equipment, it's important to use a mono-

GRAPH: GREGG DINDERMAN / S&T, FILTER IMAGES: BAADER PLANETARIUM

▶ **SPECTRAL SPREAD** This series of Jupiter images was taken through each of the Johnson-Cousins photometric filters. Note how the highest contrast is seen in the ultraviolet (U) and blue (B) wavelengths and decreases as the wavelength increases or reddens.



chrome camera equipped with a color filter wheel loaded with photometric filters. Most any cooled or uncooled camera is suitable, as you won't be taking extremely long exposures. So the one you may already be using to photograph the planets should suffice.

You also need to know the pixel scale of your entire system. For example, I use a 12-inch (305-mm) telescope operating at a focal length of 1,500 with a camera equipped with a Sony IMX290 sensor having 2.9-µm-square pixels. Using the formula 206.265 × (*pixel size*) / (*focal length*) yields an image scale of 0.4 arcsecond per pixel.

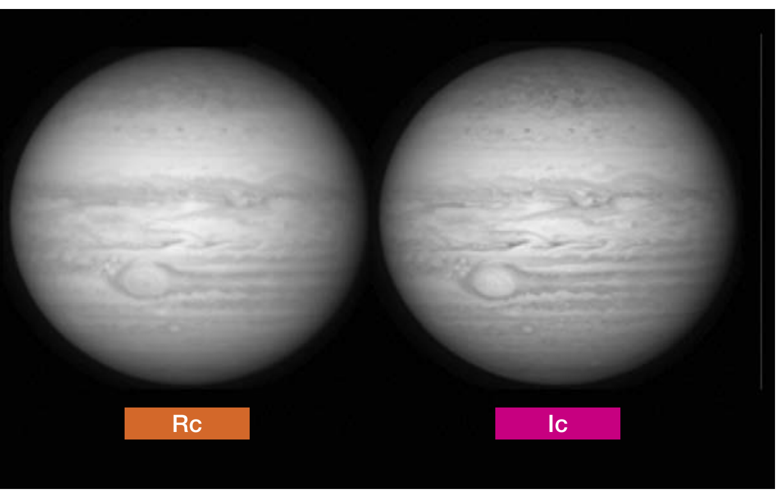
Key to getting good photometric results is to avoid overexposing the planet. It's important to keep the level of the histogram at a reasonable value, because as a pixel approaches its saturation point, the signal becomes non-linear. I recommend keeping the maximum histogram value below 80%.

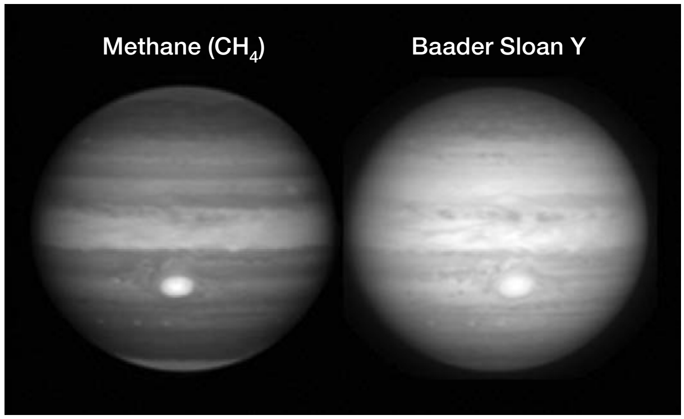
It's helpful to calibrate both the target solar system body and the comparison-star images with flat-field, bias, and dark frames just like in stellar photometry. However, using a low-noise CMOS sensor, I find I can forgo these calibration frames by making sure my sensor is free of dust and stacking video frames to produce a high signal-to-noise ratio result. Don't perform any additional post-processing like sharpening or wavelets, and save your stacked result in FITS format.

Finally, there is another important tip to use when you take the videos of the comparison stars: They should be recorded intentionally out of focus. Focused stars are vulnerable to fast seeing variations, which result in a loss of light and somewhat incorrect values. Unfocused stars behave similar to planetary disks, which don't twinkle due to their angular size as seen from Earth. The unfocused star will require a longer exposure, which produces consistent intensity readings. For the same reason, videos of at least 15 to 30 seconds are recommended.

Measuring Your Images

To measure the luminosity value of your target, open the calibrated planet image in a program with photometric tools, such as *IRIS* (**https://is.gd/irisastro**). Next, adjust the display of the





▲ **ADDITIONAL WAVELENGTHS** The methane (CH_4) and Y filters are also useful additions to a planetary imager's arsenal of tools. The methane filter passes a narrow swath of the spectrum centered at 890 nanometers and reveals areas deeper within Jupiter's atmosphere. The Y filter passes light between about 950 and 1,150 nanometers.

image (the ***Threshold*** sliders seen on the bottom of page 66) so that the background noise is just visible. This will make the planet appear saturated, but don't worry, this is only for display purposes, and the image itself isn't being modified.

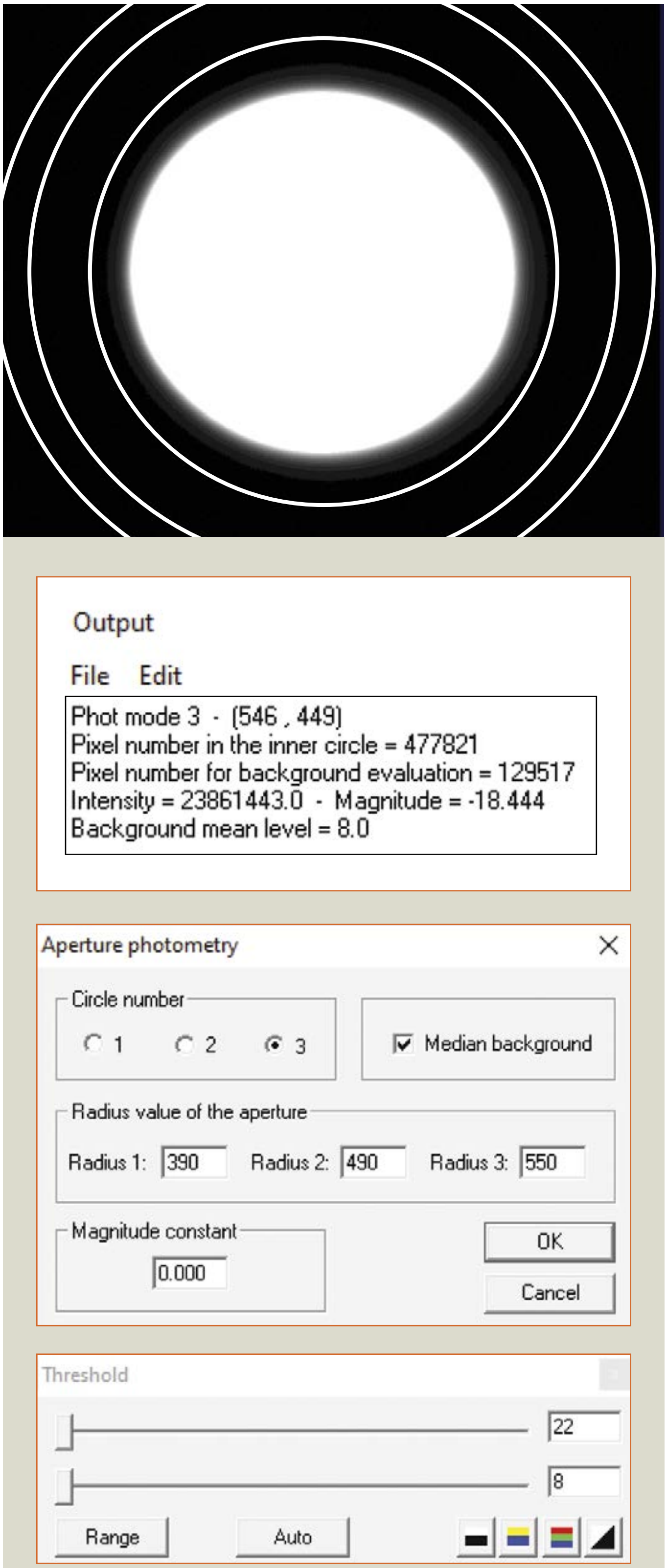
Select ***Analysis*** > ***Aperture photometry*** from the pulldown menu. A window opens where you set the areas to be measured. Circle 1 should just encompass the entire object, for example Jupiter. Circle 2 should be slightly larger. The third circle sets the outer limit of sky background that will be measured and subtracted from the target body's luminosity measurement. The area between the first and second aperture is ignored, as it generally contains light scatter around your target that can contaminate the photometric measurements. With these set, click OK, and then click on the object to be measured. A small window will pop up containing the measured information, the most important of which are the intensity and magnitude.

However, the magnitude information is the relative, rather than the actual, magnitude. For the latter value, perform these same actions on your comparison star of known magnitude, and use the formula provided from the AAVSO method:

$$M = (m - c) + C + T \times D$$

where m is the relative (measured) magnitude of the planet, c is the relative magnitude of the comparison star, and C is the catalog magnitude of the comparison star, T is the transformation of magnitude, and D the transformation of color, producing M, the actual magnitude of the planet. T and D are coefficients that are necessary to convert your system data to the Johnson-Cousins or Sloan catalog system. You can find these system values in a paper published by Anthony Mallama in the journal *Icarus* found at **https://is.gd/planetalbedo**.

Then, once you know the apparent magnitude of the planet in a given band, you can determine its geometric albedo. This requires first calculating its normalized magnitude (the equivalent of the absolute magnitude of stars but applied to solar system objects). The *normalized magnitude* is how bright the planet



▲ **APERTURE IS KEY** Measuring the signal of a planet in *IRIS* using its ***Aperture photometry*** tool is similar to measuring a star, except the first circle needs to be large in order to encompass the entire planet.

would be if we could observe it at a distance of 1 astronomical unit (au) and a perfect elongation of 180°.

The equations to calculate the geometric albedo differ for each planet and each color, and they are complex. However, you don't need to be an accomplished mathematician to use them. Simply input the formulae in *Microsoft Excel*, and the program will do all the necessary work for you. To give one example, I measured the apparent magnitude of Jupiter in the V band to be −2.75 using two stars in Aquarius on the night of November 9, 2022; the result is extremely close to the expected value of −2.74. The equation is:

$M = m - (-0.37 \times \alpha/100) + 0.616 \times (\alpha/100) + 5 \times \log (r \times d)$

where M is the absolute magnitude, m is the apparent magnitude (−2.75), α is the phase angle in degrees (which was 8.6 that night), r is the distance between Jupiter and Earth in au (4.238), and d is the Jupiter-Sun distance in au (4.952). The coefficients of −0.37 and 0.616 characterize the behavior of Jupiter in the V band. The result is a magnitude of −9.38.

Then, I find the ratio between the flux of Jupiter to that of the Sun, which is called the *L ratio*. The equation is:

$\text{L ratio} = 10\text{\^{}}((M_{Sun} - M_{Jup})/2.5)$

M_{Sun} being simply the absolute magnitude of the Sun in V (−26.75), and M_{Jup} the previously found, normalized magnitude. The result is 1.13×10^{-7}.

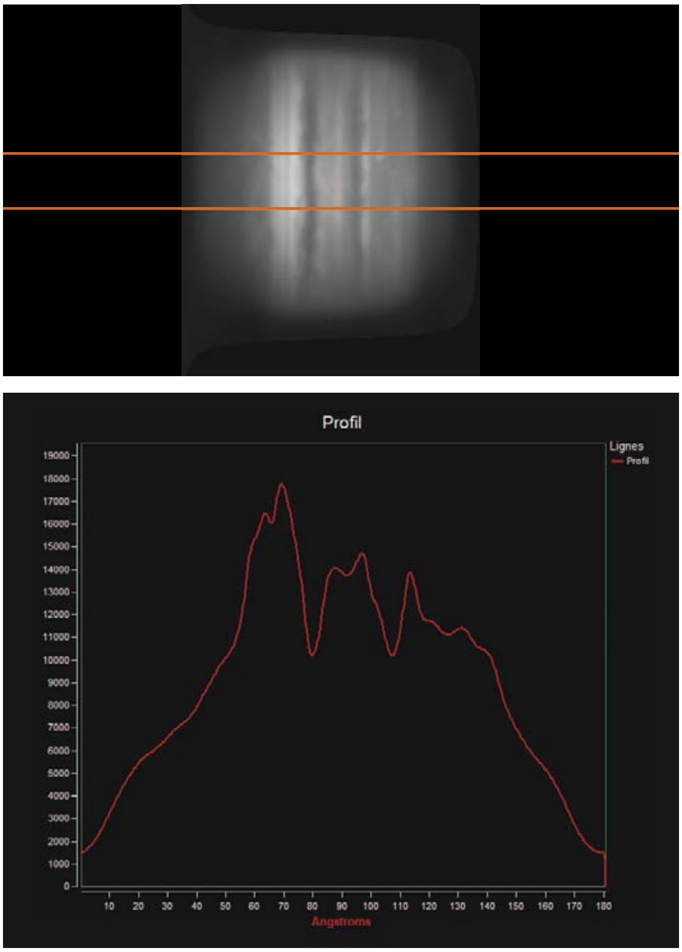
Finally, the geometric albedo is:

$\text{Albedo V} = \text{L ratio} / \sin^2 (r/\text{au})$

where r is the radius of Jupiter (69,911 km) and au is the distance of 1 au in kilometers (1.49×10^8). This produces a value of 0.52, meaning that in the V band, Jupiter was reflecting 52% of the light it receives from the Sun.

Once the geometric albedo of a planet is established, you can then measure its colors in two ways. I've determined the global photometric profile of Jupiter's zones and belts using the free software *RSpec* (**rspec-astro.com**). This program allows me to analyze a light profile across a strip of an image of my choosing. Positioning the aperture slit over the central meridian of an image spanning north to south produces a graph of the reflectivity of the belts and zones of the planet's atmosphere. I focus on longitudes that I find representative of the global state of the planet near opposition, at the hemisphere opposite that of the GRS. This profile is measured on a projected map of the calibrated image created in the program *WinJUPOS* (**https://is.gd/winJUPOS**) in order to accurately map the latitude of the features I am examining, as seen on the top of the facing page. Another method would be to aggregate a wider range of longitudes in each measurement. This method requires very good seeing conditions, so I rarely perform this action.

Finally, it's necessary to scale the albedo profile. In *IRIS*, I measure the intensity of the entire globe with the ***Aperture photometry*** tool described earlier, and in a second measurement I use a circle that only covers the center of the Equatorial Zone (EZ). Then I determine the ratio between the intensity value of the EZ as if it had the same surface as the whole planet and divide the former by the latter. The result is then



▲ **WIDE SWATH** The program *RSpec* lets you define the region of an image you want to measure and generates a graph displaying the intensity of the signal within the region of interest.

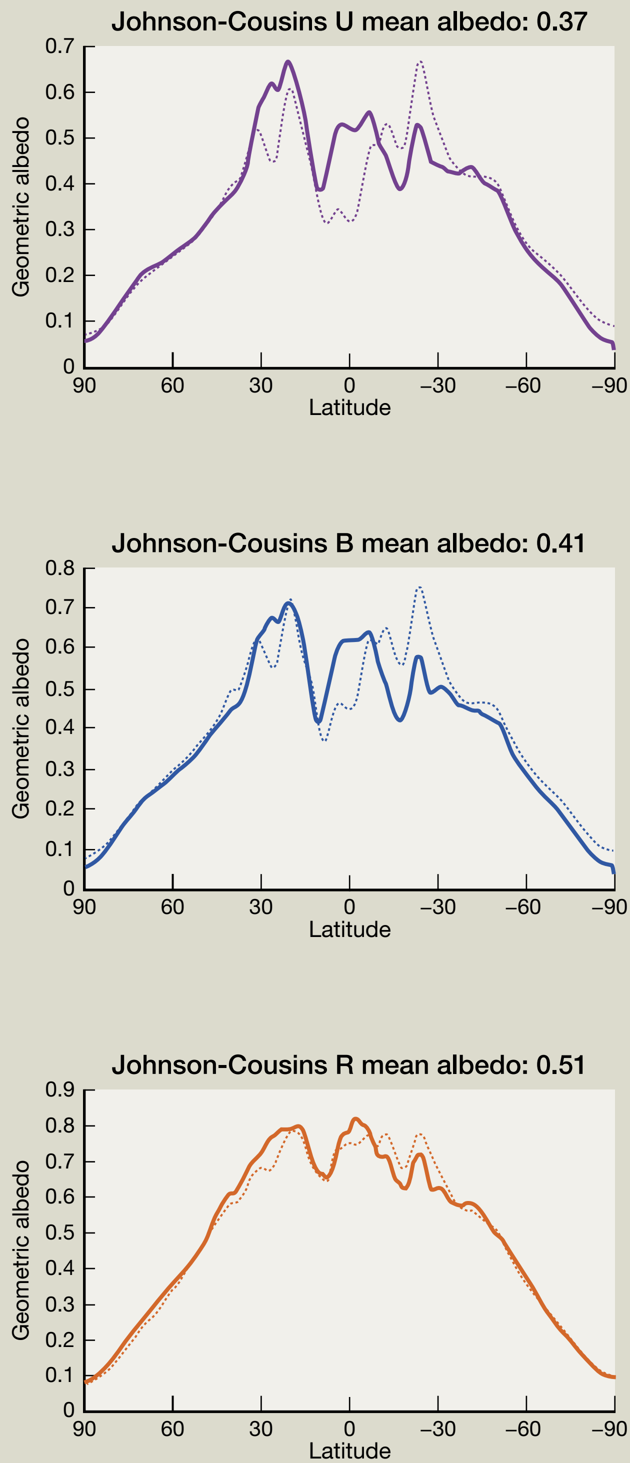
multiplied by the global albedo value to produce the albedo measurement of the EZ. The same method can be applied to any other regions of interest.

Monitoring Changes in Jupiter's Atmosphere

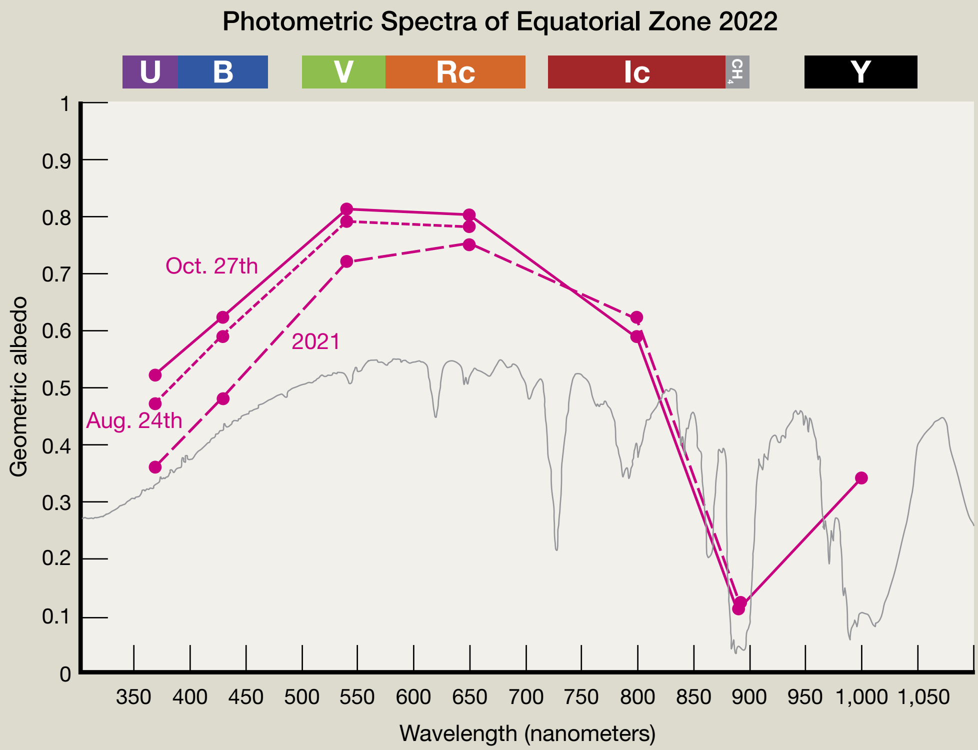
High-resolution imaging closely tracks changes in Jupiter's appearance, but those images don't tell us everything. Meteorological events have additional consequences for the albedo of the belts, zones, and ovals due to the upwelling of material from deeper within the planet's atmosphere. Simply put, those changes not only modify the shape of the clouds but also their colors as well. A well-known example of this occurred in 2006 when Philippine amateur Christopher Go noticed Oval BA had changed color from white to red.

I've also photometrically monitored individual storms on Jupiter like the GRS or Oval BA using the same technique as used for the EZ described earlier.

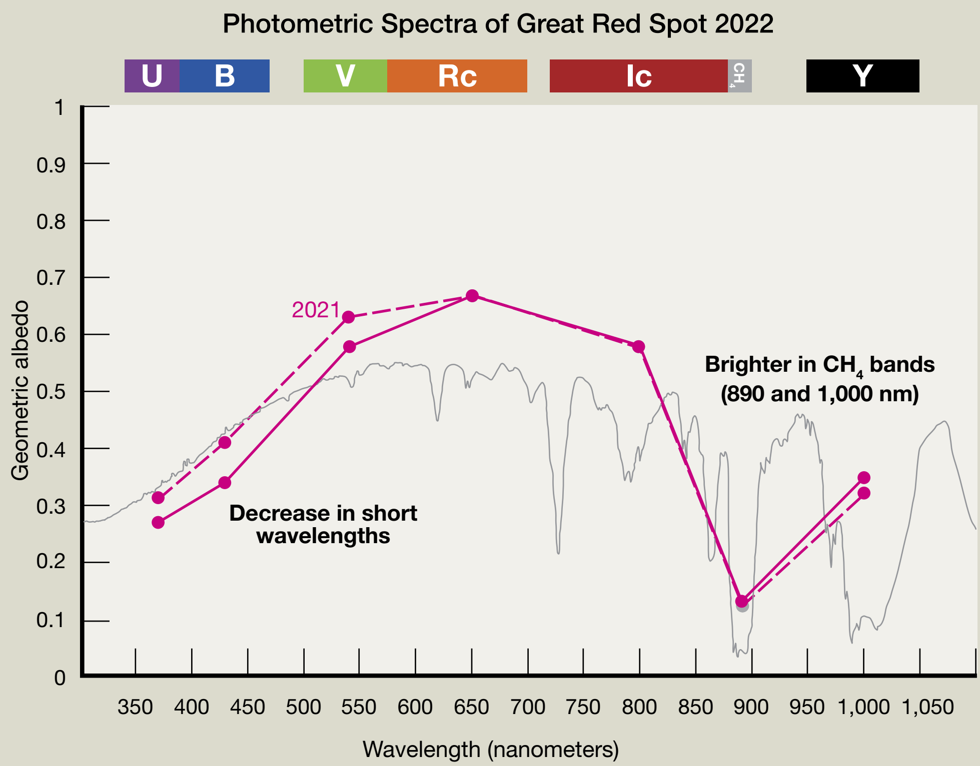
Both of these spots exhibit color variations in some key bands, such as UV, B, or CH_4. When a red spot intensifies, it becomes darker in UV and B and brighter in CH_4. As men-



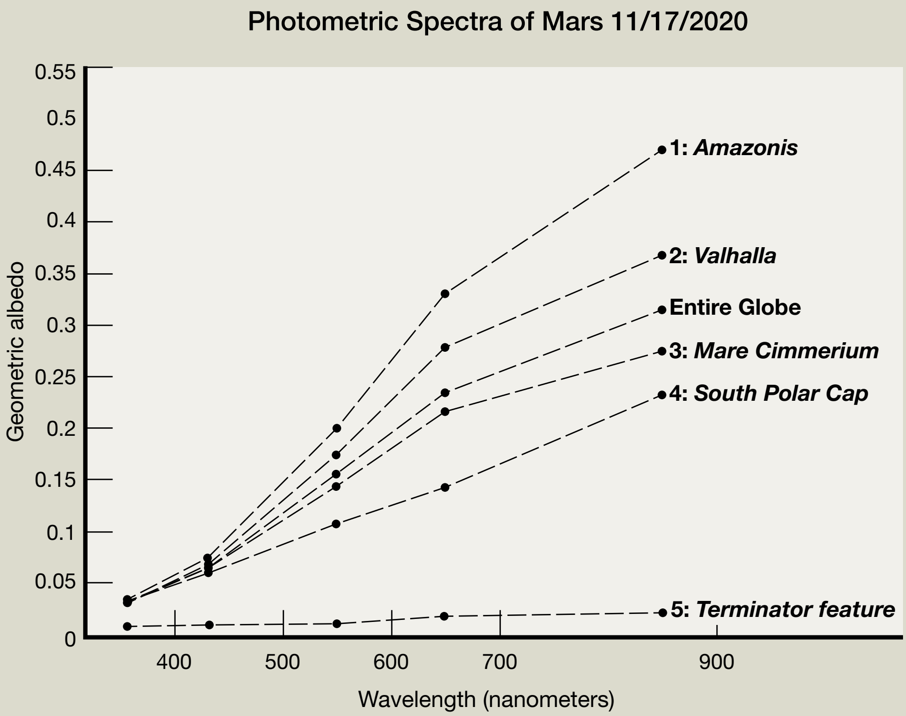
▲ **SPECTRAL PLOTS** These graphs show the measured albedo changes seen in Jupiter's zones and belts between 2021 (dotted line) and 2022 (solid line) in ultraviolet, blue, and red wavelengths. Note that the greatest differences are seen in the shorter (ultraviolet and blue) spectral regions.

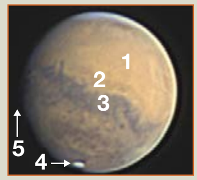


SPECTRAL GRAPH Another way to present the results is a photometric spectrum, with each point plotted in its spectroscopic region. This graph plots the differences seen above in Jupiter's Equatorial Zone (EZ) between August 24 and October 27, 2022. The spectrum of the feature appears higher than that of the globe (solid gray line) because the EZ is measured at the central meridian while the globe reading measures the mean albedo of the entire planetary globe.



QUANTIFIED CHANGES These albedo measurements of the GRS show that it reddened slightly in 2022 compared to the previous year. Its albedo dropped in UV, B, and V, but not in R or I.





◀ **LUCKY CATCH** This graph plots spectroscopic albedo of various features on Mars recorded on the night of November 17, 2020. At the time, a long cloud (5) appeared just beyond the sunrise terminator, allowing the author to record a full set of photometric measurements before it disappeared.

tioned earlier, the GRS reddened noticeably from 2014 to 2020, but when I started this work in 2021, it had suddenly become paler. However, in 2022, a more intense tint had returned. My measurements of its albedo from 2021 to 2022 successfully quantify the variations; in 2021 the value was almost equal to the geometric albedo of the whole globe in U and B (36% and 41%), but in 2022, it had fallen to 27% and 34%, respectively. You can see that in the graph at the bottom of the facing page. On the other hand, note that its albedo did not change in the R band. The same brightness in red, less bright in blue produces a change in color. I've also calculated a slightly higher albedo in CH_4: 12% versus 11% in 2021. If correct, this agrees with the findings of professional astronomers studying the planet.

Monitoring the Other Planets

Jupiter is by far the most dynamic planet to study using photometry, but the other nearby worlds also yield interesting results. Storms also appear in the atmospheres of Saturn, Neptune, and Uranus, which stand out notably. On the ice giants, these storms significantly increase the signal in the I band and don't require high resolution to detect.

Mars is also an exciting subject to study using photometry. While many albedo features remain fairly constant, the planet's thin atmosphere can sometimes produce surprises. On the evening of November 17, 2020, I was imaging Mars with my friend Emmanuel Beaudoin as part of an international team attempting to detect aurorae on it. That evening, we caught an unusual feature. While we initially focused on the possibility that we had succeeded in capturing aurorae, after careful analysis we concluded that it was a kind of cloud. In fact, it was a very long, fast-evolving cloud that appeared beyond the planet's sunrise terminator.

Still, the exercise was a success, in that I was able to measure the albedo of the feature across the spectrum. The results show that the signal from the cloud was slightly higher in the red and infrared bands. The professional astronomer on the team thus hypothesized that it was likely composed of carbon dioxide.

Using these techniques, you can contribute valuable data to groups and organizations that monitor the large bodies in the solar system, such as The Association of Lunar and Planetary Observers (ALPO, **https://alpo-astronomy.org**), the British Astronomical Association (**https://britastro.org**), the French Astronomical Society (**http://www.astrosurf.com/planetessaf**), or the Planetary Virtual Observatory & Laboratory (**http://pvol2.ehu.eus/pvol2**). My work here is inspired by the extensive work that ALPO coordinator Richard Schmude performed for decades. Currently, very few amateurs pursue this approach to planetary imaging. But with more of us studying the planets photometrically, we can help expand our knowledge of our neighboring worlds.

■ **CHRISTOPHE PELLIER** is a French planet imager and Vice President of the Commission of Planetary Observations of the French Astronomical Society. See more of his work at **www.planetary-astronomy-and-imaging.com**.

Nikon's Z6III Camera

This new mirrorless camera proves superb for nightscape photography, with one shortcoming.

Nikon Z6III

U.S. Price: $2,499.95
Nikonusa.com

What We Like

Easy to frame and focus

Good features for night use

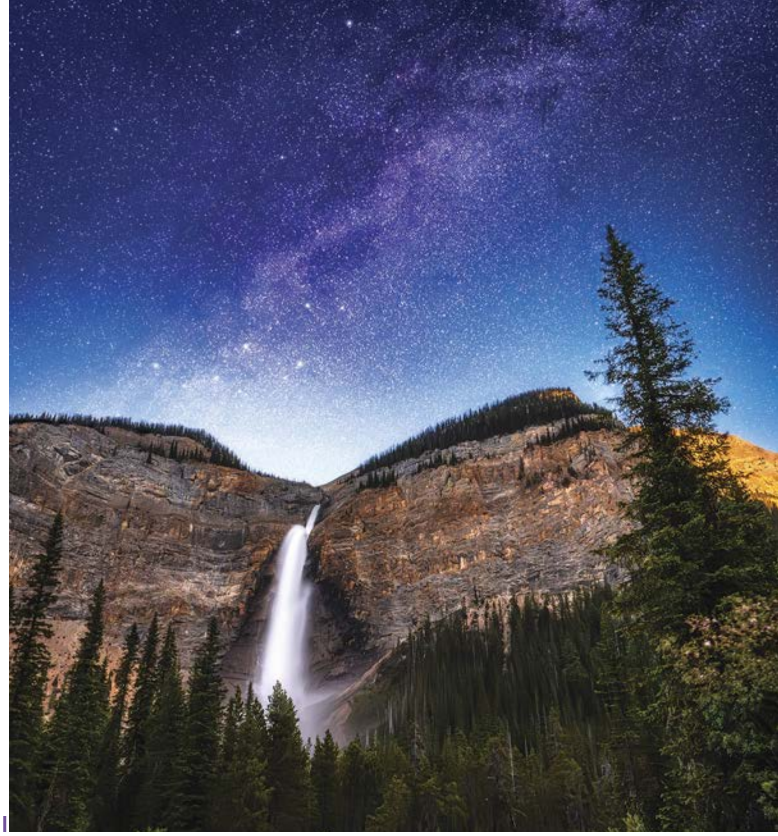
Excellent for low-light video and time-lapse sequences

What We Don't Like

Lower dynamic range than previous Z6 models

Sensor exposed when changing lenses

Some non-Nikon batteries do not work



▲▼ The Milky Way rises above Takakkaw Falls in Yoho National Park, British Columbia, Canada, on a perfect July night. This is a stack of two 3-minute untracked exposures at f/2.8 for the ground, blended with a stack of four 1-minute tracked exposures at f/2 for the sky recorded at ISO 800 with the Nikkor 20-mm lens on the MSM Nomad tracker shown below.

WHILE ASTRO CAMERAS with cooled CMOS sensors dominate the realm of deep-sky imaging, traditional off-the-shelf DSLRs and mirrorless cameras remain the prime choice for nightscape astrophotography. However, Sony no longer makes DSLRs, and neither Canon nor Nikon has introduced a new DSLR since early 2020. Only Ricoh/Pentax remains stalwartly committed to DSLRs. For every other camera brand, mirrorless models fill their product lines.

I reviewed Nikon's original mirrorless camera, the Z6 (*S&T:* Aug. 2019, p. 68), shortly after it was introduced. In mid-2024 the company issued the third generation in its mid-level Z6 series. Like its two predecessors, the Z6III offers a 24.5-megapixel, backside-illuminated (BSI) 35.9 × 23.9-mm sensor with 5.9-micron-square pixels in a 6,048 × 4,032 array.

Using a unit purchased locally, I tested it for the demands of nightscape photography, curious to see if ease of use and image quality have improved in the model's third iteration.

Noise Performance

We expect every new generation of camera to offer incrementally lower noise. However, in comparing the Z6III's images to ones I shot in 2019 with the original Z6, the new camera's noise levels don't appear to be any different. Noise was on par with other cameras with similar megapixel counts. In same-night tests, I found the new camera's noise level comparable to my 20-megapixel Canon R6 from 2020.

Images taken with equivalent exposures over a range of ISO settings showed noise increasing at each bump up in ISO. Noise in nightscapes is most obvious in dark foregrounds when they are brightened in processing by raising the Shadows slider, as I did for my examples. In my tests, ISO 3200 produced good results, with ISO 6400 quite usable with today's AI-driven noise reduction. Above those ISO settings, I judged the lifted shadows too noisy to be usable.

Random hot pixels that pepper long exposures, especially on warm nights, is the form of noise that can be independent of ISO. This is the thermal noise that applying dark calibration frames can eliminate. Like most other cameras, the Z6III offers a Long Exposure Noise Reduction (***LENR***) option for taking a dark frame and subtracting it in-camera. This proved effective at getting rid of the majority of hot pixels, which can be difficult to deal with later in processing.

In sets of 8-minute dark frames taken separately at room temperature, there were no glows from warm electronics or internal infrared heat sources. Dark frames looked uniform. While a ***Pixel Mapping*** option promises to reduce hot pixels, I found it made little difference.

While 24 megapixels is low by today's standards, for nightscapes it's a good balance of resolution versus noise. While the smaller pixels (or photosites) of higher-megapixel cameras yield higher resolution, they

ALL IMAGES ARE BY THE AUTHOR

cannot collect as many photons over a given exposure time. As the signal goes down, the all-important signal-to-noise ratio gets worse. For example, I performed same-night tests with my 45-megapixel Canon R5, which I have used with good success on nightscapes. But, as expected, its images were noisier at high ISOs. The extra detail it could theoretically capture got lost amid the higher noise.

ISO Invariance and Dynamic Range

Early reviewers of the Z6III discovered the camera suffers from a lower dynamic range than previous models in the series. This is the range of tonal values a camera can capture, from the dark shadows just above the noise floor, to just below the point where bright highlights are clipped. How can a new camera be worse than earlier generations?

The answer is that camera makers now value readout speed above other key specs. The Z6III's sensor design is said to be "partially stacked," referring to additional layers of signal processing circuitry behind some of the photosites to speed up readout times. Its electronics can transfer a complete 24-megapixel image in just 14 milliseconds, according to **DPReview.com**. Fast readout speeds allow higher frame rates in continuous modes (the Z6III can fire up to twenty 14-bit RAW files per second) as well as faster auto-focusing during continuous shooting and higher frame rates in videos. These are all useful capabilities for wildlife and sports photography and for capturing solar eclipses. However, making a sensor faster for high-speed shooters comes at the cost of dynamic range for us slow-moving astrophotographers!

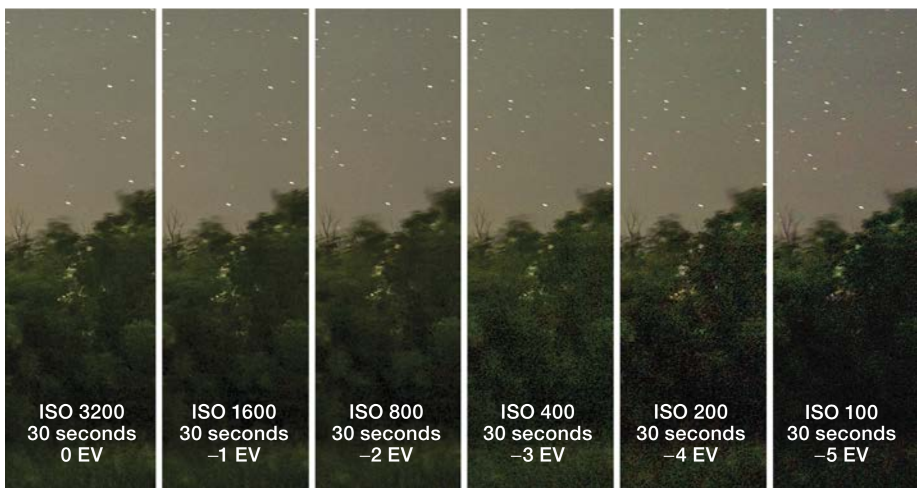
The Z6III also has what is called an "ISO invariant" sensor. With such a design it's possible to shoot at a lower ISO then stretch the results during processing to get results similar to shooting at a higher ISO. However, despite the Z6III's ISO invariant sensor, my testing on nightscapes revealed that the camera has about one EV (Exposure Value, equal to one f-stop) less dynamic range than its predecessors. Where the original Z6 could be underexposed by –4 EV and still recover good details in the shadows, I found the Z6III's limit is an underexposure of no more than –3 EV. With any greater level of underexposure, boosting the shadows in processing resulted in excessive noise and image artifacts.

A Secret Base ISO

The negative dynamic range trait is partly mitigated by a sensor specification Nikon and other manufacturers rarely publicize: what the camera's base ISO settings are. Like most models, the Z6III uses a base ISO of 100 then electronically amplifies the signal to create a brighter image at higher ISOs.

But for still images, a second set of electronics kicks in at ISO 800, making the Z6III's sensor "dual-gain" with a second, higher base ISO. I demonstrate this in the series on page 72 that starts with a properly exposed 8-minute image at ISO 100. I then cut the exposure time down by 5 EV to 15 seconds for severe underexposure. Brightening the image in camera by increasing the ISO produced awful results. Until ISO 800. At this second base ISO the image suddenly exhibits a huge improvement in quality and lower noise, despite the image still being underexposed by –2 EV. From

▲ Each image in this starlit scene was shot at the same equivalent exposure. The dark ground has had the shadows boosted by 100% in processing. As expected, noise gets worse with each increase in ISO, notably so above ISO 6400.



▲ Beginning with a properly exposed shot at far left, each image progressing towards the right was underexposed by –1 to –5 EV by lowering the ISO, then brightened during processing by +1 to +5 stops to compensate. An underexposure of –3 EV proved to be the Z6III's limit when lifting dark shadow content.

then up, increasing the ISO made little change — noise remained similar. How can this be?

The difference here compared to the "ISO versus Noise Comparison" set in the middle of page 71 is that now the exposure time (15 seconds) and aperture (f/2) aren't changing, so the same number of photons are hitting the sensor for each exposure. The signal is constant. In practice, this means that when shooting nightscapes with the Z6III it's best to use an ISO of at least 800. Brightening low-ISO images after the fact produces poor results for dark, starlit scenes. Twilight and moonlight scenes are more forgiving.

Focusing and Framing

The Z6III provides great aids to getting images that are accurately framed and focused. It offers a ***Starlight View*** option, a feature shared with all of Nikon's most recent cameras. Activating it brightens the live view enough to show the Milky Way and at least the silhouette of a dark foreground. This minimizes the need to shoot lots of high-ISO trial-and-error framing shots.

The auto-focus system also proved sensitive enough to work on stars, at least when the camera is paired with a fast lens. Auto-focusing by tapping on a star on the rear touch-screen proved quite accurate. Manual focusing is also easy to do. The Z6III offers magnifications up to what the camera calls 200% for precise focusing by hand.

◀ *Top:* While the Nikon Z6III has a mechanical shutter, it remains open even when the camera is switched off. This risks exposing the sensor to dust. *Upper middle:* Like Canon cameras, the Z6III uses a flip-out, vari-angle screen, rather than Nikon's usual tilt-up screen. The design facilitates shooting at any orientation. *Lower middle:* The top panel features a backlit LCD displaying settings and running countdowns of times in extended exposures, time-lapses, and LENR darks. *Bottom:* Ports include USB-C (top) for file transfer and external power, a full-size HDMI (middle) for video out, and a proprietary DC-2 shutter release port like other Nikons.

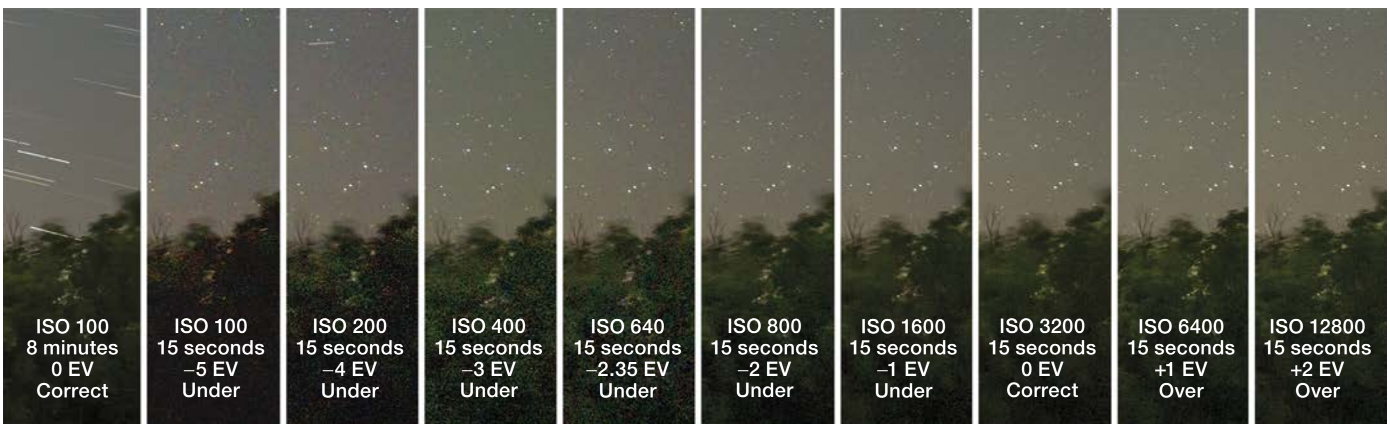
Even better, when turning on the camera, auto-focus lenses snapped to their infinity setting by default. That was the case not just with the 20-mm Nikkor lens I used but also with the third-party lenses I tested with the camera — a huge convenience when shooting under the stars. I wish my Canon cameras could do that!

Astro-Friendly Features

While the Z6III doesn't have any unique attributes for astrophotography, it does include the same night-friendly features found on other late-model Nikons.

For example, in the ***Custom Settings*** menu, turning on ***Extended Shutter Speeds*** allows internally timed exposures as long as 900 seconds (15 minutes). You can combine those with the built-in intervalometer to set up sequences of multi-minute exposures without the need for an external intervalometer. I did wish for a 45-second option between the standard 30-second setting and the next jump up to 60 seconds.

The ***Exposure Delay*** setting provides up to a 3-second delay between pressing the shutter button and the start of the exposure, to minimize vibration without needing a remote release. This is better than using a self-timer, as it avoids that function's annoying beeps



▲ This series begins at the far left with a properly exposed image recorded at ISO 100. Each subsequent image is underexposed by using a very short shutter speed. Gradually increasing the ISO brightens the images but yields poor results until the Z6III's second "base ISO" of 800 is reached, where the noise level suddenly improves.

▲ Being a mirrorless camera, the Z6III is always in Live View. With ***Show Effects of Settings*** turned on (left), the view at night is good enough to display the Milky Way. But turning on ***Starlight View*** (center) further brightens the scene for framing. Zooming in at the highest magnification (right) reveals stars to allow manual focusing in most fields.

and flashing warning light.

The Z6III has an option called ***Warm Display Colors***. This turns all the menus red, with a choice of overall brightness — excellent for preserving night vision. However, the Z6III lacks the illuminated back buttons found in the Z 8 and Z 9 models. Pity, as that would make for less fumbling in the dark. The lack of lights extends to not having any visible indication that an exposure is in progress, leaving the user to wonder, "Did I fire the shutter? Did the camera turn off?"

While the top panel does provide a running countdown of exposure time and of time remaining during an LENR dark frame, it does so only for exposures 60 seconds and longer.

Despite these complaints, the Z6III proved a pleasure to use for nightscape photography. Although I have a coterie of Canons to pick from, I now turn to the Nikon Z6III for many of my nightscape nights.

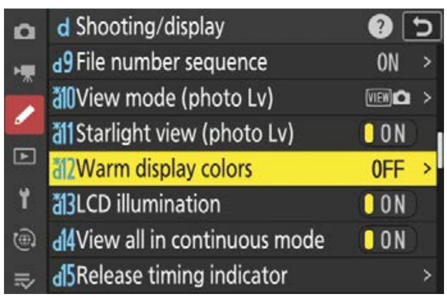
Time-Lapse and Video Sequences

The Z6III's internal intervalometer has the same functions as in other Nikons. It's useful for shooting time-lapses, whether you record the result as a video file or, for the most control later in processing, recording all the individual RAW files.

By setting the camera to ***A*** (Aperture Priority Auto-Exposure) and to ***Auto ISO***, the camera can shoot demanding day-to-night time-lapses, automatically decreasing the shutter speed then increasing the ISO to accommodate the change in brightness from daylight to full darkness. The Z6III also meters dark scenes well, something DSLRs and early mirrorless cameras failed at. Additionally, the ***Exposure Smoothing*** option largely eliminates frame-to-frame flickering — the bane of time-lapse shooters.

The internal EN-EL15c battery provided about three hours of continuous shooting. However, the Z6III can be fussy about what batteries it recognizes; third-party EN-EL15 batteries failed to work. For longer sessions I ran the camera off an external battery through a USB-C connection.

Like all cameras today, the Z6III is also a superb video camera. My go-to camera for real-time 4K (3,840 × 2,160 pixels) videos of aurorae had been my Canon R6. The Nikon Z6III has proved better. For one, it can shoot videos up to 6K (6,048 × 3,402 pixels) in RAW formats, or 5K (5,376 × 3,024 pixels) in compressed H.265 or H.264 video codecs. But I find the main advantage is that, as with Sony cameras, the Z6III can shoot as slow as ¼ second in video. Canons can go as slow as only ⅛ second. That one-stop advantage allows low-light videos to be shot at, say, ISO 25,600 vs. ISO 51,200, producing a significant reduction of noise in the final video. While the slow shutter speed produces motion blurring, for aurora photography that's not an issue, and the lower noise is welcome. Video samples of an aurora and a time-lapse I shot with the Z6III are on Vimeo at **https://is.gd/z6iiivids**.



▲ ***Warm Display Colors*** allows turning either the entire screen red, image included, or just the menus, leaving the image appearing normal, a very useful function for nightscape photography. Placing this function in the customizable "i" menu allows quick access at night.

Recommendations

If you own a Nikon Z6 or Z6II, upgrading to the Z6III will be hard to justify, at least for astroimaging. Indeed, in some respects the older models are better for low-light still images. However, the Z6III's night-friendly features are wonderful. As such, if you are using an older Nikon DSLR, or indeed a DSLR of any brand, the Z6III is a superb choice if you're upgrading to a mirrorless camera.

While DSLR lenses can be adapted to the Z6III, the new lenses made for mirrorless cameras are so much better that they alone make the move to mirrorless worthwhile. (See my feature on choosing lenses for nightscapes, *S&T:* Jan. 2022, p. 28.) Budget for at least one new Z-mount lens — The Nikkor 20 mm proved superb.

Although camera makers are catering more to videographers and sports shooters, I applaud Nikon for providing cameras with attractive features only astrophotographers will appreciate. The new Z6III is a fine example.

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

Homage to Hubble

An offhand challenge leads to a fantastic work of art.

▲ Lauren Wingert's Hubble replica (above) is nearly indistinguishable from the original.

A FEW YEARS AGO, I ground an 8-inch (200-mm) f/4 mirror, thinking I'd use it to build a travel scope for my astronomy club. I never got around to it, so last January I took the mirror to our swap meet, where Lauren Wingert, whose projects you've seen several times in this column already, saw it and said, "I could do something with that." She and I got to talking about what she might build, and more or less out of the blue I said, "Why don't you make a replica of the Hubble Space Telescope?"

Lauren got that look in her eye, the one that says, "Ha! I got this!" She picked up a focuser at the swap meet and went home, and within a couple of days she started sending me emails. "Look, I found a bucket that will work for the back end," and "Hey, did you know bottomless cake pans fit perfectly into the cut-off bucket bottom? And the lid makes a great mirror cell."

I was already a fan of 5-gallon-bucket secondary cages, so I knew she was off to a good start.

Lauren's brother, Brian, says she has good "astro luck," and he's right. When Lauren needed a secondary and spider assembly, one of our other club members offered to let her part out a Meade scope that the member found too big and ungainly. Lauren traded a wide-angle eyepiece for it, and suddenly she had practically everything she needed. Not only did that provide the secondary and spider, but it also gave her a Sonotube OTA that she could use for the upper two-thirds of the Hubble replica, plus a Dobsonian base (coincidentally built a few years earlier by yours truly) for the whole works to rest in.

Brian's Bicycle Dob (*S&T:* Jan. 2024, p. 70) uses a Lazy Susan for azimuth, and Lauren liked the smoothness of it, so she replaced my Teflon-and-Formica azimuth bearing with a Lazy Susan and added carpeting around it to provide just the right amount of friction.

Then it was on to the OTA. Lauren admits that "I didn't have much of a plan, per se." She just looked around for inspiration and kept coming up with Hubble-looking parts. A soda-can bottom cut open and spread out makes a

▲ A bottomless cake pan fits within the bucket perfectly and provides a firm seat for the upper tube assembly.

▲ The bucket lid makes an excellent primary mirror cell.

ALL IMAGES COURTESY OF LAUREN WINGERT UNLESS OTHERWISE NOTED; LAUREN'S HUBBLE REPLACING THE REAL HUBBLE IN ORBIT: LAUREN WINGERT / NASA perfect satellite dish. Disk-drive reader arms provide bling for the dish attachment. A floor vent for a forced-air heating system makes a perfect solar panel. And so on.

The mirror cell is particularly ingenious. The lid to Lauren's bucket had a crisscross molded into it nearly an inch deep for strength, so Lauren cut out the four pie-shaped wedges between them, leaving just enough plastic to capture the mirror without touching it. She drilled holes and inserted carriage bolts for bottom support and collimation and added clips to hold the mirror down. It worked like a charm!

The altitude bearings looked better attached to the wide section, but that wasn't the right balance point, so Lauren added weight all around the perimeter of the mirror cell to compensate. Slots in the lid provided perfect pockets to add a coil of lead wire to each. Lauren then covered the lead coils with flocking material to provide a black view from the focuser.

When it came time to cut the cardboard tube for the upper end, Lauren found herself unwilling to trust her luck. She could just envision cutting it an inch too short and having to redesign everything. So she bolted trusses (extendable painter's poles) to the side of the bucket, cut the top off the parts scope (knowing there was plenty of bottom left for the final OTA), and used the adjustable trusses to fine-tune the upper OTA length. Then she cut and mounted the solid tube. Lauren says,

◀ Lauren and her Hubble replica stand ready for a night of observing.

"The downside of doing it that way is that I had to move the focuser and spider assembly to the longer section of the Sonotube. It was a little extra work, but not so bad."

With the OTA roughed out, now was the time for bling. The real Hubble scope is studded with access panels, handholds for astronauts, and various other thingumbobs and doohickeys, and Lauren wanted her replica to sport the same look. So she gathered up hard-drive parts, wiring conduit, ball-bearing races, heat sinks, and whatever else she thought might look good. She laid the most spacey-looking pieces down on the upper section, then put reflective foil duct tape over the whole works.

The lower end required some shimming to remove the bucket's natural taper and bulk it up a little to better match the Hubble's proportions. Lauren used cardboard layers to even out the taper, and Styrofoam tiles to add the needed thickness and texture. Then she added more bling and foil-taped that section, too.

Yet more bling went on top of that and around back to provide a final techie touch. Lauren says, "The bottom is a little steampunked out. I figure the bottom is going to be rarely seen, so I took artistic liberty with that."

On the other end, she matched the Hubble's iconic sun shield almost perfectly. It's a sheet of rigid pet-door plastic cut to shape with ordinary kitchen aluminum foil glued to it, attached to the top-end cake pan with an ordinary door hinge. How did she make it stay open? "I checked an entire bin of hinges for one that was tight," she explained.

The solar panels were surprisingly easy to make. The heating-system floor grates already had the right look, so it was a simple matter of painting them black, adding edge trim, wires, and sparkly contact paper underneath to contrast against the black paint. As Lauren proudly says, "The grates Hubbled up nicely!"

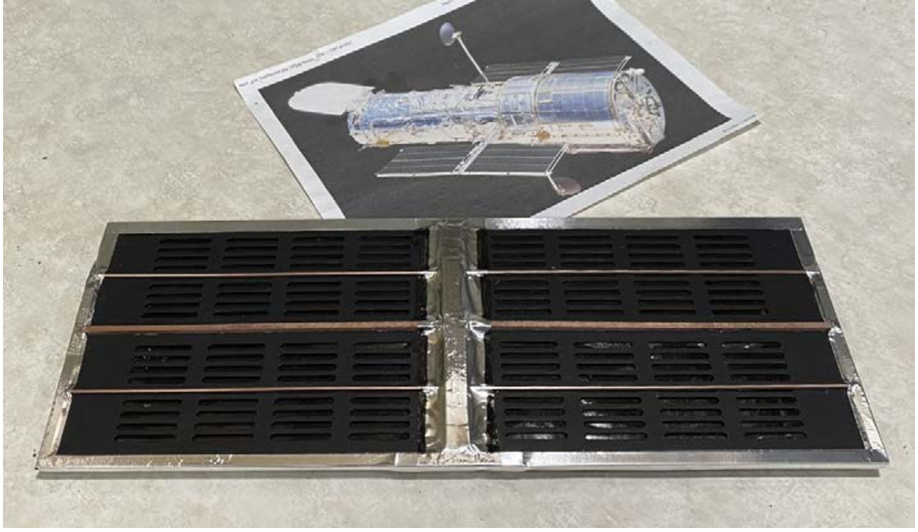
The focuser sits just above the left-side solar panel, so Lauren initially figured that she'd have to remove that panel when observing, but it turns out with an eyepiece in the focuser the panel doesn't get in the way.

▲ The primary mirror rests securely in its bucket-lid cell.

▲ Aluminum foil makes the focuser look like just another piece of random Hubble hardware.

▲ The bottom of a Sam's Cola can covered in foil made a perfect dish antenna.

LAUREN WITH HER SCOPE: JERRY OLTION



▲ The air vent "Hubbled up" beautifully to make a convincing solar panel.

The altitude bearings tuck in below the solar panels and are painted black to be unobtrusive. The rocker box is also black for the same reason. Even during the daytime, the mount fades into the background and all you see is the Hubble Space Telescope floating there above the ground.

Lauren did have to widen the rocker box to accept the wider scope, but that was a short day's work. The scope was a bit low to the ground in that mount, but Lauren says, "More astro luck! I already had the perfect base with an eyepiece drawer built in." That's the base she built for the Zip Dob she bought from Mel Bartels a few years ago (*S&T:* July 2021, p. 72). Resting on that short table, the scope is at the perfect height for observing while seated in a comfortable chair.

Lauren says, "I didn't feel the need to make a spider and secondary cage when I could just rob it from the donor scope. Instant upper OTA with another cake pan for the edge! I love the scavenger thing!"

One complication: The donor scope was an 8″ f/7, which meant the 1.1″ secondary mirror was too small. An 8″ f/4 primary requires a secondary with at least a 1.9″ minor axis. Also, the donor secondary mount was a bear to collimate. Fortunately, I had a spare 2″ secondary and some extra time, so I made a lightweight mount for it, and we swapped that onto the original spider. (More on that secondary mount in an upcoming column.)

Despite the lead weights down in the bottom, the scope was still a touch top-heavy. Rather than add more weight, Lauren bought a set of high-friction lid-support hinges, the kind that keep your cedar chest lid from falling back down and smashing your knuckles. They move freely going up but provide adjustable friction going down. Lauren set them to counter the extra nose weight, and the scope is now stable at all angles, even with a heavy eyepiece.

With all that bling and the lead weights at the bottom, I expected this scope to be a hefty haul, but the base weighs in at 18 pounds, and the scope itself is only 23 lb. That's about the same as a typical 8″ Dobsonian.

Lauren tested the scope in her backyard, but I had the honor of joining her for its first dark-sky outing. My first impression as she lifted the scope out of the car was astonishment at how perfect it looked even close up. Then she started assembling it, and my astonishment continued to grow. The radio dish attaches magnetically. The solar panels slide onto exposed bolts and don't even need nuts to secure them. Likewise for the high-friction hinges. The scope set up within minutes, and we were ready to observe. Arcturus was the first bright star visible in the twilight, so we turned to that and . . . and . . . this thing is a real telescope!

Since I made the primary mirror, commenting on the crispness of the view would be bragging. It took me a while to even notice, to be honest, because I couldn't stop giggling. I was looking through the Hubble Space Telescope! It was a dream come true. A dream turned into reality thanks to Lauren's imagination and dedication.

◀ Lauren says, "Measure five times, cut once." She marked up the donor telescope's tube to make really sure she was right before she started cutting.

▼ The moment of truth: Lauren cuts the old tube to length.

■ Contributing Editor **JERRY OLTION** thinks these may be the most beautiful Hubble photos ever taken.

What Are the Galilean Moons?

▲ **GALILEO'S MOONS** From left to right, they are Io, Europa, Ganymede, and Callisto. They appear here scaled to the moons' relative sizes and placed in order of distance from Jupiter.

THE GALILEAN MOONS are the four largest moons of the planet Jupiter.

History. The name honors Galileo Galilei, who discovered them in 1610 using the newly invented telescope. The find was one of the most earthshaking in the history of science. The four moons were the first new solar system worlds identified since antiquity, and their unveiling revolutionized observational astronomy by demonstrating that optics could reveal far more in the heavens than the naked eye could.

Most significantly, Galileo's revelation provided unequivocal evidence that worlds circled other bodies besides Earth. That realization helped upend the long-accepted geocentric system of Claudius Ptolemy, which held that our planet was the center of the universe and all bodies revolved around it.

Galileo labeled the four moons I, II, III, and IV, in order of their increasing distance from Jupiter. But in time they gained names drawn from classical mythology: Io, Europa, Ganymede, and Callisto. All were lovers of Zeus in the Greek mythos. (Zeus's equivalent in the Roman world was Jupiter.)

Science. The Galilean moons look tiny beside Jupiter, but they are major solar system bodies. Io, Ganymede, and Callisto are all larger than our Moon, and Europa is only slightly smaller. All other Jovian moons — the current count is close to 100 — are orders of magnitude smaller than the Galilean moons.

Each of the four big satellites boasts its own superlative. Io is the most volcanically active body in the solar system, with more than 400 active volcanoes. Europa is the smoothest, and Callisto is the most heavily cratered. Ganymede, for its part, is the largest moon in the entire solar system — appropriate, given that Jupiter is the largest planet. Notably, the outer three Galilean moons stand out from Io in likely having oceans of liquid water beneath their icy crusts (*S&T:* Apr. 2022, p. 14).

Observing. For a novice observer of the night sky, one of the most memorable moments is their first sight of Jupiter through a telescope. Suddenly, where the unaided eye saw just the planet, up to four tiny dots appear arrayed around it. It's like a mini solar system, with those four worlds orbiting the king of planets. If it weren't for Jupiter's brightness overwhelming theirs, they'd actually be visible to the naked eye. But through even a small telescope, the Galilean moons are not only easily visible but resolve into disks that are clearly not stars but worlds of their own.

Observers see the moons strung in a rough line on one or both sides of the planet, like beads on a necklace. That's because the moons circle Jupiter in the plane of its equator, and the Jovian axis is tipped only about 3° from its orbit, so we view that miniature "solar system" almost edge-on.

Of course, the number of moons you can see at any time changes constantly as they revolve around Jupiter. All four may appear on one side of the planet, for instance, or two on each side. Or you may see fewer than four, because one or more of the moons may then be behind or in front of Jupiter.

To find out where the moons are on any given night this month, turn to page 51 to see our "Jupiter's Moons" graphic and "Phenomena of Jupiter's Moons." This table lists key events occurring between the moons and the planet, including when a moon disappears behind Jupiter or within its shadow as well as when a moon or its shadow passes over the planet's face.

For other nights beyond this month, consult our interactive tool (**https://is.gd/GalileanMoons**). It displays the four satellites' positions for any date and time between January 1900 and December 2100. The tool is customizable, so you can change the view depending on whether your telescope shows the sky north up, south up, or mirror-reversed. Happy observing! ■

◁ ANCIENT PLANETARY

Bob Fera and Eric Coles

MWP1 is an unusually old and large planetary nebula in Cygnus. Around 150,000 years ago, a Sun-like star cast off its outer layers, creating shells of dust and gas that today span some 15 light-years across.

DETAILS: *PlaneWave CDK20 Corrected Dall-Kirkham telescope and Moravian C3-61000 Pro camera. Total exposure: 15.8 hours through color and narrowband filters.*

A SCORPION'S RETREAT

Vikas Chander

Sagittarius and Scorpius stand high above Delicate Arch in Utah's Arches National Park. The colorful Rho Ophiuchi complex is seen at top right, while several smaller, pinkish nebulae line the plane of the Milky Way.

DETAILS: *Nikon D810A camera and Zeiss 35-mm lens. Composite of 2 exposures: 240 seconds for sky and 480 seconds for ground at f2.8, ISO 800.*

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An Unexpected Joy

Last May's breathtaking aurora caught the author off guard in the most rewarding way.

THE GREEN AND RED blob materialized right before my eyes on the monitor, fed from a TV camera stationed in downtown Portland, Oregon. It was Friday, May 10th, and the solar storm that evening was so intense that it triggered an auroral display so vivid it could be seen from the heart of the city.

I work in a television newsroom, and just before our 11 p.m. newscast that night, I happened to glance up at one of our sky-camera video feeds. The camera was pointed north, and out of nowhere a shimmering green curtain drifted across the monitor. I couldn't believe it. With all our urban light pollution, the manifestation of the aurora borealis caught me off guard.

I dashed upstairs and onto the station's roof and beheld a grand light show. Pillars of mostly white but some pale-green hues, with hints of red or pink, appeared and disappeared in the sky, stretching from the north to high overhead. Portland's bright lights no doubt diminished the aurora's grandeur, but the fact that it was visible from the city's center at all demonstrated that geomagnetic storm's enormous power. It was a G5, the most extreme on NOAA's Space Weather Prediction Center chart.

When the newscast ended at 11:30, three of us — a fellow reporter, the newscast's producer, and I — jumped in a car for an impromptu hour-and-a-half drive to the northeast of Portland. Out there beneath the darker sky over Trout Lake, Washington, the aurora's ghostly ribbons of light danced among the stars while croaking frogs provided the soundtrack.

Because of people like me — broadly, the news media — the public was aware of the chance to catch a glimpse of the northern lights. So that night and even through the weekend, people flocked to state parks and other areas away from urban lights, causing congestion and disturbing an otherwise quiet night.

▲ With Washington's Mount Adams in the distance, the aurora reflects off Trout Lake in the early-morning hours of May 11, 2024.

TOM SCHWABEL PHOTOGRAPHY

Despite the crowds and their unfamiliarity with dark-sky etiquette, I experienced a wonderful sense of community. People of all stripes gathered among strangers for a common purpose, united by the magnificence of the cosmos and inspired to consider their place in the universe, even if just for a few minutes. I was overcome with the recognition that the sky is for everyone.

On a professional level, to be part of something that allows me to inform people about their world, their universe, is fulfilling. And sometimes, even if momentarily, an unexpected joy can emerge from the darkness that often seems to pervade our world.

■ **STEVE BENHAM** is a digital content producer at KATU Television in Portland, Oregon as well as an avid amateur astronomer.


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