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SKY & TELESCOPE

THE ESSENTIAL GUIDE TO ASTRONOMY

OCTOBER 2022

The Mystery of Hot Jupiters

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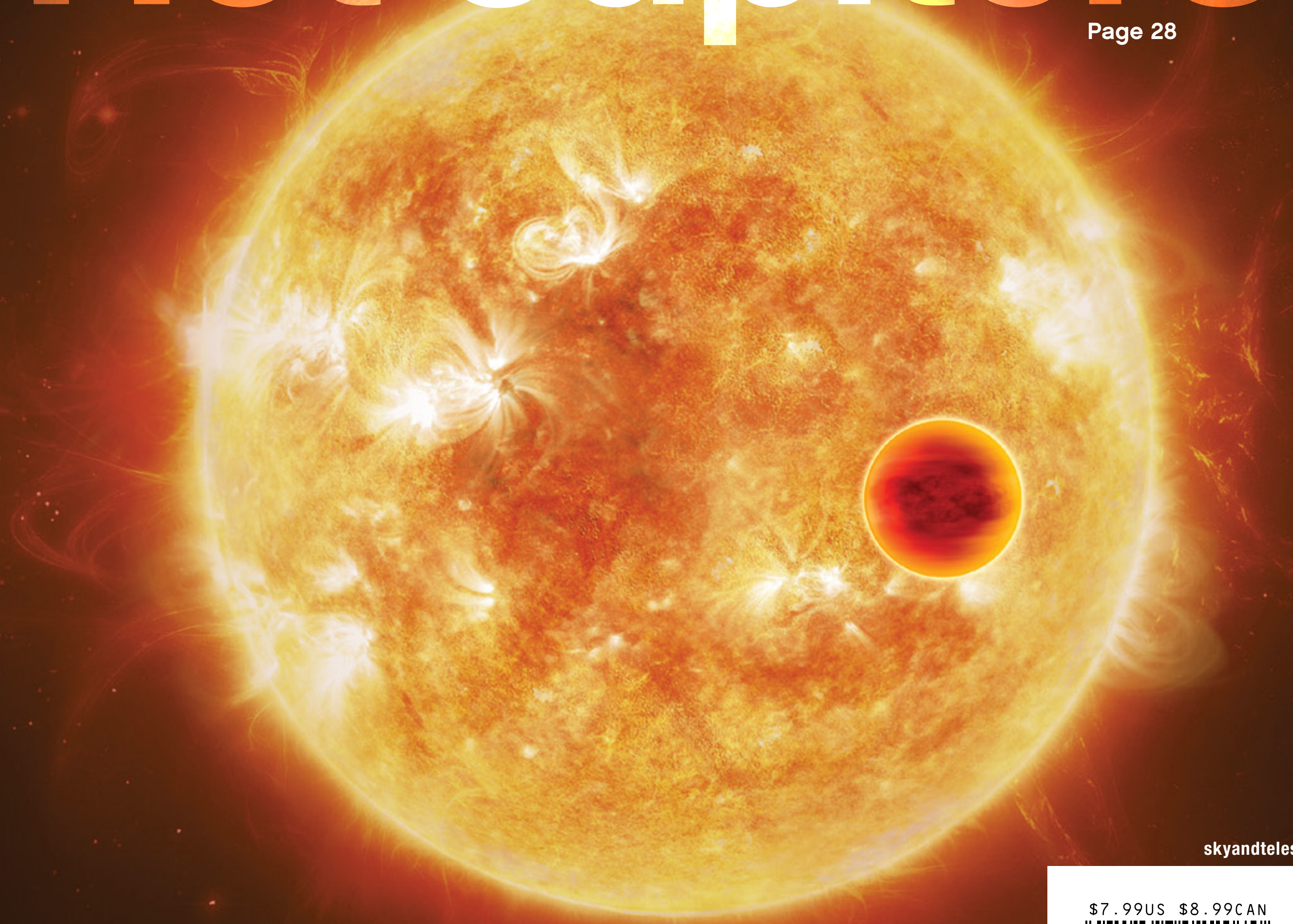

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Artist's concept of a planet close to its star

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In Good Company

HOW WOULD YOU DEFINE the community you belong to as an astronomer? All of us surely have our own delineation. Perhaps it's the group of friends you observe with, or the club you belong to, or the star parties you attend. Maybe it's simply all astronomers.

I would define our community even more broadly than that. To get an idea of what I mean, I point you to Alan Whitman's article on page 20. It's ostensibly about the finest emission nebulae in the sky — the Veil, Lagoon, Tarantula, and other nebulous wonders. But considered a certain way, his piece is as much about people as about clouds.

You won't see a single image of a person in his article, but it's remarkably well-peopled. Altogether, more than 30 surnames appear in it, and every one of those individuals, as I see it, is a member of our community.

Who are they? Some are stargazers Alan has observed with, quotes, or thanks, among them several Americans and Australians, two Argentinians, a South African, and a Dutchman based in Chile. Most of this handful of observers are men, but two are women. They also span a range of ages: In describing M42, the Great Orion Nebula, Alan compares his sight now, at age 75, with that of "keen-eyed" 18-year-old Zane Landers.

▲ Two fellow members of our community: William Herschel and Williamina Fleming

HERSCHEL: LEMUEL FRANCIS ABBOTT / WIKIMEDIA COMMONS / PUBLIC DOMAIN; FLEMING: CFA, HARVARD & SMITHSONIAN / PUBLIC DOMAIN

Thus, for Alan, the astronomical community comprises many nationalities, ages, and genders.

It extends back in time as well, I'd argue. The article mentions famous astronomers like William Herschel, E. E. Barnard, and Williamina Fleming, as well as lesser-known ones, such as the French astronomer Nicolas-Claude Fabri de Peiresc (1580–1637) and the American astronomer Lewis Swift (1820–1913).

Some of these past luminaries crop up as surnames only, out of their association with certain objects or areas. Thus, we read of Bok globules and the Huygens Region, of celestial objects labeled Messier or Collinder, Trumpler or Wolf-Rayet. Other last names are linked to books, such as Burnham, or to instruments, including the Dobsonian and the Hubble Space Telescope.

As we read these historic names in passing, it's easy to forget that all represent people who lived and loved the stars, just as we do. They're as much a part of our community as any astronomers alive today.

Of course, there's an elephant in the room here: Most were white and male. Our community today sorely needs to better reflect the diversity we see in society by more successfully welcoming people of all genders, races, ethnicities, and economic backgrounds. Only then will we truly be able to say we're in good company.

Peter

Editor in Chief

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The Essential Guide to Astronomy

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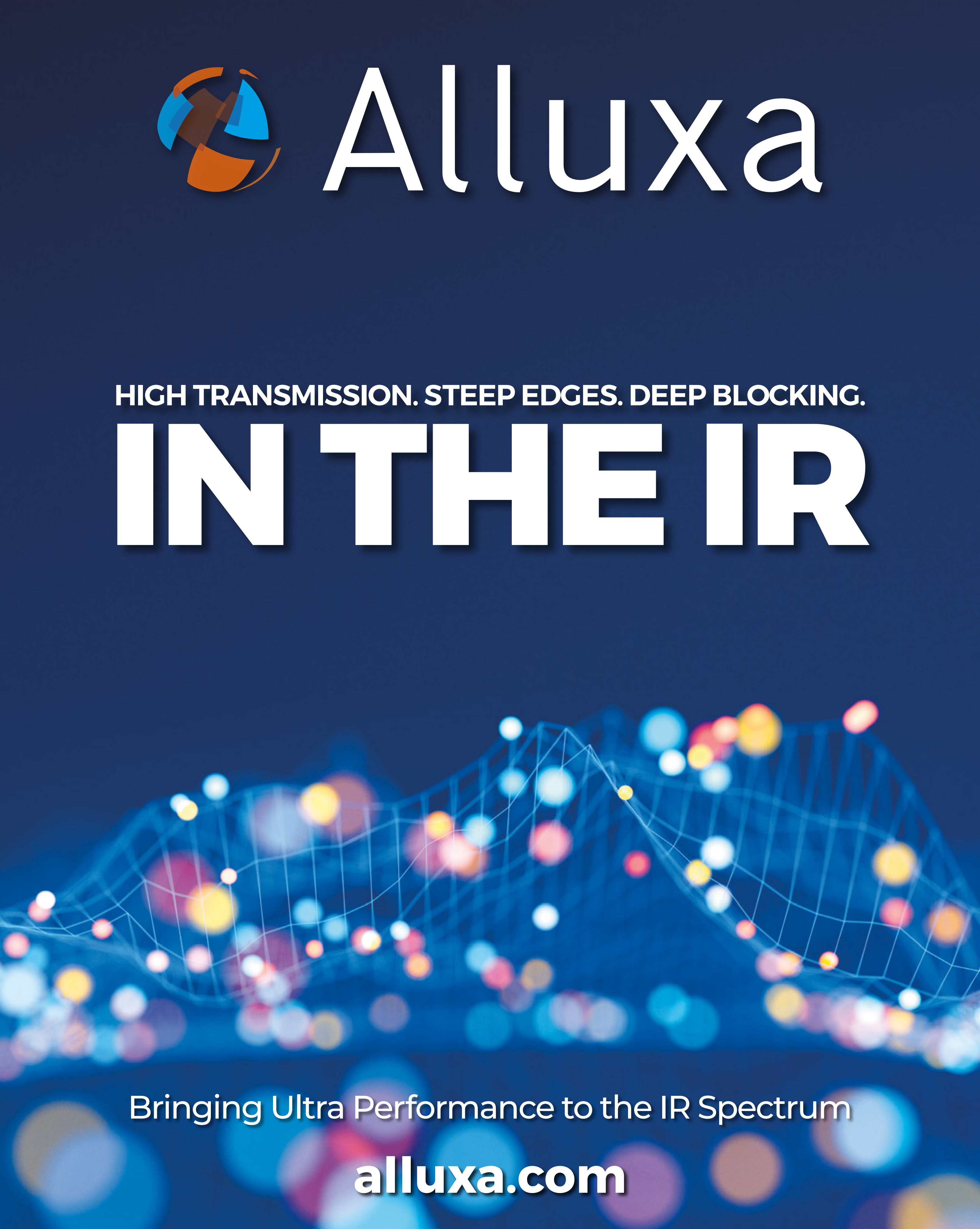
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RANDY STRAUSS

A Simple Milky Way

I thoroughly enjoyed Ade Ashford's "An Astrophotography Jargon Buster" (*S&T:* June 2022, p. 54). As a back-to-basics kind of astronomer, I enjoy seeing what my Canon EOS Rebel SL2 camera with its APS-C sensor and 18-to-55-mm lens on a basic tripod can deliver. I captured the Milky Way's core on a cold (30°F), calm, cloudless morning in late April at a nearby state park [see above]. I used *Sequator* to stack the 20-second sub-exposures and *GIMP* to bring out the details. It was refreshingly easy and a whole lot of fun. The only equipment failure was the single pair of socks I wore. Next time, two pairs!

Randy Strauss
Papillion, Nebraska

Galactic Treasures

I am an amateur astronomer, astrophotographer, and avid reader of *S&T*. Steve Gottlieb's "Let's Get Together" (*S&T:* June 2022, p. 36) is an excellent introduction to the topic of interacting galaxies. Not only are they beautiful objects for amateurs to image, but it's also fascinating to study the various stages they're at in their mergers.

Gottlieb's article was well presented, with great examples and options for the amateur to dive into this area of astronomy. A lot of this article hit home for me: I got back into astronomy and astrophotography when living in northern California (where Gottlieb is located). That's also where I started imaging galaxy interactions.

However, I do want to emphasize that while Gottlieb used his 18-inch scope, one can image many galactic mergers with an 11-inch scope if they have the patience to learn the proper techniques. I truly hope others with big scopes will take the time to look at these treasures of the heavens. I can guarantee they will not be disappointed.

Bruce A. Donzanti
Apopka, Florida

Historic Comets

John Bortle, quoted in Joe Rao's intriguing article "A New Meteor Shower?" (*S&T:* May 2022, p. 34), suggested that George Van Biesbroeck may have been the first to glimpse a comet's solid nucleus. He was not.

It is generally agreed that two other famed astronomers, Fernand Baldet and Vesto M. Slipher, independently observed a solid nucleus during the even closer approach of another periodic comet, 7P/Pons-Winnecke, in June 1927. In the 32-inch refractor at the Paris Observatory, Meudon, Baldet espied a "point stellaire unique" inside a 2-to-3-arcsecond condensation at the center of the 3° naked-eye coma. Because it never exceeded the size of the telescope's Airy diffraction disk, he inferred that the nucleus could be no larger than about 5 km at the comet's 0.039 astronomical unit distance.

At Lowell Observatory in Flagstaff, Arizona, Slipher likewise found a "perfectly stellar" nucleus in the 24-inch Clark refractor. He judged it to be about a tenth the apparent sizes of the disks of Jupiter's Galilean satellites, leading him to conclude that it "was not more than two or three miles [3.2 to 4.8 km] in diameter." As upper limits, Baldet's and Slipher's estimates are both close to the currently established value of about 5.2 km for 7P/Pons-Winnecke.

Van Biesbroeck did report a "nucleus" in 73P/Schwassmann-Wachmann 3 in the Yerkes 40-inch refractor throughout May, but it was "elongated" or only "nearly stellar" — never purely stellar like 7P's. Indeed, the "nucleus" magnitudes reported by Van Biesbroeck imply diameters that far exceed the current maximum estimate for 73P's core.

Joseph N. Marcus
St. Louis, Missouri

A New Meteor Shower

Thank you for Joe Rao's article about a potential new meteor shower. From the clear, transparent skies of Mathias, West Virginia, with a limiting magnitude of 6.5, I observed 20 Tau Herculids (THR) and 9 sporadic meteors from 11:36 p.m. to 12:36 a.m. EDT. The average brightness for the THR was about 4th magnitude. I also saw a fireball with a 3-minute train at 12:04 a.m. that was yellow-orange.

George W. Gliba
Screech Owl Hill Observatory
Mathias, West Virginia

Catching Gravitational Waves

A friend sent me his copy of the June issue, as I have a deep engagement in the gravitational-wave field. Specifically, I led the Advanced Laser Interferometer Gravitational-Wave Observatory (LIGO) Project that realized the detectors that have been so successful, and I served as the Spokesperson for the LIGO Scientific Collaboration from 2017 to 2019.

I really liked the overall tenor and depth of "What Gravitational Waves Have Taught Us About Black Holes" (*S&T:* June 2022, p. 12) by Camille M. Carlisle. It felt like it could serve as both a gentle introduction and a deep coverage that would satisfy many astrophysicists who do not work in the field (yet!).

David Shoemaker
Acton, Massachusetts

I really enjoyed your recent article on gravitational waves and black holes. I have a couple of questions. When gravitational waves alter the lengths of the detectors, for how long a period of time will the length stay changed, or is it just a split-second occurrence?

On page 13, it says "If you could convert the energy of a binary black hole merger into light, it would be brighter than all the stars in the observable universe." Does it mean all the stars put together? If so, that's incredible!

Mike Witkoski
Enola, Pennsylvania

Camille M. Carlisle replies: *It depends on the masses of the objects involved, but ballpark, the detectors' lengths oscillate for about a second in total. Mergers involving more massive objects shake the detectors for a shorter period of time, because the waves' frequency goes down as the mass goes up — the result of which is, the signal falls in LIGO's sensitivity range for a shorter period of time. There's a nice comparison of four signals' lengths at* ***https://is.gd/LIGO2017****.*

As to your second question: Yes, that's exactly what it means — it's crazy! LIGO scientist Shane Larson (Northwestern University) explains the calculation in his blog ***https://is.gd/MyBrainIsMelting****.*

Thank you for the article by Camille M. Carlisle on black hole mergers. It's an excellent article. Kudos to Carlisle for her thorough and engaging writing style.

James Edgar
Editor, RASC *Observer's Handbook*
Melville, Saskatchewan

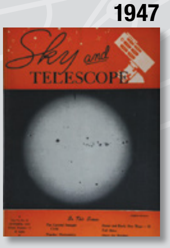
FOR THE RECORD

- In the "Select Targets for Beginning Sketchers" sidebar on page 59 of the June issue, the Owl Cluster is NGC 457.
- The image at the top right of page 64 in the August issue is M8.

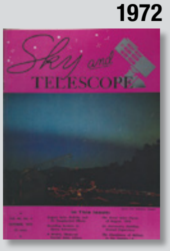
SUBMISSIONS: Write to *Sky & Telescope*, 1374 Massachusetts Ave., 4th Floor, Cambridge, MA 02138, USA or email: letters@skyandtelescope.org. Please limit your comments to 250 words; letters may be edited for brevity and clarity.

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

1947



1972



1997

◖ October 1947

Biggest Sunspot "Never before has the sun's surface been so closely watched as now. . . . This interest was fathered by the discovery that radio reception varies with changes in solar activity. . . . Wartime needs stimulated the study of these solar effects, with the result that many people who had never heard of sunspots before became quite conscious of them. . . .

"The largest single sunspot (penumbral area including umbrae) ever recorded appeared in March, 1947. By April, this spot had divided into several parts which grew to form the largest group of spots ever observed. . . .

When largest, it appeared to cover more than one [percent] of the apparent solar disk, its area being 6,300,000,000 square miles, 5,400 millions of the actual solar hemisphere."

The records mentioned by Seth B. Nicholson still hold.

◖ October 1972

Telescope Meet "As is traditional at Stellafane, awards were tailored to the telescopes on hand. . . . The 12-inch f/5.3 reflector of Albert H. Nagler received first prize for Newtonians. An engineer from Spring Valley, New York, he refigured another amateur's mirror and made the unique perforated diagonal [that] permits guiding on an object while it is being photographed . . . Most of the light (equivalent to that gathered by a 10-inch aperture) is reflected toward the camera . . . but some (from a six-inch annulus at the center of the primary) enters the perforation and goes through a 2x Barlow and diagonal to the guiding eyepiece . . ."

Many optical entrepreneurs got their start at this annual telescope-making convention in Springfield, Vermont. In 1977, the same Al Nagler would form Tele Vue Optics, well-known for its line of exquisite eyepieces and small refractors.

◖ October 1997

Moon's Birth "The idea that something the size of Mars sideswiped the Earth in its infancy to form the Moon is not new; researchers Wiliam K. Hartmann and Donald R. Davis first offered the 'Big Splat' scenario in the mid-1970s. . . . Building [on] this earlier work, Shigeru Ida (Tokyo Institute of Technology) and Robin M. Canup and Glen R. Stewart (University of Colorado) have now simulated the collision's aftermath with unprecedented detail.

"They find that the massive cloud of vaporized rock ejected by the impact flattens into a disk within a few months. . . . Canup notes that only impactors with 2½ to 3 times the mass of Mars can create a disk with a Moon's worth of matter outside the Roche limit. The catch, she says, is that the Earth-Moon system is then left with about twice the angular momentum it has today . . ."

Canup and others continue to refine details of this impact, which remains the leading theory of the Moon's origin.

STARS

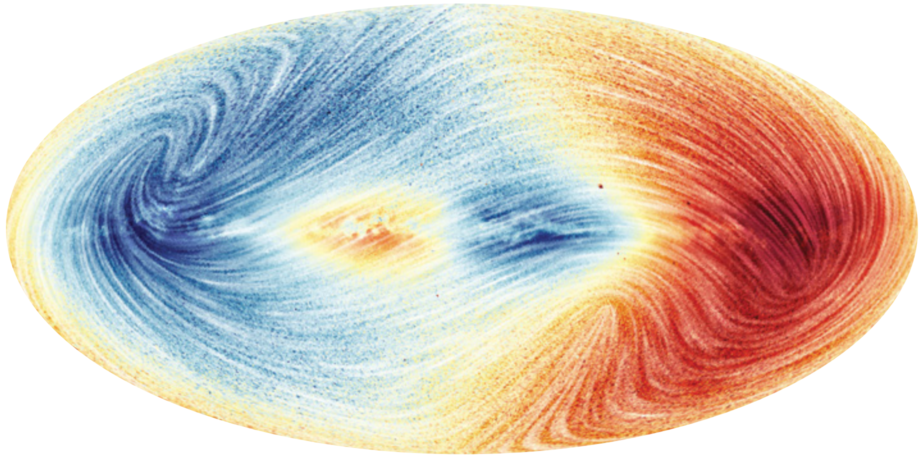
The Gaia Revolution: New Data, Strange Stars

THE GAIA MISSION, run by the European Space Agency, released its third data set on June 13th, which includes new details on 1.8 billion stars in the Milky Way and beyond.

"[This] day has been anticipated by the entire astronomical community," says Ricardo Schiavon (Liverpool John Moores University, UK). "I, for instance, woke up way too early and could not go back to sleep thinking about it!"

The newest data, which accompany a series of studies that will appear in a special issue of *Astronomy & Astrophysics*, contain information on 1.2 million stars in the Andromeda Galaxy, millions of entire galaxies and quasars, and more than 100,000 objects in our cosmic backyard, including solar system moons, asteroids, and comets.

Most anticipated, though, is the first-ever release of Gaia's spectroscopy, obtained for 220 million stars in the largest-ever low-resolution spectroscopic survey. For a subset of 33 million stars, the spectra reveal their motions toward and away from Earth. By combining



▲ This velocity map of the Milky Way shows our galaxy's rotation as stars move toward us (blue) and away (red). Traces represent stars' proper motions across the sky.

these *radial velocities* with Gaia's already measured *proper motions* across the sky, astronomers can obtain stars' 3D velocities through space. (Previous releases have provided stars' 3D positions.)

In addition to radial velocities, the chemical fingerprints in spectra can also reveal a star's key characteristics, including its temperature, mass, rotation, and composition.

Gaia's repeat measurements are also adding the dimension of time to studies of stars' shape changes, which cause their brightnesses to vary. In addition to regular variations, occasional instabilities can sweep like a tsunami across a boiling stellar surface. Gaia has now spotted thousands of these tsunamis — including on stars that current theory says shouldn't have them.

The newest release includes observations taken between July 2014 and May 2017. That's half again the timeframe covered by the second data release. Gaia is expected to release another incremental dataset before publishing the full analysis of all the data the space telescope has collected. Our view of the stars, our galaxy, and their histories will only continue to sharpen in the years to come.

■ **MONICA YOUNG**

Read more about the data's potential at https://is.gd/GaiaDR3.

PROFESSIONAL TELESCOPES

Wildfire Threatens Kitt Peak Observatory

THE CONTRERAS FIRE threatened the historic Kitt Peak National Observatory in southern Arizona this summer, reaching the summit on June 17th. The fire also impacted the surrounding communities of the Tohono O'odham Nation. The wildfire started on June 11th and burned almost 30,000 acres until monsoon rains aided its containment by June 25th. As of press time, access to the observatory remains limited to essential personnel.

Aerial and ground crews successfully held the line around the observatory. Kitt Peak associate director Michelle Edwards and safety manager Joe Davis,

▲ The Contreras fire burned on the slopes of Kitt Peak on June 16th.

both of whom were able to view the outside of the structures at the peak, reported that "all physical scientific observatory structures are still standing." A dorm, a cabin, and a small shed were lost in the fire.

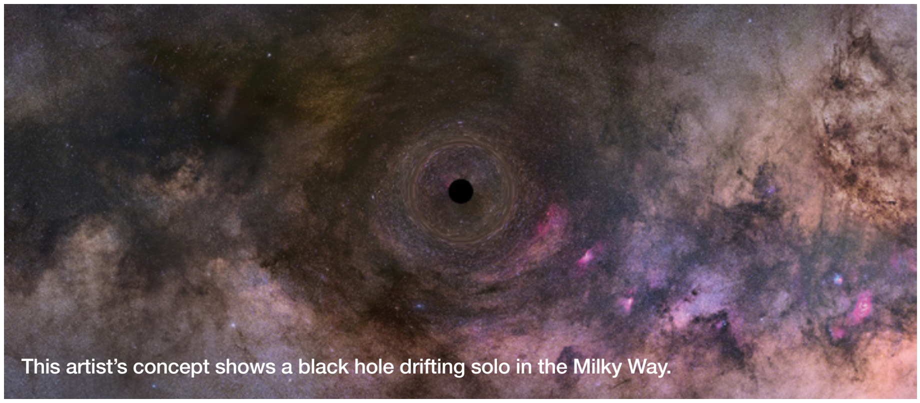
"We will have a much better understanding of the full extent of the damage in coming weeks," adds Shari Lifson (Association of Universities for Research in Astronomy). "All we know now is that it seems as if the prior assessment that all of the domes and other scientific structures are intact is correct." It will likely take months to resume observations.

Due to climate change and worsening heat waves, wildfire threats to observatories in the American Southwest have become increasingly common, including two recent burns that reached the Lick and Mount Wilson observatories (*S&T:* Jan. 2021, p. 12). No other wildfire has come so close to Kit Peak since its construction.

■ **DAVID DICKINSON**

BLACK HOLES

First Rogue Black Hole Candidate Found


This artist's concept shows a black hole drifting solo in the Milky Way.

TWO TEAMS OF ASTRONOMERS have used the Hubble Space Telescope to make what might be the first detection of a stellar-mass black hole drifting alone through our Milky Way.

Black holes in our galaxy usually only reveal themselves in binaries, either by snacking on siphoned material or by their gravitational influence on their companion. But there are an estimated 100 million black holes, wandering solo through the Milky Way, that evade direct detection.

Now, after a decade of monitoring the galactic center with ground-based telescopes and years of meticulous follow-up observations with the Hubble Space Telescope, astronomers have tracked down a solitary black hole candidate roughly 5,000 light-years away.

The discovery came by way of *gravitational microlensing*, which involves a chance alignment between a visible background star and an invisible foreground object. The gravity of the foreground object bends the background light, magnifying it like a lens and subtly shifting its position on the sky. The way the background star brightens and shifts reveals the foreground object's mass, distance, and velocity.

Typically, microlensing brightens background stars for a few weeks, but the object's intense gravity stretched the duration to almost nine months. What's more, the color of the background star remained constant throughout the event; had the foreground object also been a star, their colors would have mixed temporarily.

Intrigued, two teams — one led by Kailash Sahu (Space Telescope Science Institute) and another by Casey Lam (University of California, Berkeley) — investigated follow-up Hubble observations. Both teams analyzed the 2011 brightening event and made extremely precise measurements of the background star's apparent shift in position in the years afterward. As-yet unknown differences in the analyses resulted in the teams arriving at divergent answers for the foreground object's mass: between 5.8 and 8.4 solar masses for Sahu's team and 1.6 to 4.4 solar masses for Lam's team.

The latter result leaves the object's nature open to interpretation: If it's at the lower end, it could be a neutron star instead. The results will appear in *Astrophysical Journal* and *Astrophysical Journal Letters*, respectively.

Additional discoveries like this one, says Adam Ingram (Newcastle University, UK), who wasn't involved in either study, will give astronomers a better feel for the population of black holes typical to our galaxy.

■ COLIN STUART

The Wild Winds of Mars

NASA's Perseverance rover is using its cameras and other sensors to record the winds in Jezero Crater, enabling scientists to analyze the winds' role in lifting dust into the Martian air. Astronomers have witnessed dust storms on Mars for centuries, but it remains unclear how so much surface material becomes airborne. An analysis from the rover's first 216 sols on Mars, published in the May 27th *Science Advances*, shows that winds play an important part. Perseverance has watched hundreds of dust devils cross the crater. However, rare wind gusts appear to kick far more dust into the air than the smaller daily whirlwinds do. The frame above comes from a video (**https://is.gd/Marswinds**) that shows a wind gust lifting up a massive cloud of dust, the first time such an event has been filmed on Mars. The rover witnessed two other gust-lifting events, the biggest of which formed a huge cloud covering 4 square kilometers (1.5 square miles). "We think these gust-liftings are infrequent," says team lead Claire Newman (Aeolis Research), "but could be responsible for a large fraction of the background dust that hovers all the time in the Martian atmosphere."

■ DAVID DICKINSON

BLACK HOLE: FECYT / IAC; DUST ON MARS: NASA / JPL-CALTECH / SSI

EXOPLANETS

White Dwarf Reveals Planetary System Chaos

In this artist's illustration, a white dwarf star siphons off debris from shattered objects in a planetary system.

NEW OBSERVATIONS found evidence of both rocky-metallic and icy worlds falling onto a white dwarf, indicating past orbital chaos within the system.

G238-44, a white dwarf 86 light-years away, is accreting two very different kinds of objects simultaneously, Ted Johnson (University of California, Los Angeles) told the 240th meeting of the American Astronomical Society in Pasadena, California. "This has never been observed before," he said.

White dwarfs are the compact cores of low-mass stars, which first balloon into red giants — a fate that awaits our Sun in some 5 billion years — before blowing off their outer layers in planetary nebulae. These stars' evolution can cause them to devour close-in planets, while the orbits of more distant worlds become jumbled. Indeed, a third of white dwarfs have shown signs of atmospheric "pollution," unexpected amounts of elements heavier than helium that suggest rocky debris has rained down onto the stellar core.

But on G238-44, the surface's chemical composition — as measured by NASA's Far Ultraviolet Spectroscopic Explorer, the Keck Telescope in Hawai'i, and the Hubble Space Telescope — doesn't match that of any single solar system object.

According to Johnson, the polluting material is best described as 1.7 parts Mercury-like debris — typical rocky stuff — and one part more similar to the icy Kuiper Belt objects in the solar system's outskirts. The findings suggest that the star's planetary system had experienced extreme tumult, which flung remote icy bodies inward.

Dennis Bodewits (Auburn University), who was not involved in the study, found the result intriguing, but suggests a single, complex object, such as Ceres, could have polluted the white dwarf. Johnson agrees it's possible but thinks the two-body scenario is more likely.

With just one strange white dwarf, it's difficult to draw definitive conclusions. Future observations may yield additional cases. "It's an interesting find," says Bodewits, "but I wish there were more."

■ **GOVERT SCHILLING**

SPACE

Starlink Satellites Are Brighter Again

UPDATES TO SPACEX'S Starlink satellites have made them brighter again, though they are still dimmer than the original design.

Due to the concerns of the astronomy community, SpaceX voluntarily began installing sunshades on their Starlink satellites two years ago. These VisorSats were about 1.3 magnitudes dimmer than the original satellites (*S&T:* June 2021, p. 16). But as newer satellites have shifted to using lasers rather than radio for communication, the company has omitted visors from Starlinks as of late last year.

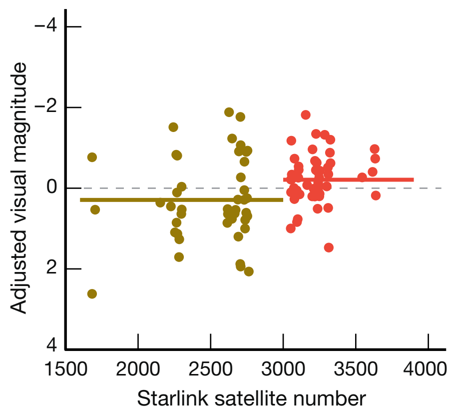
SpaceX engineer David Goldstein discussed these changes with the Federation of Astronomical Societies on May 7th. He added that the company has added dielectric mirrors to the Earth-facing side of the Starlink chassis, to reflect sunlight away from observers directly below the spacecraft.

I analyzed magnitudes of the new design, recorded earlier this year by satellite observer Jay Respler. After adjusting observed magnitudes for the satellites' distance from the observer and angle relative to the Sun, I found that the new spacecraft are about 60% brighter than the VisorSats. (And even the VisorSat design wasn't able to meet the 7th-magnitude limit astronomers had recommended to minimize interference with both research and enjoyment of the night sky.) However, the new satellites still represent an improvement of about 0.8 magnitude compared to the original design.

In May, SpaceX CEO Elon Musk spoke of building a new generation of Starlinks that will be much larger and heavier than the current model, at 7 meters (23 feet) long and 1¼ tons. Starlink 2.0 could end up exceeding the brightness of the current satellites.

In response to the growing number of satellites in low-Earth orbit, the International Astronomical Union (IAU) is establishing a Centre for the Protection of the Dark and Quiet Sky from Satellite Constellation Interference. Under the management of astronomers Piero Benvenuti (IAU), Connie Walker (NSF's NOIRLab), and Federico Di Vruno (Square Kilometer Array Observatory), this center will serve those seeking to preserve dark skies.

■ **ANTHONY MALLAMA**



▲ The newest Starlink spacecraft (orange dots) average about 0.5 magnitude brighter than VisorSats after adjusting for distance and solar angle. The scatter in the plot comes from variations in satellite orientation.

WHITE DWARF: NASA / ESA / JOSEPH OLMSTED (STSCI); MAGNITUDES OF STARLINK SATELLITES: ANTHONY MALLAMA

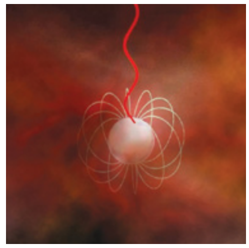
FAST RADIO BURSTS

Unusual Source Deepens Radio Burst Mystery

JUST WHEN WE WERE beginning to think we understood the mysterious radio flashes known as *fast radio bursts* (FRBs), new observations make clear how much we still have to learn.

The FRB 20190520B is one of a kind, Chen-Hui Niu (Chinese Academy of Sciences) and colleagues announce June 8th in *Nature*. It flared again and again in observations recorded by China's Five-hundred-meter Aperture Spherical Radio Telescope, putting the source among the few percent of FRBs that repeat. However, unlike most repeaters, this one never turned off. A low, persistent buzz of radio waves emanates from the same source.

Perhaps most importantly, the radio bursts appear to come from an extreme environment, one with an abundance of ionized gas and strong magnetic fields. Niu and colleagues base the latter claim on the FRB's smear across frequencies, known as its *dispersion measure*. This effect, which occurs when radio waves pass through a plasma, is common to FRBs. Astronomers think it indicates the bursts travel extreme distances through sparse intergalactic plasma.



◀ In this illustration of a fast radio burst scenario, a magnetar is embedded in dense plasma.

If that were the case, this FRB's radio waves would have traveled for more than 7 billion years. But when Niu and team used the Karl G. Jansky Very Large Array and the Canada-France-Hawaii Telescope to pinpoint the FRB's location, they placed it in a dwarf galaxy only 2.9 billion light-years away. The researchers realized that most of the signal's smear had to come from much denser plasma around the FRB itself.

"I agree with the paper's suggestion that the high dispersion measure is probably due to the immediate environment," says FRB expert Adam Lanman (McGill University, Canada), who wasn't part of the study.

The discovery also throws into question whether magnetars are behind *all* FRBs. "I would say that this discovery favors an explosive event," contends team member Di Li (Chinese Academy of Sciences). "But I cannot say that it rules out a magnetar."

■ MONICA YOUNG

DARK SKIES

What We Know About Light Pollution — And What We Don't

THE INTERNATIONAL DARK-SKY ASSOCIATION has summarized more than 300 peer-reviewed studies on the effects of light pollution in a report titled "Artificial Light at Night: State of the Science 2022."

"Our goal was to provide dark-sky advocates with a reliable summary of science results in accessible language that will help them explain the issues to others," explains John Barentine (Dark Sky Consulting).

One of the biggest issues facing dark skies are LED lights. While LED replacements of other light sources consume less energy, their lower cost ultimately results in over-lighting, the report finds. In addition, LEDs typically emit bluer light, which harms wildlife and human health as well as astronomy.

Mounting evidence shows that light pollution harms animals on all scales, hindering food-finding, reproduction, migration, and communication among birds, pollinators and other insects, amphibians, mammals, and even fish.

Artificial light at night may also wreak havoc on human hormonal systems. However, scientists still debate the influence of outdoor versus indoor light at night, and other factors may contribute to negative outcomes.

There are also mixed results when it comes to research on lighting and safety. The report notes that decision makers often substitute their intuition when scientific guidance is lacking, resulting in more light than necessary. Carefully designed studies of artificial light's impacts on safety are needed, the report concludes.

Finally, the report addresses growing light pollution from space: Thousands of satellites in low-Earth orbit now streak through twilight skies, and they also have an aggregate effect. Researchers calculate that the rising number of satellites and accompanying space debris have already increased sky glow by about 10%. It isn't noticeable yet but could be in the future.

The IDA plans to update the document in light of future developments.

■ JAN HATTENBACH

Find more details and a link to the full report at https://is.gd/IDAreport.

IN BRIEF

A Galactic Mystery

The spiral galaxy M81 in Ursa Major is much like our own Milky Way. But when Eric Bell (University of Michigan) went in search of faint dwarf galaxies around M81 using the Hyper Suprime-Cam on the Subaru Telescope on Mauna Kea, Hawai'i, he found something unexpected. While he discovered seven ultra-faint satellites like the ones around our own galaxy (six are candidates that will need Hubble or James Webb Space Telescope observations to confirm their identity), he didn't find them around M81. Instead, they cluster to one side, around a much smaller neighboring galaxy in the group, NGC 3077. So what happened to the satellites circling M81? It's possible that its gravitational field creates tidal forces that rip apart any smaller galaxies that venture too close. But if tidal forces are to blame, Bell says, then that's a puzzle, too: "Tides are just gravity, so they're already incorporated in models of galaxy formation." Observations like this one may help refine models, but for now, the mystery of the missing satellites remains unsolved.

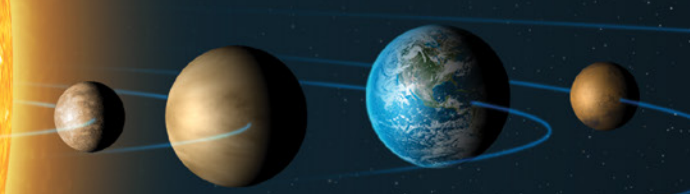
■ MONICA YOUNG

BILL SAXTON / NRAO / AUI / NSF

KEEP DIST

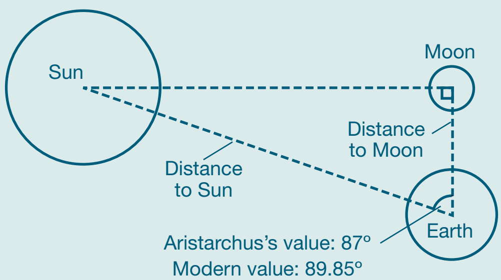
Cows can't jump over the moon, no one has ever touched a star, and according to the opening crawl of *Star Wars*, galaxies are "far, far away." But if rulers and tape measures don't work in the wider universe, how do astronomers gauge cosmic distances? How did we endow the night sky with a third dimension? And, given that space is expanding, what does the concept of distance mean anyway?

Many people struggle with these ideas. Separations of thousands or millions of light-years quickly lose their meaning when the method behind the measurement eludes you. So we've decided to tackle the matter head-on, starting in the solar system and expanding out to the farthest reaches of the cosmos. Buckle up for our crash course in cosmic surveying.

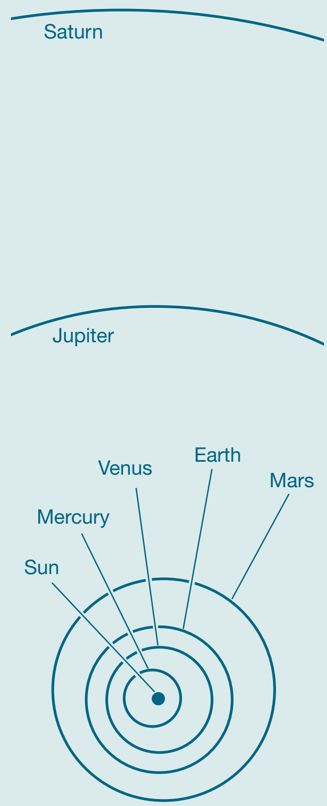


Step 1. The Solar System

Greek astronomer Aristarchus of Samos (3rd century BC) was one of the first to tackle the problem of taking a ruler to the universe: He determined the relative distances of the Sun and the Moon from Earth. Aristarchus tried to measure the angle between the Sun and the Moon on the sky at the exact moment of a half-moon (either first or last quarter). You might think the answer is obvious (90°), but that's only true if the Sun is at an infinite distance. Aristarchus arrived at a value of 87°, which told him the Sun is 19 times farther away than the Moon. Completely wrong — it's actually 390 times more distant, and the angle that Aristarchus was after is in fact 89.85° — but at least it was a start.



In the early 17th century, German astronomer Johannes Kepler derived his laws of planetary motion. His third law (the square of a planet's orbital period is proportional to the cube of its distance from the Sun) enabled him to calculate the relative sizes of all planetary orbits. It's simple: Jupiter's orbital period is 11.86 years, or 11.86 times the orbital period of Earth. Square this number (11.86 × 11.86 = 140.66) and take the cube of the result ($\sqrt[3]{140.66} = 5.2$), and you arrive at the relative size of Jupiter's orbit compared to Earth's. However, absolute distances were still unknown — Kepler could draw a correct map of the solar system, but he didn't know the map's scale.

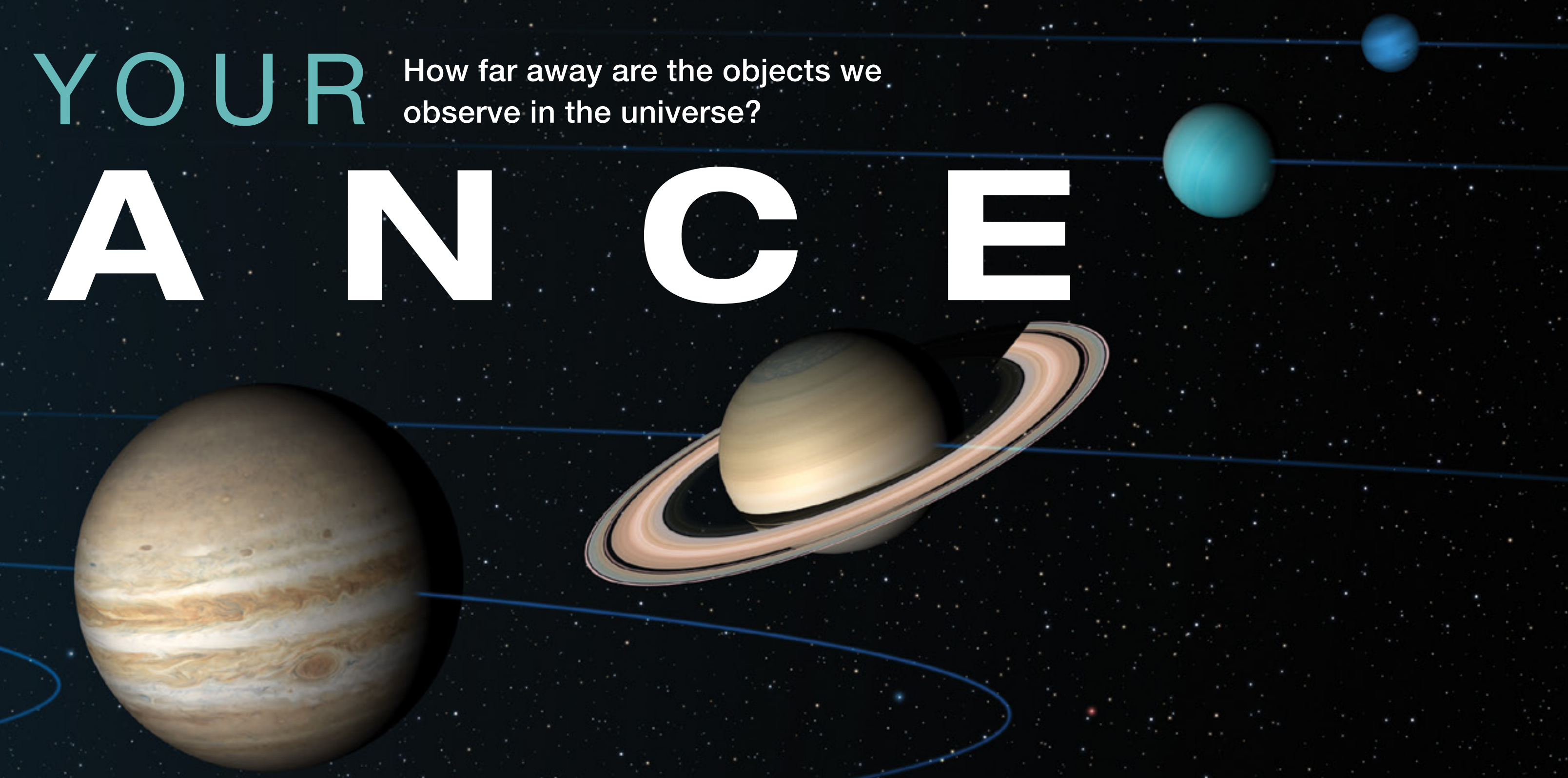


ALL ILLUSTRATIONS: CASEY REED; ALL DIAGRAMS: LEAH TISCIONE / S&T

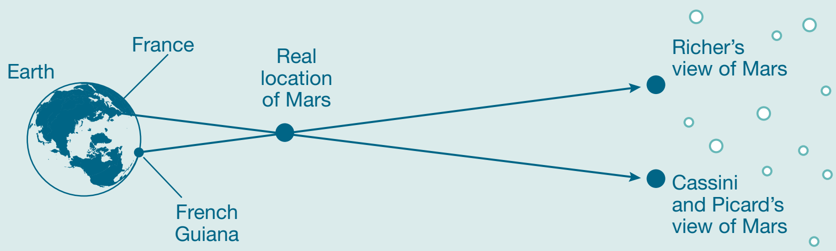
YOUR

How far away are the objects we observe in the universe?

A N C E



Parallax came to the rescue in the late 17th century. You're probably familiar with the principle: First shut your left eye, then your right eye, and nearby objects appear to shift with respect to the background. The larger the shift, the closer the object is. Gian Domenico Cassini, Jean Picard, and Jean Richer measured the position of Mars among the stars at exactly the same time, but from different parts of the globe, in France and French Guiana. Their estimate of the distance of Mars was only 7% off. Later, timing measurements by observers watching Venus pass across the face of the Sun from different places on Earth, as well as parallax measurements of the near-Earth asteroid 433 Eros, gave even more reliable results (*S&T:* Jan. 2012, p. 70).



The most precise distance estimates in the solar system ping targets with radio waves, which travel at the speed of light. Send a powerful radar pulse to the Moon, Venus, or an asteroid; measure how long it takes before you receive the faint echo; and it's straightforward to calculate the distance, with a precision of less than an inch. The same can be done by pinging a spacecraft that's orbiting a remote planet.

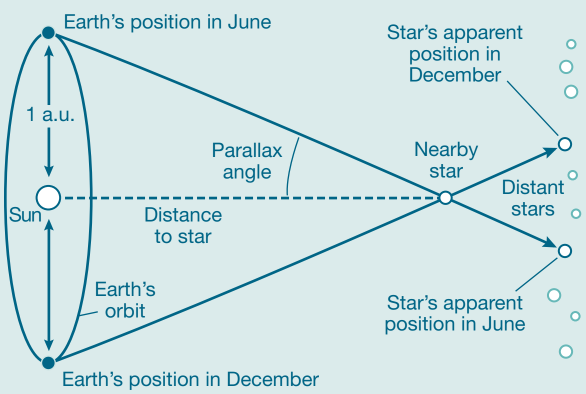
Some 2,300 years after Aristarchus, we've finally come to grips with the size and scale of the solar system. But what about the distances to the stars?

To Stars, Clusters, and Nebulae

Step 2. Stars, Clusters, and Nebulae

If each and every star in the universe had the same true luminosity as the Sun, gauging stars' distances would be easy: A star's apparent brightness would immediately tell you how distant it is, because a light source looks fainter the farther away it is. In fact, 17th-century Dutch astronomer Christiaan Huygens calculated the distance to Sirius (the brightest star in the night sky) by *assuming* it has the same luminosity as the Sun. Huygens concluded that Sirius had to be 27,664 times farther away than the Sun, corresponding to a distance of 0.437 light-year. "A bullet would spend almost seven hundred thousand years in its journey" between Earth and Sirius, Huygens wrote in his 1698 book *Cosmotheoros*. Parallax measurements (see next section) have since revealed that Sirius is actually 8.61 light-years away, implying that it is much more luminous than the Sun.

The most reliable way of gauging a star's distance is by measuring its *annual parallax*. The distance between France and French Guiana is too small a baseline to notice a shift in a star's position. But the diameter of Earth's orbit (300 million kilometers) is large enough. In 1838, German astronomer Friedrich Bessel was the first to accurately measure the position of a nearby star (61 Cygni) from two opposite points of our orbit around the Sun, half a year apart. Using current ground-based telescopes, the method works fine for stars out to a few hundred light-years. The ultra-precise European space telescope Gaia has measured parallaxes for more than a billion stars out to distances of thousands of light-years, although the accuracy rapidly diminishes with distance.



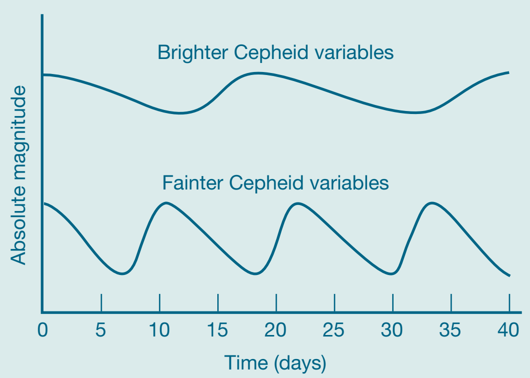
For a large collection of stars, like an open cluster or a globular cluster, astronomers can calculate a rough distance estimate by plotting each constituent star's color (or temperature) against its apparent brightness. Such a plot is called a *Hertzsprung-Russell diagram*. Astronomers know the relation between color and true luminosity for stars like the Sun that are fueled by hydrogen fusion in their cores. Comparing apparent brightness with true luminosity then yields the distance to the cluster. For gaseous nebulae, no such straightforward method exists — that's why distances to nebulae are notoriously uncertain, unless they contain stars for which distances can be derived. For instance, distance estimates for the Lagoon Nebula (M8) ranged from 4,000 to 6,000 light-years, until Gaia measurements helped confirm the lower value.

ECLIPSING BINARY SOURCE: NASA

To Galaxies

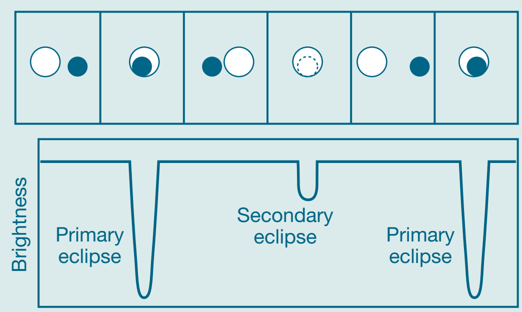
These methods and others have enabled us to chart various distances within our home galaxy. But things become more complicated — and less secure — when we reach beyond the Milky Way.

Certain variable stars, known as *Cepheids* (named after the prototype Delta Cephei), can be used as cosmic yardsticks. These stars show regular pulsations: They grow larger and smaller over time, with their energy output following suit. It turns out there's a relation between the peak luminosity and the pulsation period: The brightness variations are slower for more luminous stars and faster for the dimmer ones, as American astronomer Henrietta Leavitt discovered in the early 20th century (*S&T:* Dec. 2021, p. 12). By observing relatively nearby Cepheids, astronomers have calibrated this period-luminosity relationship. So if you see a distant Cepheid, just measure its pulsation period, use the Leavitt Law to find the star's true luminosity, compare it to its apparent brightness, and out rolls the distance.



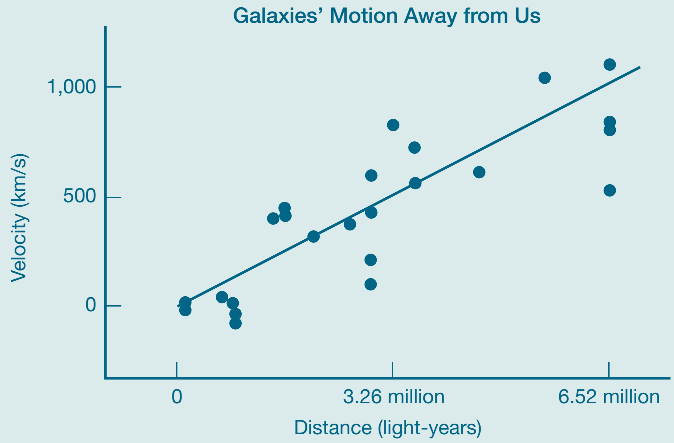
Another type of variable star for which individual distance estimates are possible is an *eclipsing binary*, in which two stars orbit a common center of gravity and mutually eclipse each other from our point of view. Although the stars are generally too close to each other to be observed separately, Doppler measurements reveal their orbital velocities: As one star approaches us, its light shifts to slightly shorter, bluer wavelengths, while the light from the receding star shifts to longer, redder ones. The result is a periodic doubling of the lines in the binary's spectrum. Combining this velocity info with how long it takes the binary to complete an orbit yields the true physical dimensions of the system. From precise eclipse timings — ingress, duration, and egress — you can then easily derive the radii of the two stars. Detailed spectroscopy tells you the *surface flux* of the stars, the amount of light emitted per unit area. If you know a star's radius and its surface flux, you can calculate its true luminosity. Finally, comparing the true luminosity to the observed apparent brightness gives you the distance.

Eclipsing binary stars

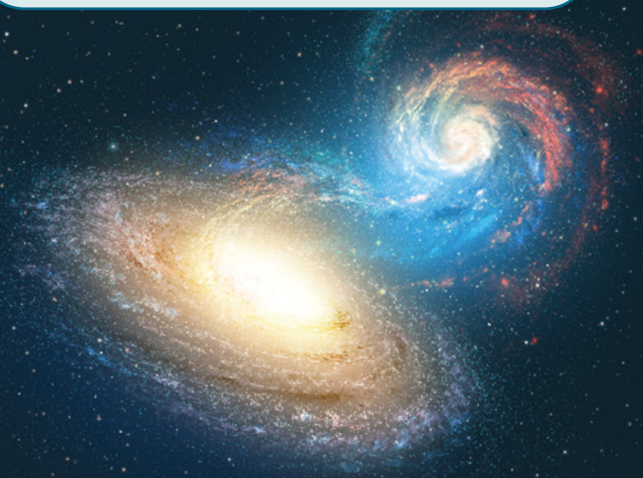


Step 3. Galaxies

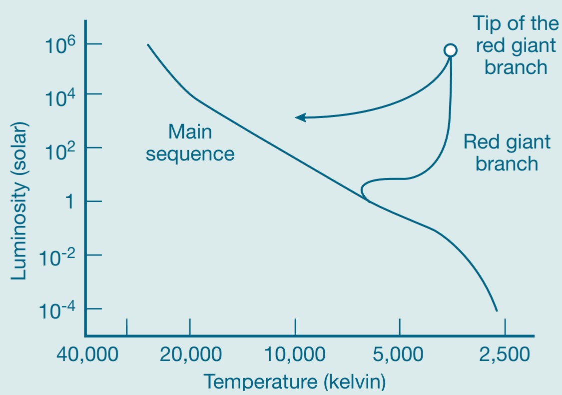
Just looking at a remote galaxy doesn't reveal its distance. In fact, in the early 20th century many astronomers assumed that "spiral nebulae" were part of our Milky Way. Others correctly believed they were huge collections of stars similar to and way beyond the Milky Way. If so, rough guesstimates of their distances could be made by simply assuming that they all have the same size and luminosity as our home galaxy — just like Huygens assumed that other stars were similar to the Sun. In fact, after American cosmology pioneer Edwin Hubble established the true nature of galaxies by measuring distances to the nearest ones (see next section), he made similar assumptions about more distant galaxies — for instance, that the brightest star-forming region in any galaxy always emits more or less the same amount of light. That enabled him to conclude that a galaxy's distance is proportional to its observed recession velocity and helped him to discover that the universe is expanding.



Today, to gauge a galaxy's distance, astronomers use *standard candles* — objects whose true luminosity is known. Extragalactic eclipsing-binary stars are generally too faint to study in much detail, but Cepheids are bright stars. In 1923, Hubble was the first to discover a Cepheid in the outer regions of the Andromeda "Nebula," enabling him to convincingly prove that the fuzzy spiral lies well outside our Milky Way Galaxy. (We now know it's 2½ million light-years away.) Using the Hubble Space Telescope, astronomers have studied Cepheids in galaxies tens of millions of light-years away. According to Adam Riess (Space Telescope Science Institute), the current best calibration of the Cepheid period-luminosity law comes from Gaia parallaxes and accurate Hubble photometry. "The result is a 1% accuracy in Cepheid distances," he says.

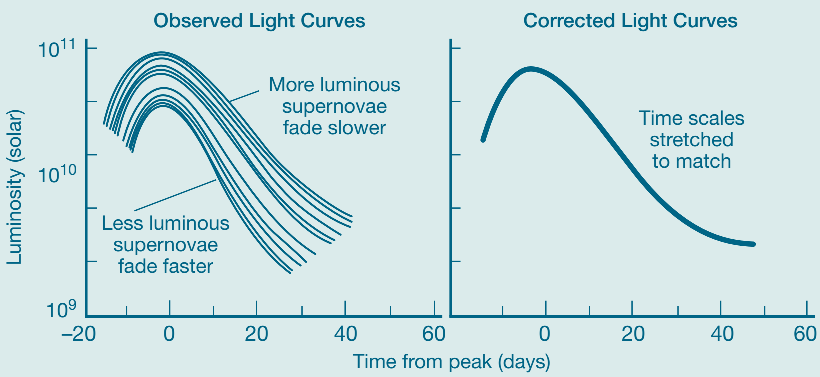


More recently, Wendy Freedman (University of Chicago) has pioneered the use of red giant stars as standard candles. Red giants are highly evolved stars that have used up the hydrogen fuel in their cores, converting it into helium. It turns out that red giants can only be so luminous: The star reaches a maximum value when the helium core becomes dense enough to generate a runaway thermonuclear explosion. So if you plot the Hertzsprung-Russell diagram for a large enough collection of red giant stars in a particular galaxy, the *tip of the red giant branch* (TRGB) is always located at the same true luminosity. "There are many advantages of the TRGB [method] over Cepheids," says Freedman. "In the future, I think that it will prove more accurate than the Cepheids."



HUBBLE DIAGRAM SOURCE: E. HUBBLE / *PROCEEDINGS OF THE NATIONAL ACADEMY OF SCIENCES* 1929; TRGB SOURCE: RICHARD POGGE; SNIA LIGHTCURVE SOURCES: C. R. NAVE / HYPERPHYSICS AND JOHN LUCEY / DURHAM UNIV.

Another useful standard candle is *Type Ia supernovae* — the catastrophic detonations of white dwarf stars. These stellar explosions can be seen over vast distances (they can rival their host galaxy's luminosity), and they always produce more or less the same amount of energy. Granted, some are more luminous than others, but astronomers can correct for that because fainter explosions fade more rapidly. All in all, it's a reliable method, and according to Riess, the calibration and accuracy of supernova Ia distances has only improved in recent years.



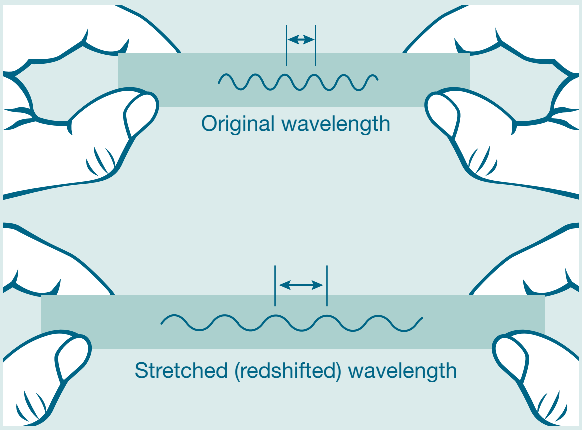
Finally, for a small number of galaxies a truly geometric distance estimate is possible. Small regions in the accretion disks around some supermassive black holes emit powerful *maser* emission (the microwave equivalent of laser light). Doppler measurements tell astronomers the line-of-sight velocities of these masers. High-resolution radio observations reveal the masers' minute motions in the plane of the sky. By combining real velocities and apparent motions, it's straightforward to derive the distance — a feat that has been successfully achieved for the active spiral galaxy M106, which turns out to be about 24 million light-years away.

So what about galaxies that are so remote that we can't discern individual stars? Here, we enter the mind-boggling world of the expanding universe, where the concept of distance starts to lose its mundane meaning.

To the Cosmos

Step 4. The Cosmos

As mentioned before, Edwin Hubble discovered the proportional relation between a galaxy's distance and its apparent recession velocity, the latter derived from the observed redward shift of the galaxy's light. The *cosmological redshift* (denoted by the letter *z*) is a reddening of the galaxy's light caused by the expansion of the universe stretching the light to longer, redder wavelengths: The longer the light waves travel through expanding space, the more they're stretched. Over the past few decades, astronomers have carefully calibrated the relationship, known as the Hubble-Lemaître Law. (Belgian cosmologist Fr. Georges Lemaître independently arrived at similar conclusions a couple of years before Hubble did.) As a result, the distance of a remote galaxy can in principle be deduced from its observed redshift alone.



There's a catch, however. The expansion of space pushes everything apart, but on top of that, galaxies are also moving *through* space. Depending on whether they're moving towards us or away from us, this motion will decrease or increase their redshift. The effect is especially important for relatively nearby galaxies, for which this additional Doppler shift can be a significant fraction of the cosmological redshift. Meanwhile, for very remote galaxies, the proportional Hubble-Lemaître Law doesn't hold, because space has not always expanded at the same rate. To disentangle all these effects, astronomers really need an independent way of measuring distances — you can't just rely on a simple redshift measurement to precisely know how far away a galaxy is.

Over time, astronomers have constructed an elaborate *cosmological distance ladder* to provide redshift-independent distance estimates of remote galaxies, based on the various methods described in the previous sections. Parallax and radar data within the solar system reveal the size of Earth's orbit, enabling annual parallax measurements of stars in the solar neighborhood. Precise Gaia parallaxes of Cepheids and red giants in our own Milky Way provide an accurate calibration of these distance indicators. Using the Leavitt Law and the TRGB method, astronomers can determine distances of galaxies out to many tens of millions of light-years. Type Ia supernova explosions in some of these galaxies then betray the true luminosity of these stellar detonations, making it possible to deduce the distances of other galaxies that also harbor exploding white dwarfs out to *billions* of light-years. In the late 1990s, such supernova-based distance estimates of extremely remote galaxies, combined with measurements of their redshifts, revealed the accelerating expansion of the universe. Cosmologists ascribe this uptick to a mysterious property of empty space known as dark energy (*S&T:* May 2018, p. 14).

And here is where our story takes a mind-bending turn:

What does distance even mean in the expanding universe? On scales of the solar system, we can understand it fairly easily. But for really remote galaxies, cosmic expansion makes the concept of distance quite tricky. In fact, many cosmologists protest that giving distances for anything farther than a couple billion light-years should be avoided.

Suppose you measure a galaxy's redshift to be $z = 1.5$, meaning that visible light emitted with a wavelength of 500 nanometers by the galaxy has been shifted by 1.5 × 500 = 750 nm to an observed infrared wavelength of 1250 nm. The Hubble-Lemaître Law tells you that the light has been traveling through expanding space for some 9.5 billion years. Intuitively, you'd conclude that the galaxy is 9.5 billion light-years away.

However, you can't simply convert the *light-travel time* into a distance. When the light was emitted 9.5 billion years ago, the universe was smaller, and the galaxy was a "mere" 5.8 billion light-years away. Because space is expanding, it took the light 9.5 billion years to reach Earth. But by the time the light finally arrives here, the galaxy's "true" (or *proper*) distance has increased to 14.6 billion light-years. (In the current cosmic moment, the latter is also equal to the *co-moving distance*, which puts everything on a grid that expands with the universe.)

There's also something called the *luminosity distance*. In a non-expanding universe, a galaxy's brightness decreases with the square of the distance: Three times farther away means nine times fainter. So you'd expect that our sample galaxy at 14.6 billion light-years is 100 times fainter than an identical galaxy at 1.46 billion light-years. But that's not how it works, explains cosmologist Ned Wright (University of California, Los Angeles). "Remote galaxies are incredibly faint," he says. "They are made fainter than the inverse square law by two factors of $1/(1 + z)$, one due to the redshift reducing the energy of photons, and the other due to the redshift reducing the photon arrival rate."

The result is that our remote galaxy at $z = 1.5$ is actually 625 times fainter than its closer twin, instead of just 100 times fainter. In a non-expanding universe, the remote galaxy would only be that faint if it were no less than 25 times farther away than the nearby one ($\sqrt{625} = 25$) — that is, at a distance of 25 × 1.46 = 36.5 billion light-years. This is the galaxy's luminosity distance.

And there's another reason why the most remote galaxies are so hard to observe. Not only are they much fainter than you would expect on the basis of their proper distance, they also are much larger on the sky than you'd think, spreading their light out and resulting in an extremely low *surface brightness*. The reason is that their perceived angular size is set at the time the light was emitted. So our sample galaxy at a proper distance of 14.6 billion light-years appears as faint as if it were 36.5 billion light-years away, but as large on the sky as it appeared 9.5 billion years ago, when its observed light was emitted at a distance of only 5.8 billion light-years. This is called the *angular size distance*.

Furthermore, all of these distances' values depend on cosmological parameters like the relative amounts of matter and dark energy in the universe and the universe's current expansion speed. Adjusting the parameters' values slightly shifts the values of the distances we calculate.

Both the luminosity distance and the angular size distance become pretty extreme for very high redshifts. A galaxy at a redshift of $z = 10$ has a light-travel-time distance of 13.3 billion years: We see the galaxy as it appeared 13.3 billion years ago, when the universe was just half a billion years old. Its proper distance is 31.4 billion light-years. However, the angular-size distance is just 2.9 billion light-years: On the sky, it appears about 10 times larger than you would expect on the basis of its current distance. Even more remarkably, the galaxy's luminosity distance is a whopping 345 billion light-years — it's 121 times fainter than you'd intuitively expect!

We've come quite a distance. Our crash course has brought us from the first thoughts about the scale of our solar system to mind-boggling concepts about remote galaxies in an ever-expanding universe. And we've only scratched the surface of the complicated topic of astronomical distance measurements, cosmic yardsticks, and universal expansion: It would take a whole book to describe each and every distance indicator and measurement technique. But after you've read this primer on cosmic surveying, your appreciation of the night sky will never be the same again. Thanks to centuries of scientific endeavor, the universe has gained depth.

■ Contributing Editor **GOVERT SCHILLING** is the author of *The Elephant in the Universe: Our Hundred-Year Search for Dark Matter* (Harvard University Press).

Observing the Finest Emission Nebulae

This curated selection includes some of the most striking targets the night sky has to offer.

COLORFUL CLOUDS The Orion Nebula captures everyone's imagination. It's easy to find south of Orion's Belt. The remarkable multiple star known as the Trapezium lies within the very high surface brightness and rather mottled Huygens Region, the brightest part of the nebula.

FRANK SACKENHEIM

More than a decade ago, I wrote that the intricate Veil Nebula is the most striking of all nebulae, surpassing the much brighter Carina, Orion, and Tarantula (*S&T:* Sept. 2011, p. 60). The Eta Carinae Nebula is by far the brightest, while the Orion Nebula is surely the most frequently observed, as well as being the most colorful. Contributing Editor Steve Gottlieb claims nothing packs as much structure into a 30′ × 40′ field as the Tarantula Nebula. And after examining a few outlined in this article, you may have your own favorite. (Note that you'll have to travel to the Southern Hemisphere for some of these.)

The Fab Four

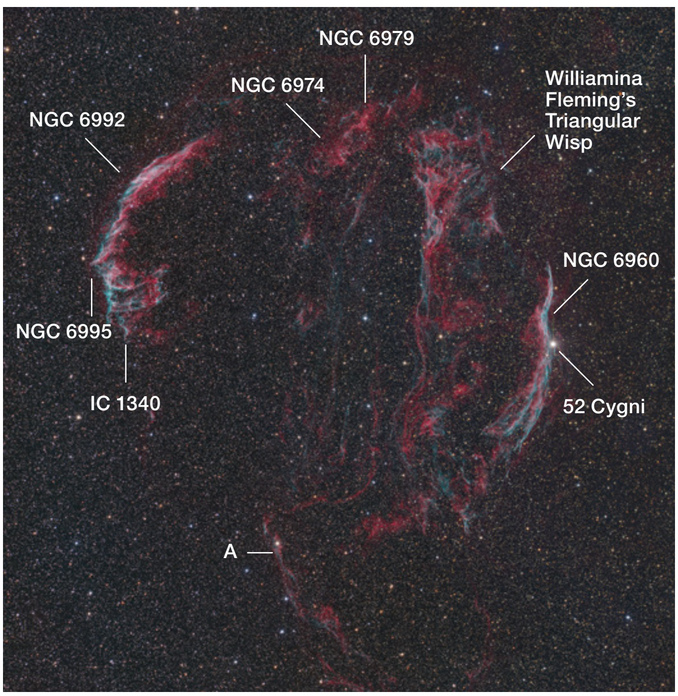
The **Veil Nebula** in Cygnus is a complex, 3°-wide supernova remnant. William Herschel discovered the main sections of the nebula in 1784. My 7×50 binoculars easily show the Veil's easternmost and brightest arc (**NGC 6992**). With an O III filter on my 16-inch telescope, this arc exhibits diagonal streaks, "bays," and "headlands." The two "fangs" of IC 1340 that project westward from **NGC 6995**'s southern end are my favorite part of the Veil. North of the yellow-and-orange double star 52 Cygni, **NGC 6960** is a spike with bright edges, while south of the star it's bifurcated.

Williamina Fleming's Triangular Wisp (named after its discoverer, and also known as Pickering's Triangle) is a lacy complex between the two main arcs. I can follow the Wisp's long tail southward for almost 2°; it's almost twice as long as either of the two brighter arcs. Faint and subtle NGC 6979 lies just east of the Wisp.

In my 2011 article, "Beyond the Familiar Veil," I described observations with my 16-inch and an O III filter at 114× of seven "small streaks and blobs" of nebulosity within the nebula that had apparently never been observed visually before; I also described Streak A, the southernmost section at the Vulpecula border that American amateur Dave Riddle had first detected a decade earlier. Right after the article's publication, Gottlieb added first detections of two patches at the southern end of the tail of Fleming's Triangular Wisp and traced Streak A to its end at declination +28.7°. And Contributing Editor Howard Banich added considerably more to the known detectable parts of the Veil Nebula in his recent article (*S&T:* Sept. 2021, p. 28). Inspired by Steve's and Howard's observations of the two sections at the southern end of the Veil in Vulpecula, this year I bought a Lumicon Gen 3 O III filter and that readily showed both of those sections of nebulosity.

In the heart of the bright, shadow-casting far southern Milky Way is the magnificent **Eta Carinae Nebula** (NGC 3372). This showpiece is framed by three naked-eye open clusters: the large and very bright IC 2602; NGC 3532, arguably the sky's finest open cluster; and NGC 3114.

The huge Eta Carinae Nebula has outer filaments and billows of nebulosity that, as I write in my logbook, would take hours to portray. A chevron-shaped dark lane divides the central mass, and the brightest, northern section of the nebula is triangular. Eight open clusters reside within the nebula. The best are the large, scattered cluster Collinder 228 that ornaments its southern section and Trumplers 14, 15, and 16. Arrowhead-shaped Trumpler 16 is a rich, young cluster found



▲ **SUPERNOVA REMNANT** The delicate Veil Nebula is a much-observed target, and it's easy to see why in the image above. The result of a supernova explosion some 21,000 years ago, it's now around 120 light-years across.

▲ **SOUTHERN SPIDER** Named after the hairy arachnid, the Tarantula Nebula lies in the Large Magellanic Cloud. You'll have to travel south to marvel at this intricate object.

VEIL NEBULA: SEAN WALKER / *S&T*; TARANTULA NEBULA: TRAPPIST / E. JEHIN / ESO at the southern end of the dark nebula that John Herschel named the Keyhole.

Trumpler 16 holds the tiny (22″ across) Homunculus Nebula, a bipolar and expanding shell of dust and gas that the unstable binary star Eta Carinae (a hypergiant with a massive companion) probably ejected during its 1843 outburst, when it briefly reached magnitude –1 (*S&T:* Oct. 2016, p. 26). The Homunculus is one of the very few orange deep-sky objects! One very steady night in March 2001, I used Australian amateur Andrew Murrell's 20-inch f/5 Dobsonian at 363× and was able to see the major features visible in Hubble Space Telescope images (such as the one on page 23). The Homunculus's northwestern lobe was narrower and had a tiny dusky inclusion; the southeastern lobe was wider and had two small, dark inclusions arranged along the nebula's major axis. At the waist of the lobes wee spikes extended both northeast and southwest of the hidden central star, with the northeastern spike being the sharper of the two. One evening an overcast of stratus formed, and for many hours the faintest stars that I could see through the thin, low cloud were of magnitude 3. But the Eta Carinae Nebula continuously shone through the cloud!

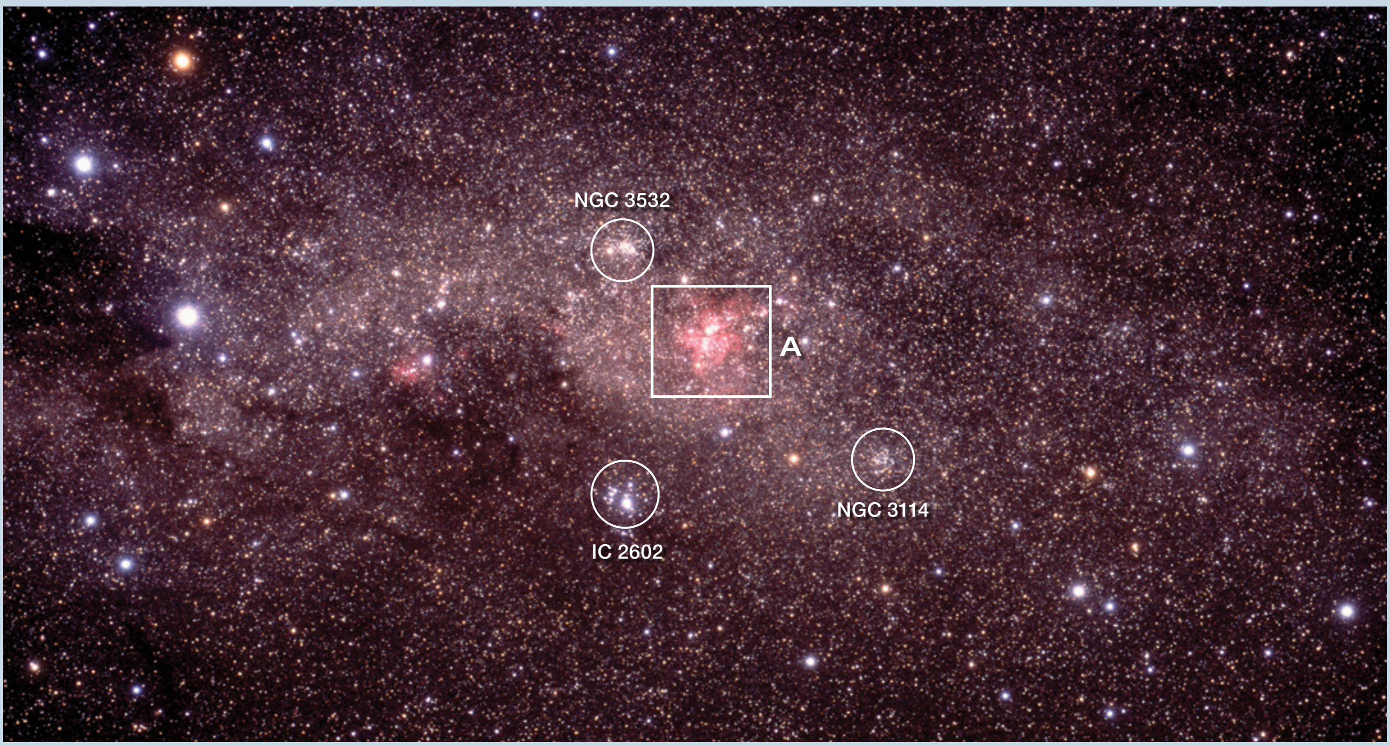
When I returned to North America and mentioned that Eta Carinae was completely hidden within the Homunculus, I was met with skepticism by famous Northern Hemisphere observers who had easily seen an "astonishingly red" Eta a few years earlier. Fortunately for me, Australian amateurs confirmed that Eta was invisible in March 2001. By January 2005, observing with my extremely generous host Tony Buckley and using his 14.5-inch Dob at 322×, I wrote: "Eta has brightened since 2001, and now there is a definite deep orange star and only the eastern lobe of the now over-powered Homunculus is easily visible — the western lobe is tough."

During the late 2000s, former *Sky & Telescope* contributing editor Les Dalrymple noted that the evolution of the Homunculus was occurring over relatively short time scales. In just five to eight years the fainter of the two lobes appeared somewhat lower in surface brightness, while the star itself was somewhat brighter. Recently, in 2019, Gottlieb reported that Eta was "very small but non-stellar."

In February this year, Dutch amateur (based in Chile) Wouter van Reeven observed Eta Carinae from the Atacama Desert. He noted that the star was naked-eye visible within the nebula, and with his 20-inch Dob it was a light, golden yellow in color and bright. South African observer Magda Streicher confirmed the color change and added it was "much more star-like." At last report Eta Carinae shone at magnitude 4.1.

Shifting our gaze northward to familiar territory, let's look at the Eta Carinae Nebula's only true rival, the Orion Nebula. French astronomer Nicolas-Claude Fabri de Peiresc discovered the **Great Orion Nebula** (M42) in 1610, shortly after the telescope's invention.

▼▶ **GEM OF THE SOUTHERN SKIES** John Herschel wrote of the Eta Carinae Nebula: "It is not easy for language to convey a full impression of the beauty and sublimity of the spectacle which this nebula offers . . ." Most observers would likely agree. The nebula lies west of the Southern Cross, surrounded by three eye-catching open clusters (labeled). Trumpler 16 is one of eight open clusters within the Eta Carinae Nebula (A) and contains one of the more striking objects in the sky: the Homunculus Nebula (B).



WIDE VIEW: AKIRA FUJII; ETA CARINAE NEBULA: FRANK SACKENHEIM; HOMUNCULUS: ESA / HUBBLE / NASA

Through my 8-inch f/6 Newtonian at 116× the "bat wing" is visible as far as HD 37115 (see the image on page 20). The dark dust cloud called the Fish's Mouth is exceedingly prominent, extending right into the wondrous multiple star, the Trapezium. I detect a thin, very faint line of nebulosity across the Fish's Mouth, just northeast of the Trapezium. In very good seeing my 8-inch at 203× added the Trapezium's E and F components. A 25-inch shows E as clearly orange.

At 50× in my 8-inch I see a short spur eastward near the base of the bat wing. The opposite wing angles northwestwards from the Fish's Mouth. The widest part of M42 lies west and southwest of the Trapezium; it has some curving streaks of nebulosity within it, and some small, elongated voids. A barely discernible ribbon sweeps southwards and then continues eastwards all the way to just northeast of Iota (ι) Orionis. My 16-inch f/4.5 Newtonian at 65× with an O III filter extends the ribbon around to join up with the bat wing, forming a complete loop around a large dark area south of the rest of M42. I salute former Contributing Editor Sue French, who glimpsed the loop with her 105-mm refractor.

M42 is the most colorful nebula of them all. At low power the bright Huygens region is blue-green, even with my 75-year-old eyes. Until my mid-60s, the bat wing always presented a rusty tinge in my 16-inch. Keen-eyed 18-year-old observer Zane Landers, using a 32-inch Dob at 174× in Tucson, Arizona, reported: "The whole nebula glows a greenish-purple, with red, brown, and blue fringes all over the place."

Dust clouds separate M43 from M42, as well as sharply outlining the concave curve on the eastern side of M43. My 16-inch at 261× shows M43 as a fat comma with a prominent dark lane cutting across it, north of the illuminating star.

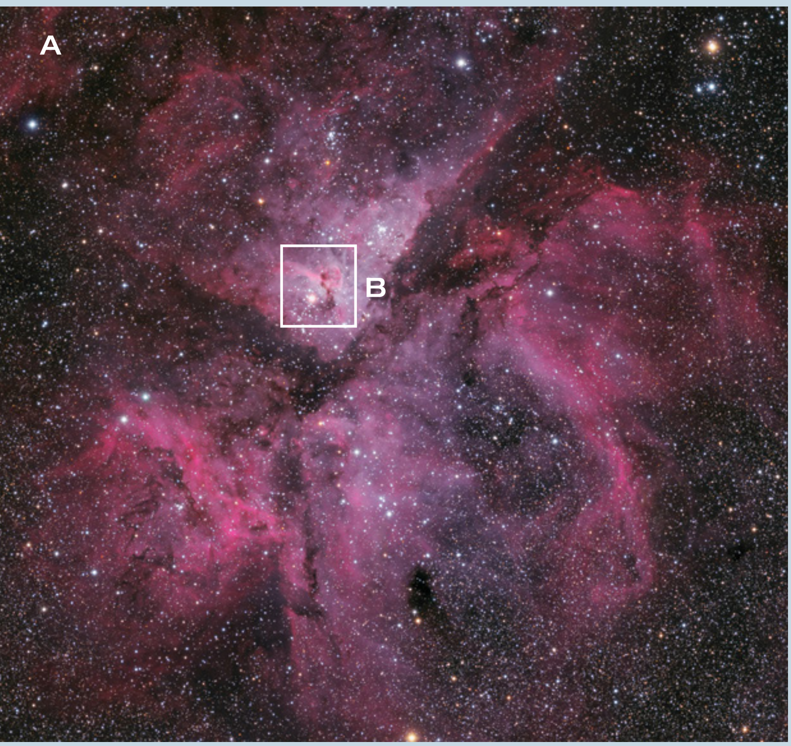
We'll head back south to find the last of the fabulous four. The **Tarantula Nebula** (NGC 2070) is an easy naked-eye object even though it's in another galaxy! The nebula lies a little north of the eastern end of the Large Magellanic Cloud's central bar. *Burnham's Celestial Handbook* notes that if it were at the distance of the Orion Nebula, it would "cover some 30° of the sky, and shine with a total brightness three times greater than that of Venus."

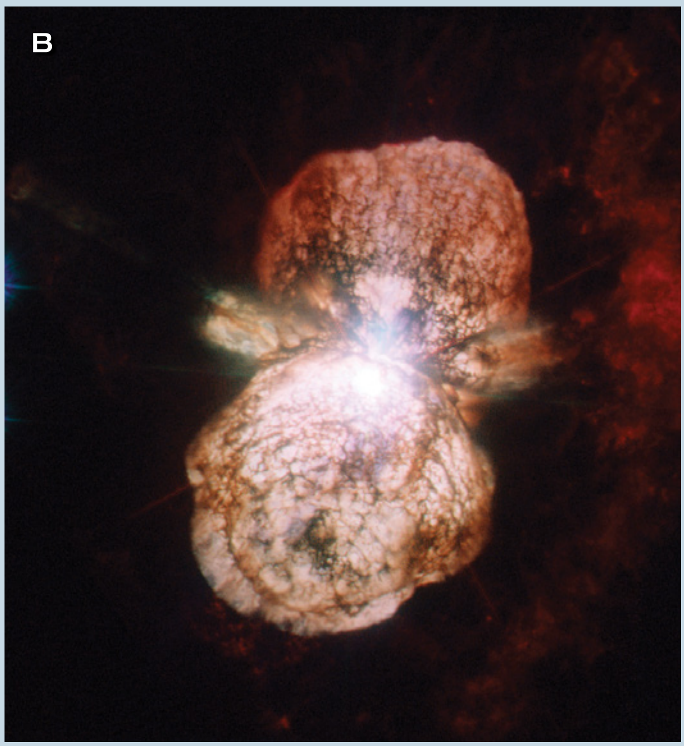
In 2001, using Buckley's 14.5-inch Dob at 215×, I logged: "The 'spider legs' are obvious with many resolved LMC stars in the central cluster. A marvelous object, like its photographs in the spider arm detail. There are many other emission nebulae and open clusters in the same low-power field of view."

The best description I've ever come across is Gottlieb's: "The view of the Tarantula through a 20-inch f/5 at 127× and O III filter was jaw-dropping! Near the center are several bright loops and arcs. Extending out are a number of convoluted loops including one heart-shaped arch which is quite large. Running out from the central region of the nebula are streaming lanes of nebulosity. One in particular extends quite a long distance and the outer loops and streamers seem to merge into some of the nearby H II regions forming a mind-boggling complex. There are perhaps 10 different loops and ribbons in the main body giving a 3-dimensional effect."

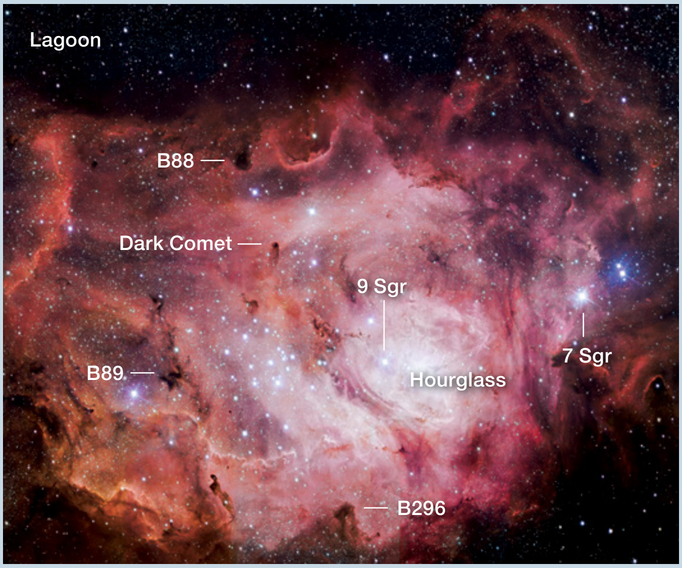
Sagittarius Delights

Swiss astronomer Jean-Philippe Loys de Cheseaux discovered the splendid **Swan Nebula** (M17) in 1745. One excellent night in 1981 at a very dark mountain site, my 8-inch Dob at





BY THE TEAPOT On summer nights, look toward Sagittarius to find three delightful sights: the Swan, the Lagoon, and the Trifid Nebulae. The Lagoon, in turn, holds several dark nebulae (shown in the image at right), including Burnham's Dark Comet.



SKY SCENE: AKIRA FUJII; SWAN: ESO; TRIFID: FRANK SACKENHEIM; LAGOON: ESO / VPHAS+ TEAM

174× revealed several narrow grey ribbons crossing the Swan's body and lower neck diagonally. I also could see the dense dust cloud that shapes the Swan's neck, which looks distinctly darker than any other area in the field of view. There was also faint nebulosity north of the swan. The associated open cluster is poorly concentrated and contributes little to the scene.

On the best night at the 1994 Mount Kobau Star Party, veteran observer John Casino's 36-inch Dobsonian with an O III filter showed the linear absorption nebulae in the Swan just as clearly as the photographs of the day.

The **Lagoon Nebula** (M8), one of the brightest naked-eye objects in the summer Milky Way, was likely known since antiquity, and so nobody should be credited as its discoverer. My 8-inch at 61× and 116× reveals the prominent curving dark channel between M8's two main lobes, the tiny Hourglass (the brightest patch of nebulosity within the Lagoon 3′ west-southwest of 9 Sagittarii), and about 40 stars in the loose open cluster that was born within the nebula. The earliest spectral type of the cluster stars is O5, implying that it's only about 2 million years old.

One of the best views I've had of the Lagoon was at Chaco Culture National Historical Park, located in a very dark corner of northern New Mexico. In "Diving into the Lagoon" (*S&T:* July 2012, p. 61), I describe my explorations of the nebula with Chaco Observatory's 25-inch Dob, using an O III filter. At 226× I saw a bright filament in the main dark channel, along its northwest bank and parallel to it. Even at that power I noted no more than a vague suggestion of the Hourglass's shape. I conducted the rest of my survey at 113×. I describe 15 dust clouds within the Lagoon, and I suggest that you hunt down the three dark nebulae that E. E. Barnard cataloged (as shown at left). Finding Burnham's Dark Comet was the main reason that I slewed the 25-inch onto the Lagoon Nebula.

The discovery of the **Trifid Nebula** (M20) is attributed to Charles Messier in 1764, although that's rather generous since he only saw stars. It was, in fact, William Herschel who discovered it 20 years later.

I see the celebrated dark lanes (B85) of the Trifid Nebula well in my 8-inch at moderate power, radiating from near the central triple star (the O8 lucida, HD 164492, powers the emission nebula). Large apertures make it a quadruple star. C. E. Barns, in his 1929 book *1,001 Celestial Wonders*, captured the essence of the Trifid: "Bulbous image trisected with dark rifts of interposing opaque dust-clouds . . ." However, both my telescope and photographs show four dark lanes, not three. The 8-inch at 60× also bagged the fainter reflection nebula to the north.

The Best of the Rest

Messier and fellow French astronomer Antoine Darquier de Pellepoix independently discovered the **Ring Nebula** (M57) in 1779 (see page 41). You'll find it in Lyra, approximately halfway between Beta (β) and Gamma (γ) Lyrae. It looks like a smoke ring even in a 60-mm refractor. My 8-inch at 116× shows M57 as oval, fainter at the ends, and noticeably brighter inside the ring than outside. There's a bright southeastern rim in my 16-inch at 261×, and on nights with excellent seeing I can glimpse the 15.7-magnitude central star at 366×.

At the 1990 Mount Kobau Star Party, Casino's 36-inch at 420× revealed a second star within the ring, plus one superposed on the nebula itself. Then, in a flash of superb seeing, I discerned broad parallel banding in the gauzy nebulosity inside the annulus. The banding's momentary appearance on a sterling night provided me with a lifetime memory. Apparently, William Parsons, the Third Earl of Rosse, had previously observed this with his 72-inch Leviathan reflector. My club's (the Royal Astronomical Society of Canada Okanagan Centre) 25-inch Dobsonian, at 317× showed the galaxy IC 1296 only 4′ west-northwest of the Ring.

SEAN WALKER / S&T

▲ **CELESTIAL ROSE** Sitting in northern Monoceros, in the middle of a triangle formed by Epsilon (ε), 13, and 18 Monocerotis, the Rosette Nebula cradles the open cluster NGC 2244. Note that 12 Monocerotis, the most obvious star on the southeastern edge of the cluster, isn't a true member but instead is a foreground star.

While comet-hunting in 1865, Lewis Swift chanced upon the **Rosette Nebula** (NGC 2237+) in Monoceros. My 7×50 binoculars reveal a formless glow around the central hole blown by the associated open cluster NGC 2244's young stars. Don't be fooled by the brightest star, yellow 12 Monoceros: It's a foreground object. The 4.8-magnitude cluster is obvious with the naked eye.

With my 16-inch the nebula formed a complete annulus at 65×, but I discerned no details without a filter. The Rosette comes alive with an Ultra High Contrast (UHC) filter: At 141× the southern side of the Rosette is the faintest, followed by the eastern side — but I see four bands of nebulosity, separated by dark lanes. The northern section is the brightest, and I note Y-shaped dark lanes there — these are chains of star-forming dark Bok globules (though the individual globules are hard to detect). On the northwestern to western sides of the nebula, dark lanes cut through in four places. The dark lanes due west are very prominent.

◀ **FIRE IN THE SKY** The beautiful Flame Nebula lies just east of second-magnitude Zeta Orionis; you'll need to shield the nebula from the star's light to enjoy it properly. Glowing IC 434 provides an attractive backdrop for the delightful but tough-to-snag Horsehead Nebula.

I reexamined the two areas with the Bok globules. The actual dark "straits" are much more prominent at 141×, but the small zigzags in the straits and some dark "coves" are more obvious at 203×. Yes, I saw a few dark coves on the margins of the straits, but I'm not certain whether they were actual Bok globules.

William Herschel discovered the **Flame Nebula** (NGC 2024) in 1786. I prefer to refer to it as the Maple Leaf Nebula, which I think is a better description. To view it, move bright Zeta (ζ) Orionis out of your eyepiece field.

This nebula is crossed by dark patches. My 80-mm apochromatic refractor and my 8-inch show only the wide, dark trunk, but my 16-inch adds three dark branches. The O III and UHC filters show *less* than the unfiltered view.

On an October morning when not only the gegenschein but also the fainter zodiacal band were visible, I observed the Flame Nebula with Chaco Observatory's 25-inch at 91× unfiltered. From the main dark trunk I saw a somewhat difficult dark branch running towards Zeta Orionis, three branches

VIKING GEAR Winter nights bring Canis Major into view and along with it the delectable nebula known as Thor's Helmet. Point your telescope 4¼° northeast of Gamma Canis Majoris. Note that north is to the left in this image.

FLAME: MASIL IMAGING TEAM; THOR'S HELMET: SSRO / PROMPT / CTIO on the far side of the trunk from Zeta, and another very difficult dark lane almost parallel to the main trunk (on the far side of the nebula from Zeta), defined by very faint nebulosity. That morning at 130× a hydrogen-beta filter gave an excellent view of the nearby faint emission nebula IC 434 and the silhouetted Horsehead Nebula (B33), including the nose.

Canis Major offers **Thor's Helmet** (NGC 2359) surrounding an 11.6-magnitude Wolf-Rayet star (HD 56925). The violent stellar winds that blow from these massive objects produce a rare type of emission nebula. William Herschel discovered the nebula in 1785.

On a crystalline night the O III filter gave a detailed view in the 16-inch at 75× — I saw the bright nebulosity (the Helmet) curved on its western side and two horns projecting out, one towards the northwest and a fainter but probably longer horn towards the east. To the southeast and south of the helmet, the scope also revealed a faint mottled area of nebulosity that is three to four times as large as the brighter area forming the helmet.

At 141× with a UHC filter the helmet looks annular, and the energizing star lies somewhat off-center; my 70-mm finder at 17× (unfiltered) also shows the nebula.

Barnard discovered the **Pacman Nebula** (NGC 281) in Cassiopeia with his 5-inch refractor in 1881. The nebula is easy to locate with an 11×80 finderscope, unfiltered. With a UHC filter in my 8-inch, the nebula is a rewarding sight at 44× — I see a hemisphere of bright nebulosity with a dark bite intruding from the flattened western edge. The triple star Burnham 1 marks the nebula's center (it becomes a quadruple at high power in excellent seeing).

With my 16-inch at 75× and a UHC filter, two lanes from the dark bite cut right through the bright nebulosity. One lane crosses the southern horn of the crescent; the second passes just east of the multiple star and continues in a long arc right through the center of the brightest nebulosity. The dark bite becomes triangular at 114×.

Final mention goes to the **North America Nebula** (NGC 7000), as it also belongs in this select group. But I described it in detail in the September issue (page 58).

I hope you'll enjoy observing these nebulae as much as I do.

◀ **OF VIDEO GAMES** Look for the Pacman Nebula some 1.7° east of Alpha (α) Cassiopeiae. Can you see why this nebula is named for a video game character?

■ Contributing Editor **ALAN WHITMAN** thanks the Southern Hemisphere observers who contributed observations of changing Eta Carinae and the Homunculus. Besides those already mentioned in the article, thanks also go to Argentinian astronomers Enzo De Bernardini and Rodolfo Ferraiuolo.

Noteworthy Nebulae

Nebula	Designation	Constellation	Mag(v)	Size/Sep	RA	Dec.
Veil	NGC 6992/5	Cygnus	7.5	60′ × 8′	20^h 56.4^m	+31° 43′
	NGC 6960	Cygnus	7.9	70′ × 6′	20^h 45.7^m	+30° 43
Eta Carinae	NGC 3372	Carina	~1	120′ × 120′	10^h 45.1^m	–59° 52′
Great Orion	M42	Orion	4	40′ × 35′	05^h 35.3^m	–05° 23′
Tarantula	NGC 2070	LMC / Dorado	~4	30′ × 20′	05^h 38.7^m	–69° 06′
Swan	M17	Sagittarius	6	20′ × 15′	18^h 20.8^m	–16° 10′
Lagoon	M8	Sagittarius	~4	45′ × 30′	18^h 03.7^m	–24° 23′
Trifid	M20	Sagittarius	6.3	20′ × 20′	18^h 03.4^m	–22° 59′
Ring	M57	Lyra	8.8	3′ × 2.4′	18^h 53.6^m	+33° 02′
Rosette	NGC 2237+	Monoceros	—	80′ × 50′	06^h 30.9^m	+05° 03′
Flame	NGC 2024	Orion	—	30′ × 30′	05^h 41.7^m	–01° 51′
Thor's Helmet	NGC 2359	Canis Major	11.6	6′ × 4′	07^h 18.5^m	–13° 16′
Pacman	NGC 281	Cassiopeia	—	35′ × 30′	00^h 52.9^m	+56° 37′
North America	NGC 7000	Cygnus	5.0	120′ × 100′	20^h 59.3^m	+44° 31′

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.

MASIL IMAGING TEAM

TOASTY JUPITERS by Rebekah I. Dawson

Star Huggers

Astronomers have found a baffling variety of gas giants in close orbits around their host stars. What are these worlds telling us about planet formation?

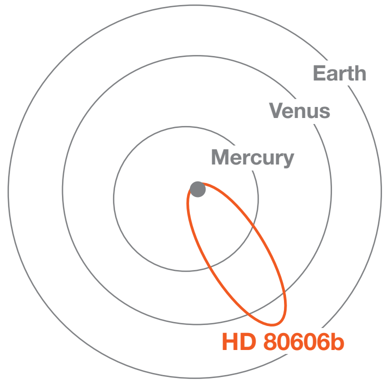
Exoplanets have turned our textbook theory for planet formation on its head. When astronomers first imagined planets around other stars, we envisioned that every star's entourage would look similar to our own solar system: planets circling their star in a flat disk, with rocky planets near the star and gas giants far out.

This setup, we had inferred, arose due to how planets form. Each planetary system begins as a spinning cloud of gas and dust that collapses into a disk. In the vast expanses of the outer, cold region of the disk, far from the young star, there's more solid material (including ice) available to build the core. Planetary cores grow large and blanket themselves in material from the surrounding disk to become gas giants. Closer to the star, only tiny embryos can grow, and they are too small to gather gas — instead, the gas cushions them like giant air bags, preventing them from bumping into each other. After a few million years the gas disk dissipates, and the tiny rocky embryos collide to form our terrestrial planets.

This theory accounts for the key characteristics of our solar system. But it doesn't fully explain many of the other planetary systems we've found.

We now know of more than 5,000 confirmed planets. Most of these worlds reside closer to their star than Mercury to the Sun. Some of these innermost exoplanets shocked us by not only being gas giants but also by taking elongated or highly tilted paths around their stars. Among the earliest exoplanet discoveries were hot Jupiters orbiting 10 times closer to their star than Mercury does (such as 51 Pegasi b, discovered in 1995), giant planets on highly elliptical orbits

▲ **ROASTED** Artist's concept of a hot Jupiter, bathed in the heat of its host star. Astronomers have found hundreds of gas giants orbiting their stars at one-tenth or less of the distance between Earth and the Sun.



EXTREME ORBIT The Jupiter-size exoplanet HD 80606b follows an elongated path around its star, taking it from 0.03 astronomical unit out to 0.89 a.u. (Solar system orbits shown for reference.)

GREGG DINDERMAN / *S&T*, SOURCE: S. R. KANE ET AL. / *JOURNAL OF GEOPHYSICAL RESEARCH: PLANETS* 2021

(such as HD 80606b, discovered in 2001, which changes its distance from its star by a factor of 30 over the course of its year), and planets orbiting in planes dramatically different from their star's rotation (such as HAT-P-11b, characterized in 2010, on a nearly polar orbit).

These early exoplanet discoveries revealed that not all planetary systems share our solar system's key characteristics. With new missions and more sensitive instruments, we learned that inner planetary systems can also be home to medium and small planets, some of which are packed very close together.

The diversity of planetary systems is teaching us that our origins theory is incomplete. We need a new blueprint that lays out why we find something like our solar system orbiting one star, a misaligned hot Jupiter on an elongated orbit around another, and a system of five tightly spaced planets close in to a third. Investigating giant planets that occupy the inner zone of solar systems is an important step in drawing this blueprint: They are likely the extreme outcomes of physical processes that are at work in many planetary systems, and they are also most at odds with our origins theory. If we understand them, then we'll be much closer to understanding the full diversity of planetary systems.

Three Scenarios

Scientists have proposed three general scenarios to explain the existence of close-in giant planets. Each expands our origins theory into a richer and more dynamic sequence, with more crosstalk between the inner solar system and regions farther out than once predicted.

In the first scenario, the giant forms right where we see it today: near the star. Dust, pebbles, asteroids, or even a whole core travel through the gas disk from the outer region to the inner region, where the lack of abundant material would have stymied a giant's formation. The resulting large core accretes surrounding gas and becomes a gas giant, forming very close to the star instead of in the outer region of the disk. This scenario is inspired by another type of extra-solar system: large, rocky super-Earths close to their stars. If super-Earths can form or arrive close to the star during the gas disk stage, some may grow into hot Jupiters.

In the second scenario, close-in giant planets originally form much farther from the star, like our own giant planets. Then, through interactions with the gas disk, the full-fledged gas giant moves inward.

Both the *in situ* and *disk-migration scenarios* keep the gas giant on a circular, coplanar orbit — at least while the gas is still around — and can plant it at a wide range of separations from its host star. These scenarios may also allow other planets to form or arrive nearby. Even if the giant planets are gravitationally disturbed after migrating or coalescing close to the star, it is hard to push them onto very elliptical orbits thereafter.

In the third scenario, gas giants migrate after the gas disk disappears, this time through a series of dramatic events. First, another planet or star in the system kicks — or perhaps gradually pulls — the gas giant onto a highly elliptical orbit. The elliptical orbit brings the gas giant periodically very close to its star. Tidal forces stretch the planet during its close approach; as it moves far away from the star, the planet returns to its spherical shape. The process repeats at the next passage. This periodic stretching generates frictional heat and saps energy from the planet's orbit, shrinking and circularizing the orbit over many passages. This *tidal migration* likely destroys any intervening planets along the way, leading to a lonely giant planet that's close to its star.

To make a hot Jupiter through tidal migration, the change to the orbit needs to be just right: too strong, and the gas giant will come so close to the star that it will be either ripped apart by tides or hit the star; too weak, and the giant won't approach its sun close enough for tides to shrink its orbit over the star's lifetime. When the close pass is just right, the orbit circularizes over time, but we may catch younger or more recently disturbed planets that are still on elongated orbits.

The Power of Populations

More than 25 years after the discovery of the first hot Jupiter, we now know of hundreds of close-in giant planets. We can make use of other properties of these planets, their stars, and their systems to test the three formation scenarios: in situ formation, disk migration, and tidal migration. Studies so far tell us that no one scenario can explain all the observed properties, and that at least two scenarios are likely at work.

Orbital properties provide powerful tests of the scenarios. If the tidal migration mechanism is at work, for example, then we expect to find young, close-in giant planets on highly elongated orbits, still in the midst of tidal circularization. In contrast, giants that formed in situ or by disk migration will always inhabit circular orbits. We now know of about two dozen hot Jupiters on elliptical orbits that point to ongoing tidal migration. What we don't know is whether the circular-

3 Earth days
Typical orbital period (or "year") of a hot Jupiter

orbit planets we see have completed tidal circularization or were never on elongated orbits to begin with.

The mechanisms that put giant planets onto elliptical orbits only rarely make hot Jupiters. We now have a good handle on how common giant planets at different distances from their host stars are. Although hot Jupiters are less common than wider-separation giant planets — about 10% of stars have a giant planet and 1% have a hot Jupiter — they are not as rare as we would expect from tidal migration. Therefore, we think that some hot Jupiters must have originated from in situ formation or disk migration.

Properties of hot Jupiters' host stars further support the dual-scenario hypothesis. Tidal circularization takes time, and we indeed see that close-in Jupiters on elliptical orbits more often appear around younger stars than those on circular orbits. However, some worlds on circular orbits are too far away to have tidally circularized, suggesting that their origins lie with one of the other mechanisms. We also observe that the elliptical hot Jupiters orbit stars that are enriched with heavier elements like oxygen, carbon, and iron. This makes sense, because we think that stars' compositions are similar to the material that was in their planet-forming disks, and in disks with more solids, more giant planets can form and either kick or gradually torque each other into new, elongated orbits. In disks with fewer solids, fewer giant planets tend to form; with fewer planet interactions possible, these worlds tend to become hot Jupiters through either disk migration or in situ formation.

Taking an inventory of which other planets, if any, accompany close-in giants gives us further reason to think that dual scenarios are commonly at work. Many hot Jupiters have no other planets nearby in their system, consistent with disruptive tidal migration. Farther out in their system, many have a distant giant planet that might have caused the initial disturbance (though we do not know for sure without more detailed observations). However, there are notable exceptions to hot Jupiters' loneliness, such as WASP-47b, a hot Jupiter with two smaller planets nearby. This planetary arrangement couldn't have formed via tidal migration. Furthermore, *warm Jupiters* orbiting farther from their star — but still close-in compared to our own solar system's *cold Jupiter* — commonly have nearby planets, suggesting many of them originated from disk migration or in situ formation.

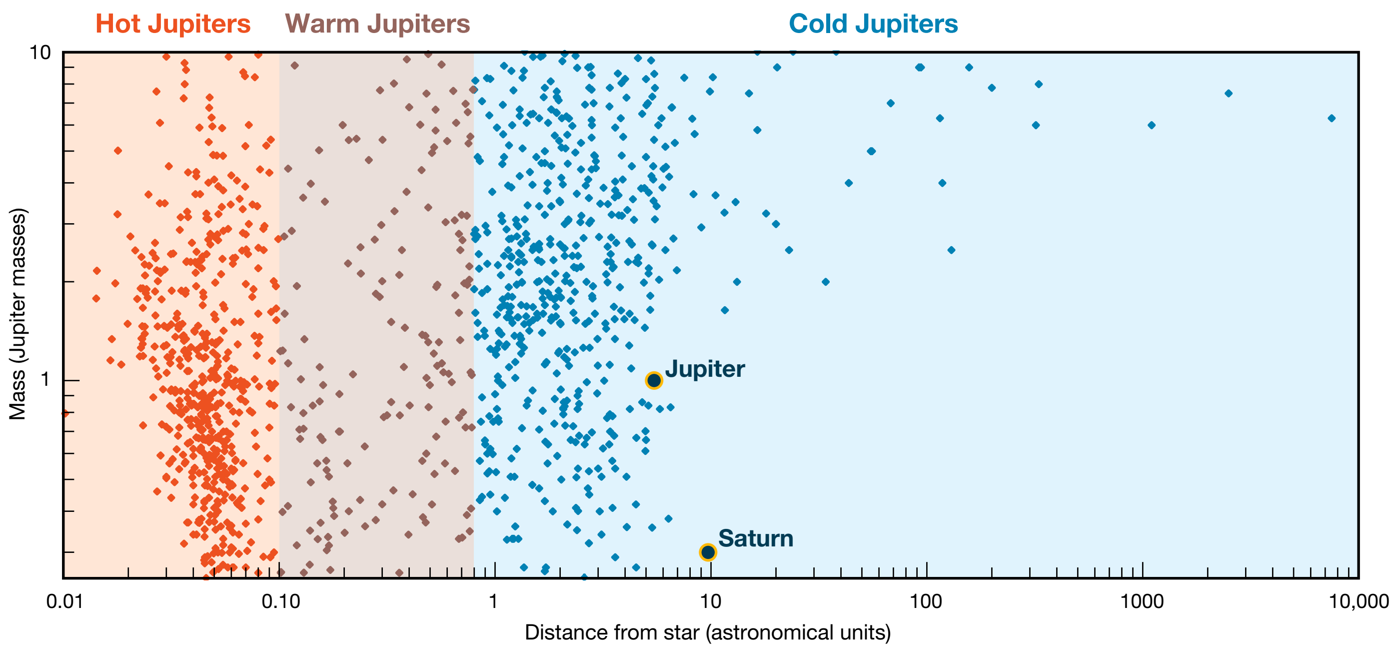
10%
Sun-like stars with a gas giant

1%
Sun-like stars with a hot Jupiter

Zooming in on Individual Systems

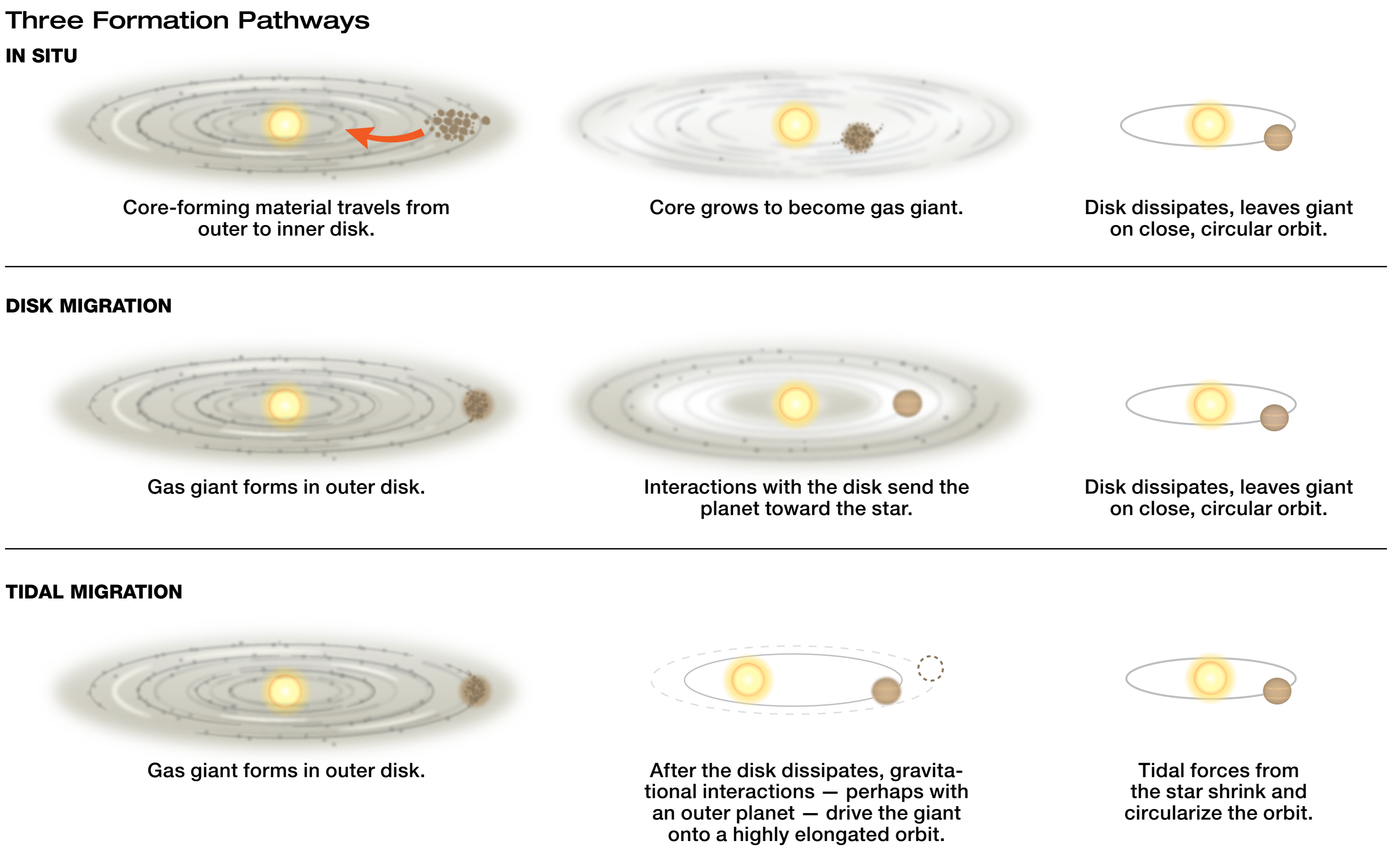
The past couple decades have brought us not only a huge expansion in the collection of known close-in giant planets but also more detailed views of individual systems. Astronomers have discovered many close-in giant planets using the transit technique, in which a planet passes in front of its star and temporarily dims the star's light. High-precision measurements and long, continuous observations from the Kepler and TESS missions have also made it possible to use a valuable new tool: *transit-timing variations*.

These variations arise because the gravitational influence of a companion planet can cause a transiting exoplanet to cross its star's face at slightly different times — sometimes



▲ **A SEA OF JUPITERS** Astronomers have discovered hundreds of gas giants around Sun-like stars, in much smaller orbits than Jupiter and Saturn occupy in the solar system. Many of these fall in the "hot Jupiter" category, giants with an orbit less than one-tenth as wide as Earth's. (Note that because each survey detects some kinds of planets better than others, the distribution here isn't the real distribution in the galaxy — it's just the distribution of discoveries so far.)

GREGG DINDERMAN / *S&T*, SOURCE: THE AUTHOR



GREGG DINDERMAN / *S&T*

arriving early, sometimes late. For example, if we were precisely observing Earth's transits from another planetary system, we could detect little periodic pushes from Venus. Hot Jupiters typically lack transit-timing variations, which is one of the ways we know they don't have other planets nearby. For warm Jupiters, the presence of such variations has given us unprecedented details about the orbital configurations of individual systems, helping answer questions raised by the population studies described in the previous section.

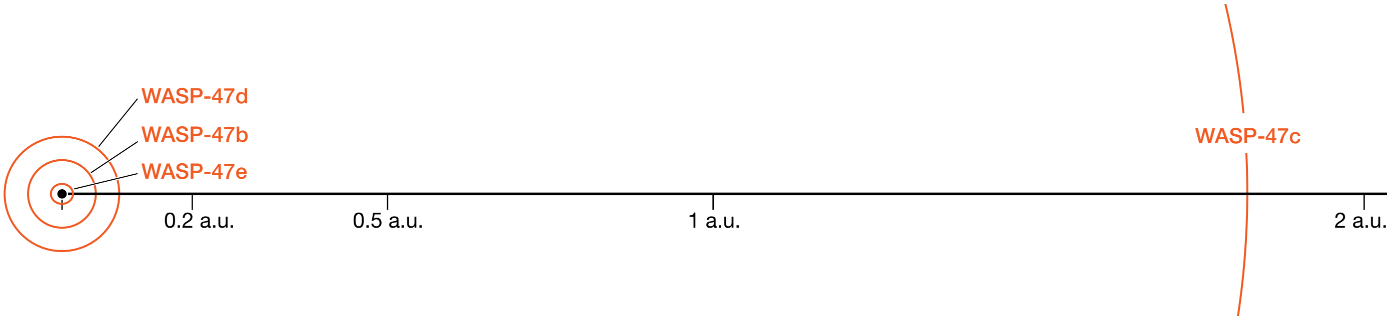
Without what we learned from transit-timing variations, the elongated orbit of warm Jupiter Kepler-419b would have made it a poster child for tidal migration. However, the variations revealed a second, non-transiting outer planet. By determining the full 3D orbit, we learned that the outer planet is not currently capable of causing tidal migration and that Kepler-419b is likely not on the way to becoming a hot Jupiter. Its history must have been more complex. One possibility is that it either formed at or migrated to its close-in location early on, and then the combined effects of the outer planet and the disappearing gas disk put it onto an elliptical orbit.

In contrast, without what we learned from transit-timing variations, the pair of close-in giant planets TOI-216b and TOI-216c would have been poster children for disk migration. The 2:1 ratio of their orbital periods implies they are either in or near a special configuration known as an *orbital resonance*, in which planets repeat their conjunctions at the same spot in their orbit. Such resonances are thought to be a signpost of disk migration, because the migration process can lock planets into this special configuration. However, transit-timing variations revealed that TOI-216's planets are only loosely locked in resonance, and that the inner planet has a more elliptical orbit than we would expect. Again, the results suggest a more complex history. One recent study suggests that either a quick disappearance of the gas disk or turbulence in the disk could make a planet pair on orbits like these. Gravitational disturbances from other planets in the system are another possibility.

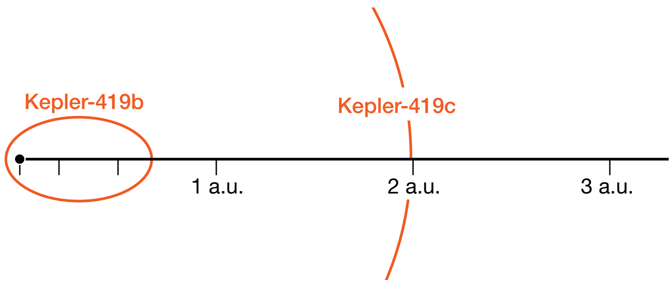
Thus, the exploration of individual systems supports the idea that we need multiple scenarios to explain close-in giant planets. We may not be able to neatly divide systems by scenario; in fact, multiple mechanisms may be at work in a single system, such as when tidal migration follows disk migration. Even a single scenario may play out differently from one system to the next, depending on factors like whether the natal disk was calm or turbulent.

Pathways Forward

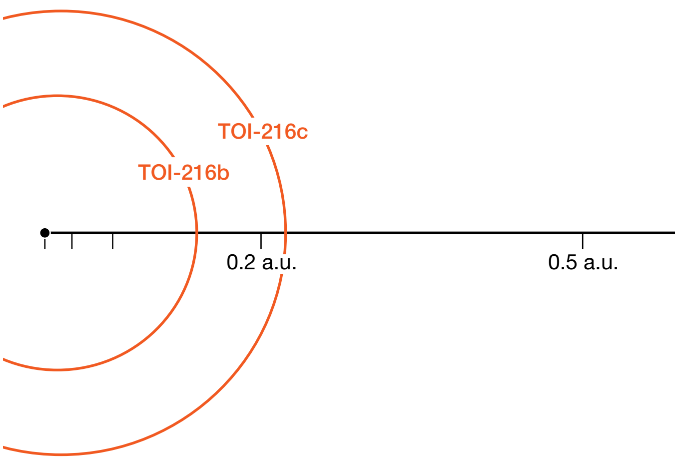
Thanks to these discoveries, we have learned that our solar system–inspired theory for planetary origins is incomplete. We're missing at least two important physical processes. Strong gravitational interactions among giant planets can elongate a planet's orbit and, in extreme cases, help deliver it close to its star. There's good evidence that many — but not all — close-in planets originate this way. The others likely



▲ **THREE'S A CROWD** The hot Jupiter WASP-47b lies sandwiched between a super-Earth and a Neptune-size planet, an unusual arrangement that's difficult to explain with tidal migration. A fourth, Jupiter-size planet orbits far beyond the trio on an elongated orbit.



▲ **UNEXPLAINED ORBIT** Kepler-419b has an elongated orbit, but its path doesn't take it close enough to its star for tidal migration. Nor can Kepler-419c make up the difference with periodic pushes.



▲ **DISSONANT** The 2:1 orbital resonance between TOI-216b and c isn't as tight as expected, suggesting that the planets didn't simply migrate together through the protoplanetary disk to their current, small orbits.

GREGG DINDERMAN / S&T, SOURCE: EXOPLANETKYOTO.ORG (3)

originate through one of the other scenarios.

Furthermore, even though our old origins theory was inspired by the solar system, we have also learned that some of the same missing processes were likely at work in our solar system, too, albeit in a less extreme way. The discovery of the Kuiper Belt and further characterization of the asteroid belt occurred in parallel with the discovery of exoplanets. Properties of these small solar-system bodies indicate that our own giant planets moved around and in some cases may have pulled one another onto elliptical orbits that later circularized (*S&T:* Mar. 2021, p. 22).

Moving forward, we still need to find a way to distinguish observationally between disk migration and in situ formation as the prominent second scenario for close-in giant planets. Future studies of giant planets' atmospheres with instruments like those attached to the James Webb Space Telescope may help us determine their formation locations, because we expect different compounds to form at different distances from the host star (*S&T:* Dec. 2020, p. 34).

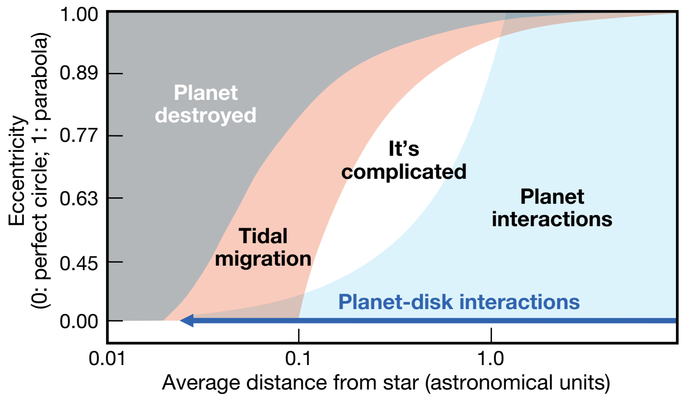
Linking atmospheres to formation locations requires in turn a better understanding of the conditions in the planet-forming disk, which astronomers are investigating with the ALMA radio telescope array. ALMA can identify different types of gas and solid particles in young natal disks and may also help us better understand the transport of solid material within a disk and whether in situ formation is even feasible.

We also need to better understand how giant planets pull each other onto elliptical orbits in the tidal-migration scenario. Is it typically a close encounter or a slow disturbance from afar? Does it happen when the system is very young and with help from the natal disk, as proposed for Kepler-419 and TOI-216, or later on after the disk has cleared? Does it occur far from or near the star? Answering these questions is crucial in order to understand other planetary systems that lack close-in giant planets but have gone through less extreme versions of these processes. In addition, we want to determine how planets wind up on tilted orbits around their stars. The Gaia mission will help test which types of gravitational interactions are commonly at work by discovering and measuring the orbits of hot Jupiters' outer companions, including whether they orbit in the same plane.

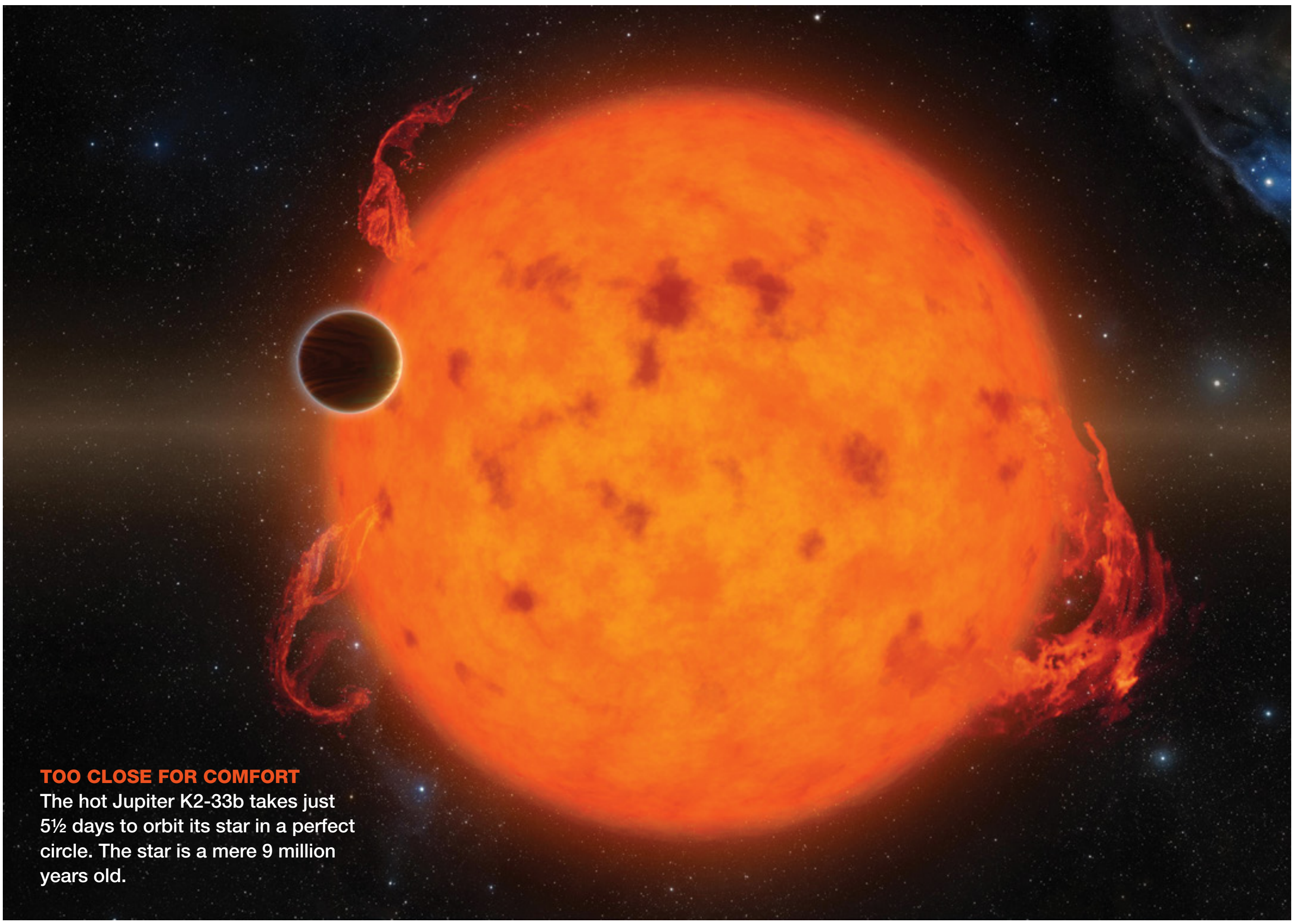
Finally, it remains an open question how a star's environment affects its planets. Astronomers recently used Gaia observations to find that hot Jupiters usually orbit stars that lie relatively close to other stars, whereas stars that keep their neighbors at a distance tend to have gas giants on wider orbits. Perhaps it's the stellar neighborhood, not just the disk and planetary interactions within a system, that determines how closely planets orbit their star.

This continued work is important because giant planets set the landscape for small planets. We think the formation and habitability of the solar system's rocky planets were affected by our giants' early history. Now that we know giant planets' histories vary dramatically from system to system, we can expect a wide range of consequences for rocky worlds. As gas giants jostle each other, they can kick icy comets toward the star, delivering water to otherwise dry, rocky worlds. In other cases, violent encounters between larger planets disturb the paths of smaller ones, causing collisions and atmospheric loss. Giant planets migrating inward during the gas-disk stage may also bring icy embryos along for the ride, which then grow and merge into watery worlds. Far from being a story solely about giant planets, then, the answer to how these worlds came to be could have implications for small planets as well, including whether life could arise as it did here.

■ **REBEKAH I. DAWSON** is an associate professor of astronomy and astrophysics at The Pennsylvania State University who studies the formation and evolution of planetary systems. She enjoys spending time outdoors on her favorite planet, Earth, and teaching her one- and three-year-olds about all the other planets that don't appear in their outer-space board books.



▲ **ORBITAL FATES** Different origin scenarios place Jupiter-size planets at different distances from their host stars (*x*-axis) and in a range of orbit shapes (*y*-axis). Planets that form in place, or those that migrate to their tight orbits while the formative gas disk remains, likely follow a simpler path (arrow, right to left) that keeps them on a circular orbit. Planet interactions, on the other hand, can throw a world onto an elongated orbit (light blue region). Some of these "eccentric" planets will lose just the right amount of orbital energy as they respond to the star's tidal pull, transitioning over time to an especially tight, circular orbit — these essentially travel down the pink region from top right to bottom left.



TOO CLOSE FOR COMFORT
The hot Jupiter K2-33b takes just 5½ days to orbit its star in a perfect circle. The star is a mere 9 million years old.

DIFFERENT SCENARIOS: GREGG DINDERMAN / *S&T*, SOURCE: THE AUTHOR; EXOPLANET ILLUSTRATION: NASA / JPL-CALTECH by Guy Consolmagno and Christopher M. Graney

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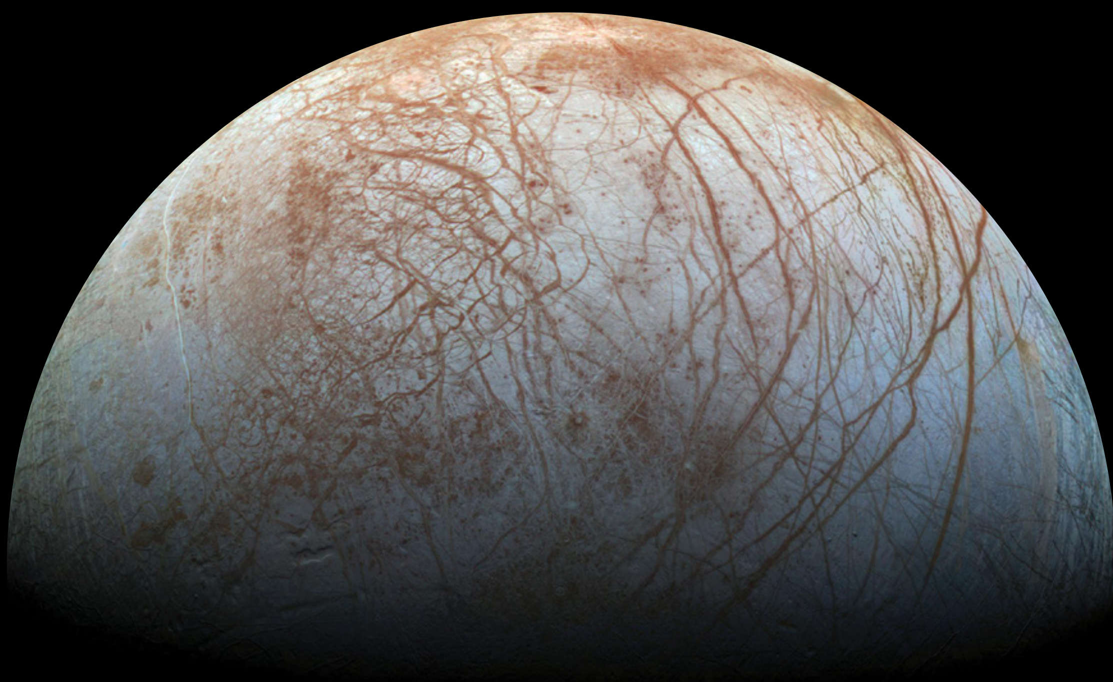

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Moons

Uncovering the nature of three Jovian satellites took some curious twists and turns.

You may remember a scene from *Harry Potter and the Order of the Phoenix* in which Harry's know-it-all friend Hermione is correcting his astronomy homework at Hogwart's. She wryly informs him that one of his answers is *almost* correct: "Europa is covered in *ice*, not mice." Jupiter's moon Europa is indeed covered in ice, but its interior is only about 10% ice — the rest is rock and iron. Ganymede and Callisto have less ice on their surfaces, but more underneath. Volcanic Io, on the other hand, isn't an icy place at all.

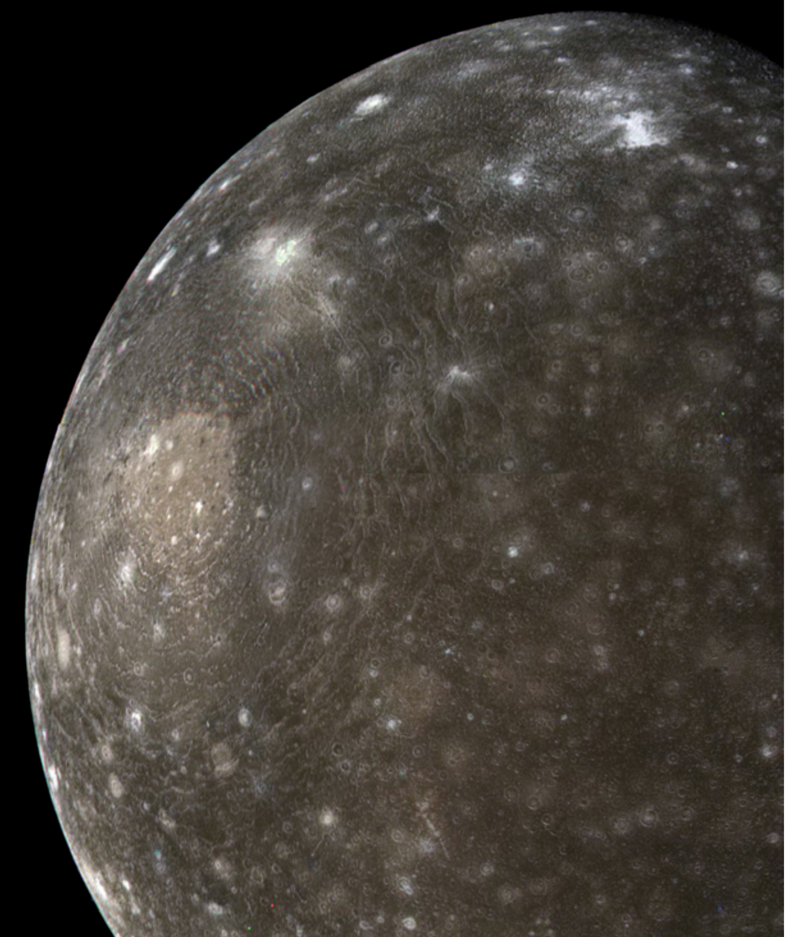
So, how did astronomers figure this out? Long before the Space Age began, two key indicators suggested that Europa, Callisto, and Ganymede should be icy: their densities and their albedos.

Getting to the Basics

Assigning values to these indicators is where the real work lies. *Density* is simply an object's mass divided by its volume. For example, a cubic centimeter of iron weighs nearly 8 grams (0.3 ounces) and a cubic centimeter of ice weighs less than 1 gram. *Albedo* is the intrinsic reflectivity of a surface. Icy surfaces have especially high albedos — think of how blindingly bright a snowy landscape can be on a sunny day. But how do we measure the density and albedo of a distant body? The task isn't as straightforward as you might expect.

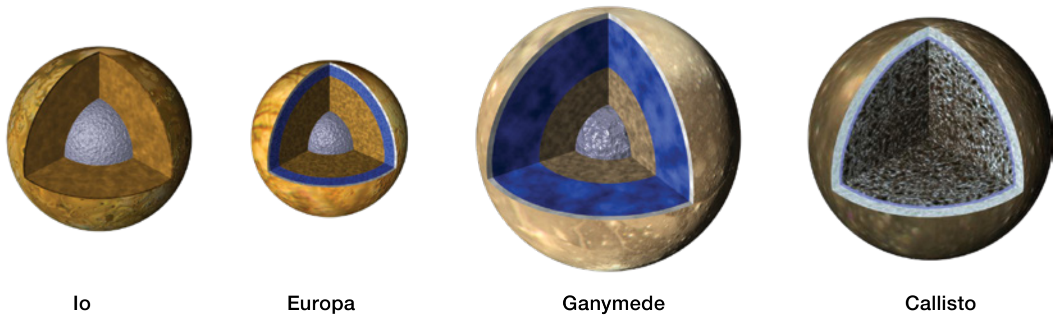
To get a handle on the first indicator, density, we first need to know the mass of a planet's moon, a task that can be very difficult. However, if more than one moon is orbiting the planet, then you can observe how each moon pulls on the others and work out the mass of each one. Doing so is a complicated calculation, but French polymath Pierre Simon Laplace accomplished it in 1805. Laplace was able to determine the masses of the Galilean satellites to within 10% to 25% of their currently accepted values.

To determine density, we need mass *and* volume. Unfortunately, you can't easily measure the width of a Jovian moon and plug that into the volume formula for a sphere. The moons appear as mere dots of light in small telescopes, and, due to diffraction effects, their apparent widths don't necessarily correspond to their actual sizes. However, that didn't stop 19th-century astronomers from trying. They employed filar micrometers with ultra-thin wires to measure the sizes of those dots, thinking they could do so to a precision we now know is absurd. Nonetheless, by the 1860s astronomers had arrived at numbers that weren't too far off from modern values. With those diameters and Laplace's masses, they



◀ **ICY JOVIAN TRIO** Three of the four Jupiter moons discovered by Galileo in 1610 are composed largely of water ice — a fact that eluded astronomers until the 20th century. Ganymede (upper left), Europa (far left), and Callisto (left), along with Io (not shown), are familiar targets for backyard telescopes.

GANYMEDE: NASA / JPL-CALTECH / SWRI / MSSS / KALLEHEIKKI KANNISTO; CALLISTO: NASA / JPL; EUROPA: NASA / JPL-CALTECH / SETI INSTITUTE



ICE HERE AND THERE These cutaway diagrams show the differences in composition among Jupiter's four largest moons. Blue and white indicate water in solid (ice) or liquid form, while the metallic (iron, nickel) cores are shown as gray and rock is indicated with brown. Io is the one moon lacking significant water, and Callisto is thought not to have a metallic core.

could calculate the densities of the Galilean moons.

The second key indicator is albedo. Observers can estimate how bright a moon is by comparing it to a "nearby" star of known magnitude. However, without knowing the size of the satellite, it's not possible to tell if it's small but shiny (high albedo), or big and dusky (low albedo). Both would reflect the same amount of sunlight. Once we know the size of the moon, we can then determine its albedo.

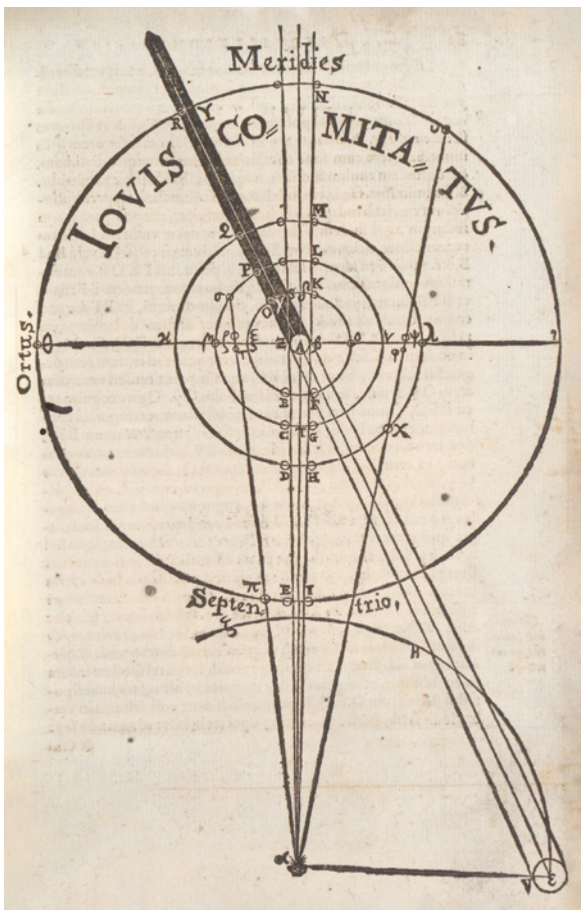
So now astronomers had the rudiments of the two indicators in hand. In the 1860s, pioneers in astrophysics like Fr. Angelo Secchi, S. J. identified the signatures of hydrogen and oxygen gases in stars' spectra, which suggested that water ice might be common in the universe. So, was some astronomer in the 19th century able to put all the pieces together and discover the icy natures of Callisto, Ganymede, and Europa? Nope! And the story of how they missed it is fascinating.

On Thin Ice

From the standpoint of the early 21st century, it's perhaps difficult to believe that there was ever a time when scientists simply weren't interested in knowing the compositions of the stars and planets. German astronomer Friedrich Wilhelm Bessel, for example, wrote in 1848 that astronomy "must lay down the rules for determining the motions of the heavenly bodies as they appear to us from the Earth"; other information, such as knowing the density, was, "not properly of astronomical interest." That meant that even with the correct data right in front of him, Bessel (and his contemporaries) might not even have thought to ask about the nature of Jupiter's moons. However, pioneers like Secchi and English astronomer William Huggins had begun to speculate on the compositions of the stars. Would some brave planetary scientist follow suit?

One way to gauge the state of knowledge of astronomers of the time is to read the books they wrote for popular audiences. Consider the 1873 edition of Reverend Thomas W. Webb's *Celestial Objects for Common Telescopes* and Simon Newcomb's widely read 1878 book, *Popular Astronomy*. What they say about Jupiter's moons is surprising. According to Newcomb, "The light of these satellites varies to an extent which it is difficult to account for, except by supposing very violent changes constantly going on on their surfaces." Newcomb was an accomplished astronomer at the U.S. Naval Observatory and should have been a reputable source, so where did he get this idea?

Webb, for his part, goes on at length, citing observers who noted radical changes in the brightnesses of the moons. For example, he writes about Callisto, "as far back as 1707 Maraldi noticed that, though usually faintest, it was sometimes brightest (a variation which he ascribes to all the satellites); in 1711 Bianchini and another once saw it for more than 1h so feeble that it could hardly be perceived; 1849, June 13 Lassell made a similar observation with far superior means . . ."



GALILEO'S MOONS This illustration by the German astronomer Fr. Christoph Scheiner, S. J. and his student Johann Georg Locher shows Jupiter, its shadow, and its four largest moons. The diagram appeared in their book *Mathematical Disquisitions*, only four years after Galileo first discovered the satellites with his crude telescope. In the book they proposed that measuring the time required for the moons to pass through the planet's shadow, or across its disk, could provide more detailed information about the Jovian system.

CROSS-SECTIONS OF JUPITER'S MOONS: NASA / JPL; JOVIAN MOON DIAGRAM: ETH-BIBLIOTHEK ZÜRICH, ALTE UND SELTENE DRUCKE / PUBLIC DOMAIN

Webb also cites other notable scientists, including German astronomer Rudolf Engelmann, England's John Herschel, and the famous Prussian lunar observers Wilhelm Beer and Johann Heinrich von Mädler. He even quotes Secchi, who described seeing the shapes of these moons as "irregular and elliptical." Indeed, many observers of the era reported various surface features on these satellites.

What are the chances they were seeing real features on Jupiter's moons? Not good. Perceiving the satellites as disks (as opposed to mere points of light) is one thing; seeing features on those disks is quite another. As most readers know, all telescopes have an inherent limit in their ability to resolve fine detail that depends on the diameter of the objective lens or mirror. Secchi's telescope had an aperture of 9.6 inches (24 cm), which gives it a theoretical resolution of about 0.5 arcsecond. Ganymede, the largest Jovian moon, never appears larger than 1.8 arcseconds across (1/1000 the diameter of the full Moon). To put it simply, seeing detail on Jupiter's moons requires a large telescope used under extremely favorable conditions (*S&T*: Jan. 2014, p. 54).

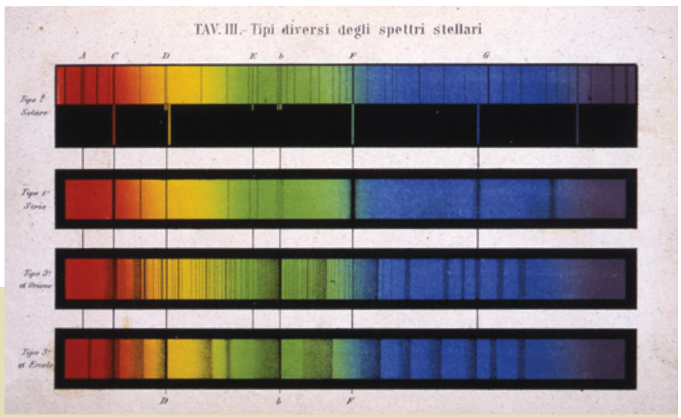
Despite the limitations of their instruments, 19th-century observers reported diameters for the moons within 10% of their actual values (accurate to about 1/10 arcsecond). Secchi's numbers, however, reflect a precision of 1/1000 arcsecond, and one of his Jovian moon drawings shows what appear to be polar caps like those seen on Mars — certainly not real features.

The preferred theory of the time to explain the moons' varying brightnesses invoked pancake-shaped objects that tumbled — one moment we might be seeing them edge-on and dim, and then later face-on and bright. And when they were in between edge-on and face-on, we'd see the moons as ellipses. Regardless of how strange this might sound today, at the time some astronomers truly thought they were seeing significant variations in the moons' brightnesses. And that would have made it impossible to determine their albedos, and therefore whether they were icy or not.

And what about density? Authors of astronomy books in the 19th century would often list each Jovian moon's mass and radius, but not bother to divide the mass by the volume to calculate their densities. The notable exception was English amateur astronomer George Frederick Chambers. His 1861 *A Handbook of Descriptive and Practical Astronomy* contains a wonderful table of sizes, masses, and densities for Jupiter's moons. However, his density figures look very odd — they're all only about 1/10 the density of water. Little in nature has that density. Gasses are far less dense than that. Everything else, even objects that float in water, are closer to water's density. Yet Chambers simply offers this information without comment.

What's surprising is that the numbers Chambers lists for size and mass are pretty good — close enough to have allowed him to compute moon densities that wouldn't be too far

▼ **COLOR VISION** The spectra of various stars as shown by the 19th-century Italian astronomer and pioneering spectroscopist Angelo Secchi. Presented here from top to bottom are the spectra of the Sun, Sirius, Betelgeuse, and Alpha Herculis (Rasalgethi). This work was the first systematic effort to classify stars by their spectra — Secchi observed about 5,000 stars — which led ultimately to the Hertzsprung-Russell diagram and our understanding of stellar evolution.



VATICAN OBSERVATORY

The Color of Ice

Why should low density and high albedo indicate the presence of water ice, instead of some other exotic material?

Firstly, water ice *should* be really common in the universe. This comes from knowing what the stars themselves are made of. Nineteenth-century pioneers in spectroscopy figured out how to split a star's light into its component colors, thus determining what elements are present. Angelo Secchi identified the spectral signature of hydrogen gas, and by the early 20th century, astronomers understood that stars are mostly composed of hydrogen, with helium coming in a distant second.

The most common elements after hydrogen and helium are oxygen, carbon, and nitrogen. Thus, the most common compounds in planets turn out to be water, methane, and ammonia — the chemicals that result from hydrogen reacting with oxygen, carbon, and nitrogen, respectively. In the outer solar system these compounds all freeze into ices. The easiest of these to freeze is water — we have snow and ice on Earth, at temperatures where methane and ammonia remain gasses. So it's reasonable to identify the low-density, high-brightness material in the moons of Jupiter as water ice.

In fact, water ice has a very distinctive spectral signature in infrared light. That was finally detected in the light from Jupiter's moons and Saturn's rings in the early 1970s, by competing teams of astronomers at the Massachusetts Institute of Technology and the University of Arizona.

from those we know today. Even though he was on the right track, it seems that, somehow, he just didn't get the arithmetic right. Unfortunately, like other astronomers of his epoch, he never used any of these data to speculate on the moons' compositions. *Not properly of astronomical interest*, perhaps.

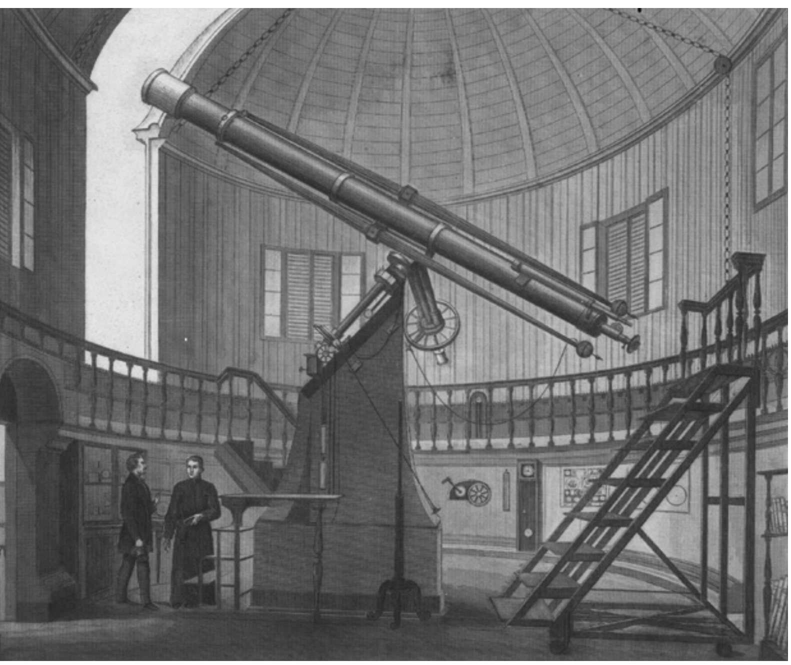
◀ **PIONEEERING OBSERVER** Angelo Secchi was a Jesuit priest and director of the Collegio Romano Observatory from 1850 until his death in 1878. He made the first measurements connecting solar activity to terrestrial magnetic storms, but his studies into the physical and chemical natures of stars and planets were his greatest achievement.

The Ice Men Cometh

So, who did finally make careful (and correct) measurements of both the brightnesses and densities of the Galilean moons, *and* consider what the data meant? Edward Charles Pickering, director of the Harvard College Observatory. In a paper published in 1907, Pickering gives tables of diameters, densities, and albedos for the moons — and his numbers are very close to modern values.

First, Pickering had to figure out the intrinsic brightness of each moon. In the 1870s he had developed a technique that measured by how much he needed to dim Jupiter's light with filters to match a moons' observed brightness. Using Engelmann's diameters, Pickering came up with albedos for the moons. His results were only about half the modern accepted values, but nevertheless he calculated that Europa is about twice as reflective as Earth's Moon. (Today we know that Europa's albedo is more than five times that of the Moon.)

▼ **TIBER TELESCOPE** This 9-inch (25-cm) Merz refractor at the Collegio Romano Observatory, located on the roof of the church of St. Ignatius in Rome, was used by the Italian astronomer Fr. Angelo Secchi to observe Jupiter's moons. After his death in 1878, the Italian government confiscated the telescope and moved it to their observatory on Montemario, Rome. It was lost in a fire in 1958.



And what's more interesting is what Pickering *did not* observe. In the 1879 *Annals of the Astronomical Observatory of Harvard College*, he wrote, "It has been thought by many astronomers that the light of the satellites of Jupiter was variable. This view is not sustained by the present measurements . . . During the past two or three years, I have frequently had occasion to compare the satellites, and in no case have I been able to perceive any marked change in their relative brightness beyond that due to the proximity of Jupiter."

That "proximity of Jupiter" seemingly is what had led other astronomers astray. When Europa is close to Jupiter and you look at it through a telescope, your eye will adjust to the brightness of the planet. This makes Europa appear dimmer than when it's farther from Jupiter's bright disk.

Pickering's explanation for this effect had actually been proposed 250 years earlier, shortly after Galileo first discovered the planet's moons. Fr. Christoph Scheiner, S. J. (famous for his dispute with Galileo over sunspots) and his student Johann Georg Locher, wrote in 1614 about this. "Anyone who can see, has seen a lesser light obscured by a greater; a weaker, by a stronger," they wrote. It appears that 19th-century astronomers didn't know about Scheiner and Locher's analysis, demonstrating that when we lose touch with past scientists, we lose knowledge.

Pickering took the novel step of actually interpreting the data in his table. "It will be noted that the densities . . . are extremely small for solid bodies," he wrote. "The density of our Moon, which is of about their size is 3.44 [times the density of water], and that of the Earth much larger . . ." And then, with density and albedo measurements in hand, he proceeded to suggest what the moons might be made of: "Their density and brightness are what we should expect if they were composed of . . ."

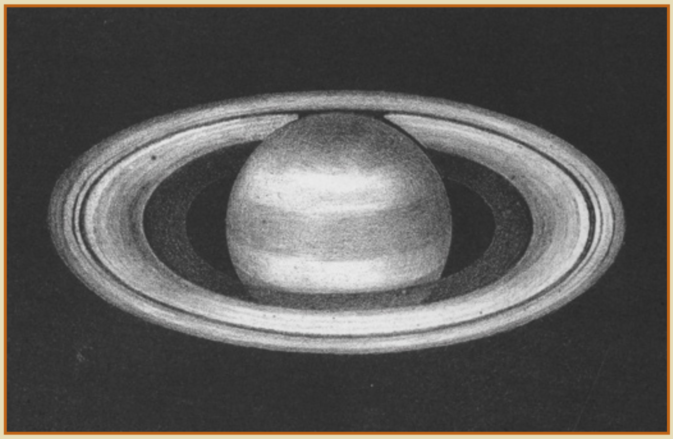
Wait for it!

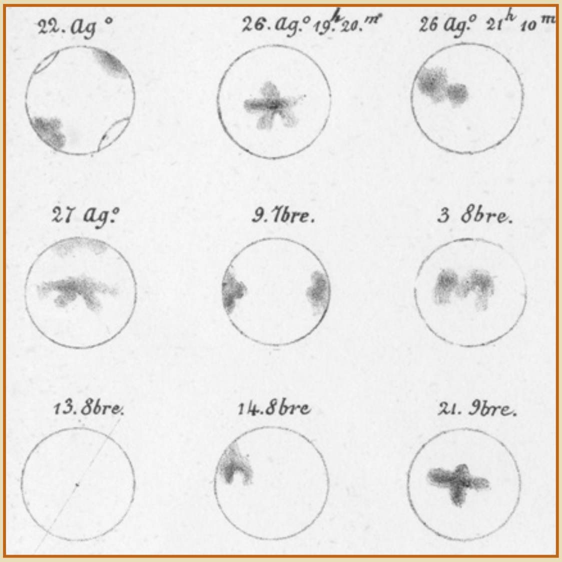
". . . loose heaps of white sand."

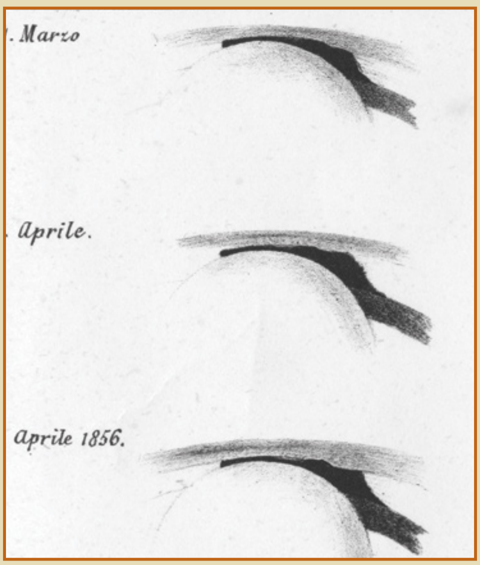
Sand? Why didn't Pickering think of ice?

For one thing, even though Secchi had identified hydrogen in stars, most astronomers hadn't yet accepted that the most abundant element in the universe was hydrogen. Pickering wouldn't have expected ice to be a common substance in space. But he was also convinced that the moons couldn't be solid because, as he explains, unless they're made of something that can change shape, like sand, ". . . it is impossible to understand how rigid bodies could assume the varying ellipticities exhibited by these bodies . . . the variations of whose

VATICAN OBSERVATORY (2)







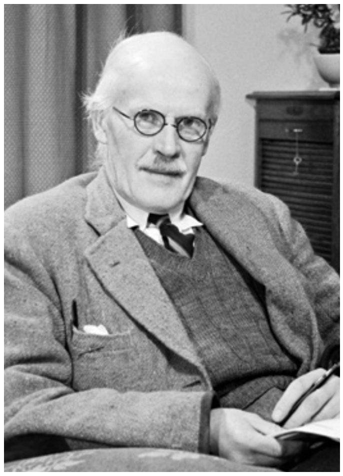
▲ **SOLAR SYSTEM SKETCHES** This series of drawings by Angelo Secchi shows (clockwise from upper left) Jupiter, Saturn, Mars, a sunspot, the shadow of Saturn's globe projected onto the rings, and, most notably, multiple sketches of Jupiter's moon Ganymede. The quality of Secchi's drawings, especially of Saturn, reveals his skill at making and recording observations; nevertheless, his 9-inch refractor could not resolve the detail shown on Ganymede's tiny disk. These renderings are from Secchi's "Descrizione del nuovo Osservatorio del Collegio Romano" in *Memorie dell' Osservatorio del Collegio Romano 1852–1856* (published in 1856).

VATICAN OBSERVATORY (6)

shape follow no obvious law."

In other words, Pickering was searching for a solution to a problem that his own observations had shown didn't exist. If the moons didn't vary in brightness, then there was no need to invoke "varying ellipticities" in the first place.

It wasn't until about 1923 that the British geophysicist Harold Jeffreys finally worked out the true nature of the moons. "The densities are comparable with the density of ice," he wrote in a paper in the *Monthly Notices of the Royal Astronomical Society*. That was about 50 years after astronomers could have (and arguably *should* have) gotten the correct answer. And it was 50 years before spectral data finally confirmed that the moons had ice on their surfaces.



◀ **INSIGHTFUL SIR** British astronomer and geophysicist Sir Harold Jeffreys was the first scientist to connect the dots and realize that Ganymede, Callisto, and Europa had densities "comparable with the density of ice."

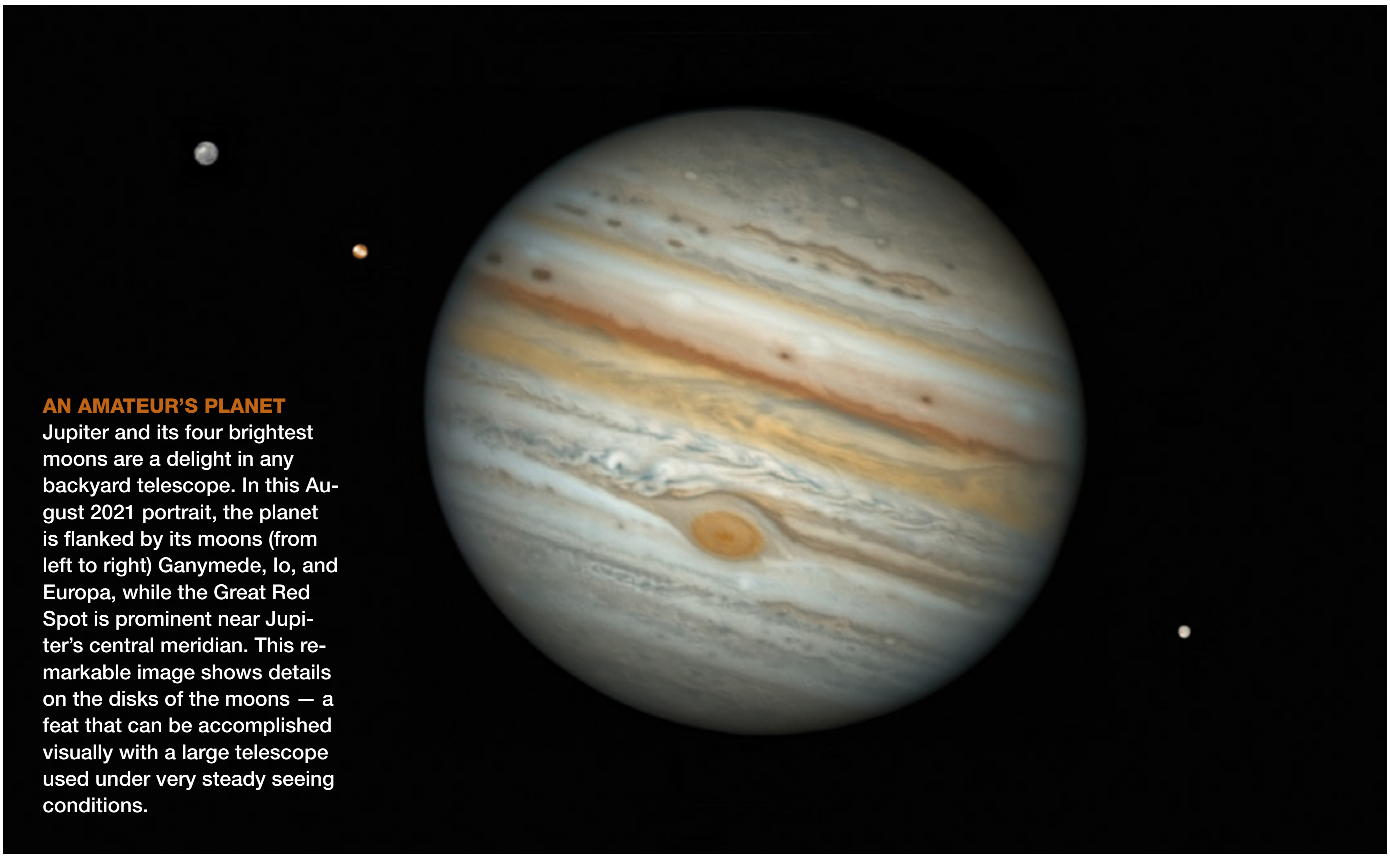
However, before we judge past astronomers too harshly, it's worth bearing in mind that it's a rare researcher who can escape getting turned around on the twisting path of scientific progress. Indeed, one of the authors can empathize. In the early 1970s, with the presence of ice on Jupiter's moons recently confirmed, Guy Consolmagno was working on his master's thesis at the Massachusetts Institute of Technology, trying to explain why Europa was covered in ice. With his computer models indicating liquid under the Europan surface, he wrote:

Given the temperatures of the interiors, and especially of the silicate layers through which liquid will be percolating, the possibility exists of simple organic chemistry taking place.... However, we stop short of postulating life forms in these mantles....

At the time, Carl Sagan was the only scientist seriously searching for life on other planets, and his work was subject to significant skepticism (and scorn) from the scientific community. *Not properly of astronomical interest.* Ten years later, though, others — including many of Sagan's students — would go on to investigate the idea of possible life under Europa's ice.

Being *almost* correct is part of science. Hermione might have some wry comment to make about that.

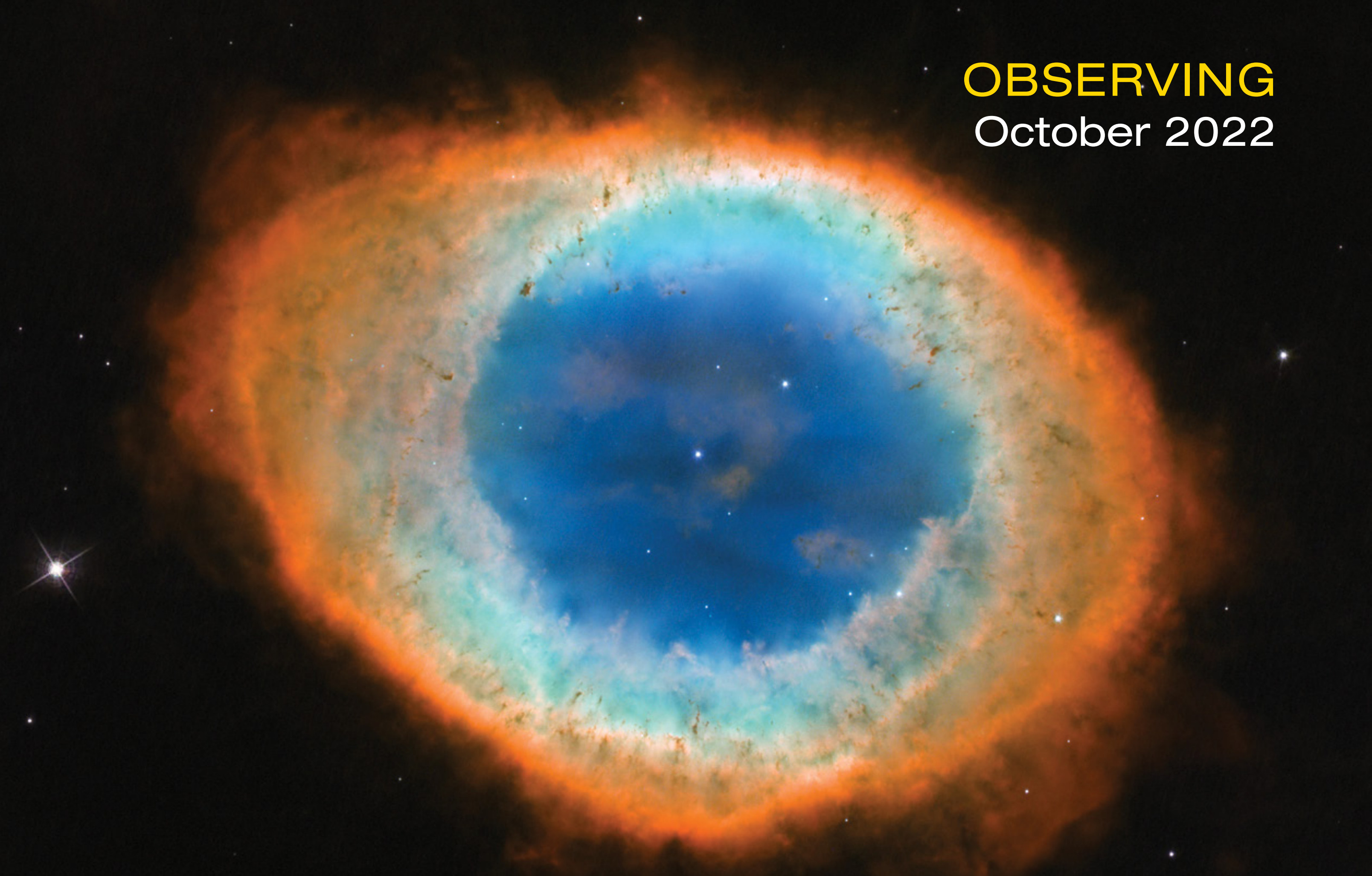
■ Br. **GUY CONSOLMAGNO**, S. J. is director of the Vatican Observatory (**vaticanobservatory.org**), which has facilities in Rome and Arizona. **CHRISTOPHER M. GRANEY** is an astronomer and historian of science with the Observatory.



AN AMATEUR'S PLANET Jupiter and its four brightest moons are a delight in any backyard telescope. In this August 2021 portrait, the planet is flanked by its moons (from left to right) Ganymede, Io, and Europa, while the Great Red Spot is prominent near Jupiter's central meridian. This remarkable image shows details on the disks of the moons — a feat that can be accomplished visually with a large telescope used under very steady seeing conditions.

HAROLD JEFFREYS: A. BARRINGTON BROWN, © GONVILLE & CAIUS COLLEGE / SCIENCE PHOTO LIBRARY; JUPITER: DAMIAN PEACH

OBSERVING
October 2022



4 **EVENING:** Algol shines at minimum brightness for roughly two hours centered at 11:23 p.m. PDT (see page 50).

5 **EVENING:** High in the south, the waxing gibbous Moon sits a little more than 6° lower left of Saturn.

7 **EVENING:** Algol shines at minimum brightness for roughly two hours centered at 11:12 p.m. EDT (8:12 p.m. PDT).

8 **EVENING:** The Moon visits Jupiter and is positioned roughly 4° lower right of the planet. Look toward the southeast to enjoy this sight. Go to page 46 for more on this and other events listed here.

12 **EVENING:** High in the east, the Moon, now waning gibbous, hangs less than 3° lower right of the Pleiades.

14 **EVENING:** Face the east-northeast to see the Moon and Mars rise in tandem in Taurus, some 3° separating them. The pair pose prettily between the “tips” of the Bull’s horns.

17 **MORNING:** The last-quarter Moon is in Gemini, around 3° right of Pollux. Watch as they climb higher in the east-southeast before sunrise.

18 **MORNING:** It’s the Crab’s turn for a lunar visit — the Moon is in Cancer and sits about 5° above the Beehive Cluster (M44).

20 **MORNING:** The waxing crescent Moon and Leo’s brightest star, Regulus, adorn the eastern horizon, with some 4½° between them.

21 **MORNING:** The Orionid meteor shower is expected to peak (turn to page 48). The waning crescent Moon shouldn’t interfere since it rises long after the radiant.

24 **DAWN:** The Moon, just one day before new, and Mercury rise in the east-northeast. This is a challenging sight to snag.

25 **NEW MOON (6:49 A.M. EDT):** A partial solar eclipse will be visible across most of Europe, northeastern Africa, the Middle East, and western Asia.

27 **DUSK:** The waxing crescent Moon and Antares sink toward the southwestern horizon in deepening twilight, with around 3° separating the pair.

27 **EVENING:** Algol shines at minimum brightness for roughly two hours centered at 9:53 p.m. PDT.

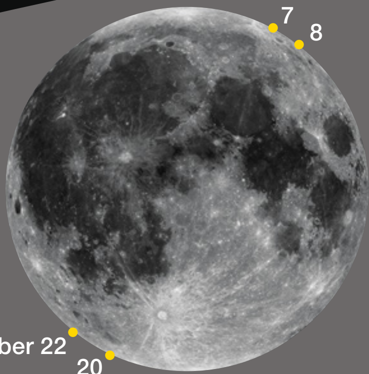
30 **EVENING:** Algol shines at minimum brightness for roughly two hours centered at 9:42 p.m. EDT.

The Ring Nebula (M57) is a planetary nebula in the constellation Lyra. Go to page 20 to read more on this and other deep-sky treasures. NASA / ESA / C. ROBERT O’DELL (VANDERBILT UNIVERSITY)

OCTOBER 2022 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					

FIRST QUARTER
October 3
00:14 UT

FULL MOON
October 9
20:55 UT

LAST QUARTER
October 17
17:15 UT

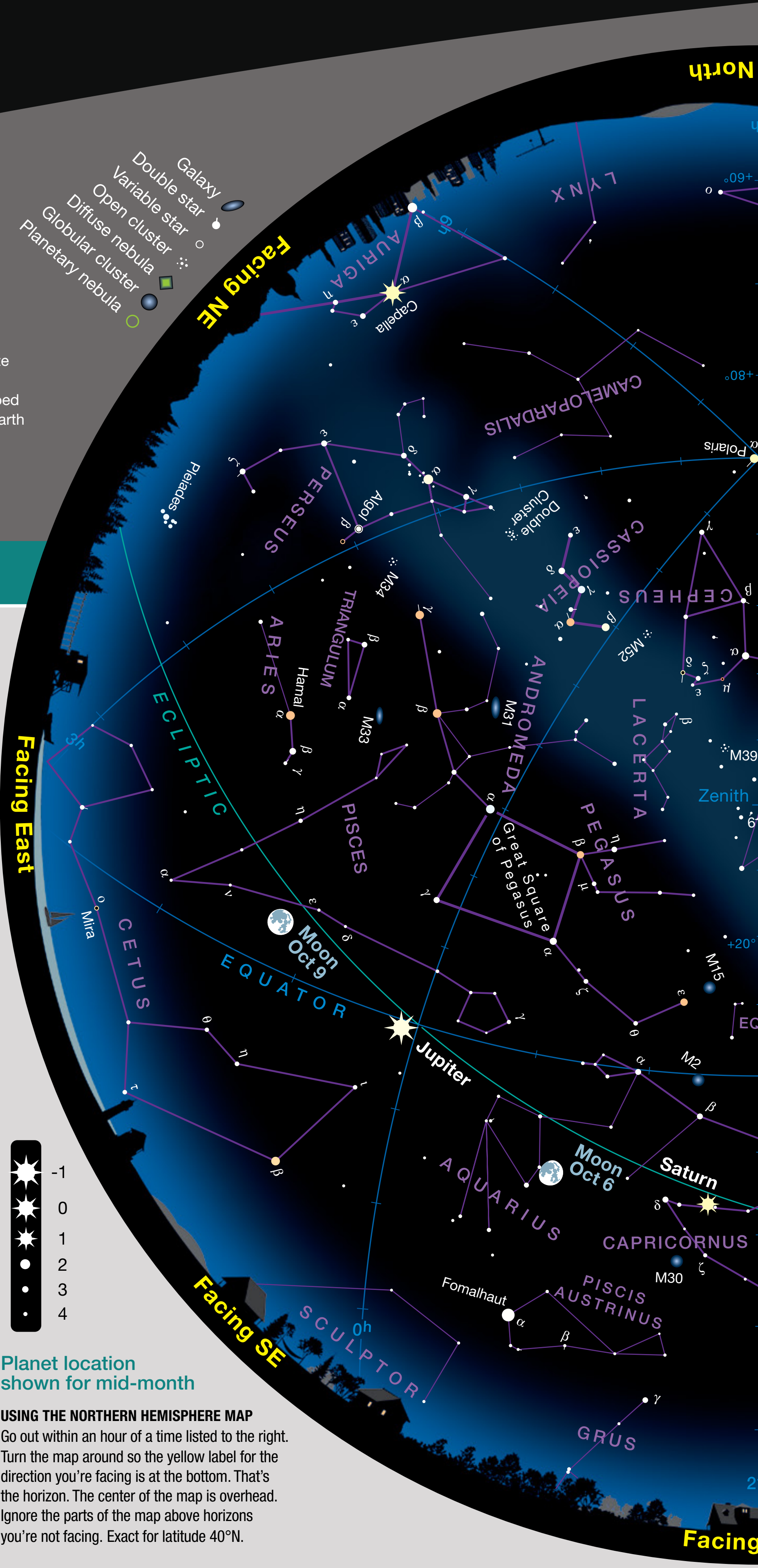
NEW MOON
October 25
10:49 UT

DISTANCES

Perigee 369,325 km	October 4, 17h UT Diameter 32′ 21″
Apogee 404,326 km	October 17, 10h UT Diameter 29′ 33″
Perigee 368,291 km	October 29, 15h UT Diameter 32′ 27″

FAVORABLE LIBRATIONS

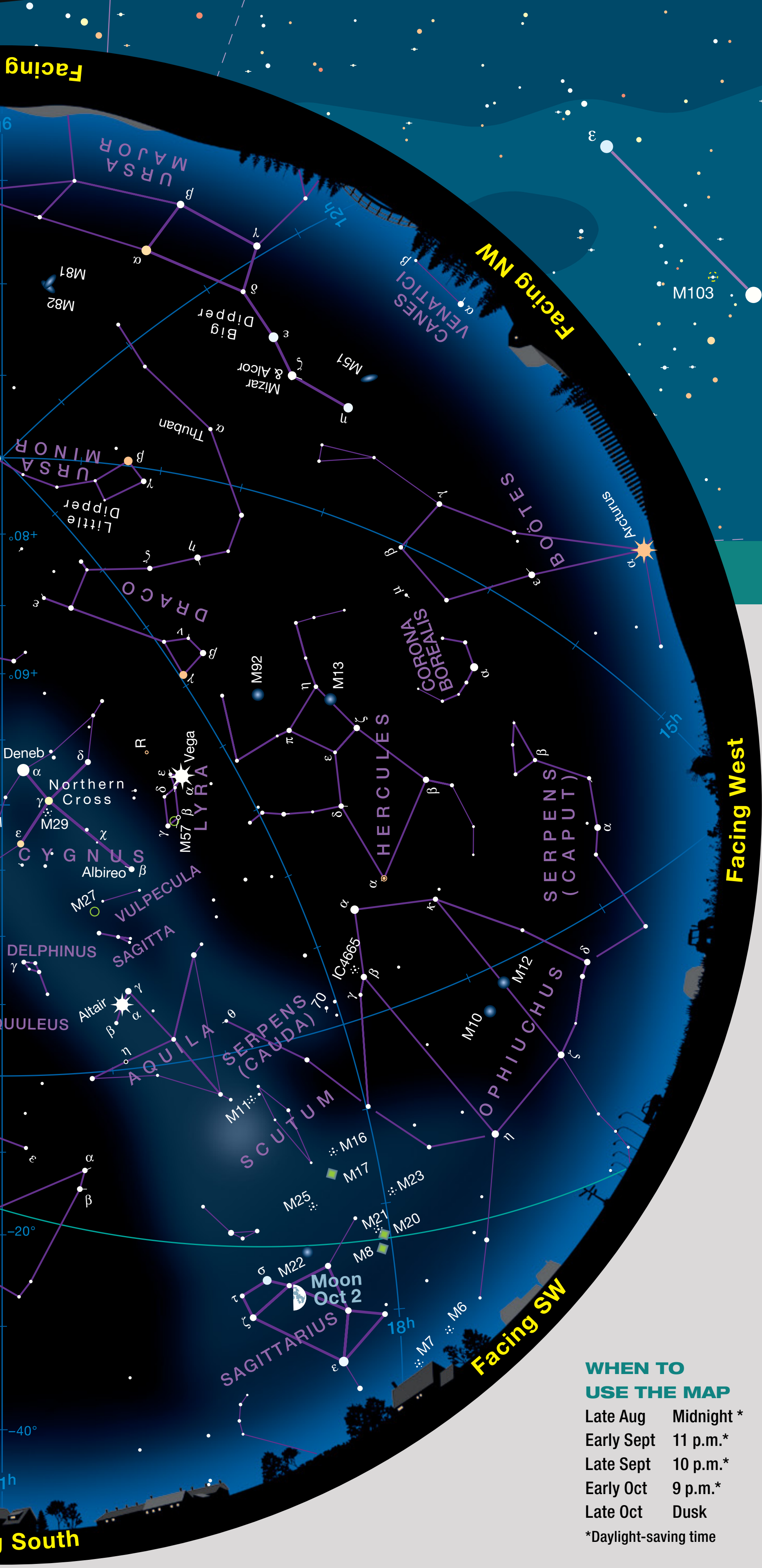
• Shi Shen Crater	October 7
• Dugan Crater	October 8
• Hausen Crater	October 20
• Andersson Crater	October 22

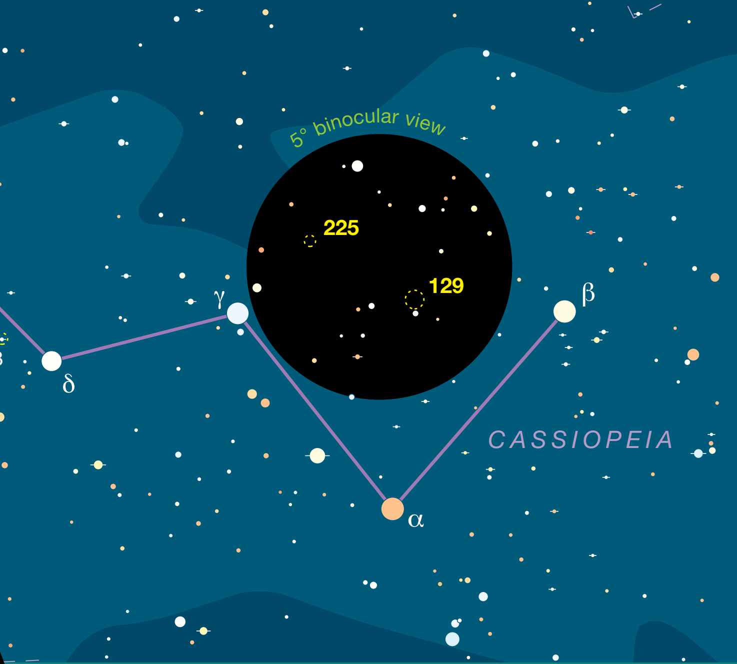


Planet location shown for mid-month

USING THE NORTHERN HEMISPHERE MAP

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





WHEN TO USE THE MAP

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

*Daylight-saving time

Binocular Highlight by Mathew Wedel

Plunge into Cassiopeia

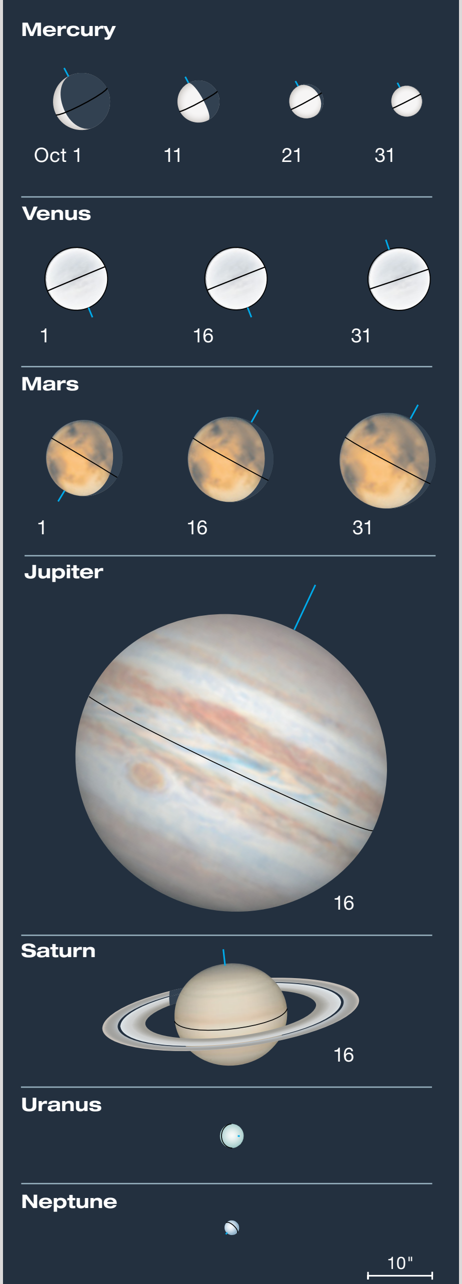
Cassiopeia, mythological queen of Aethiopia, was the first constellation I learned, but it's so rich that I'm still making new connections as I explore it further. This month we'll look at two open clusters that let us "see" the depth of space.

Start with 6th-magnitude **NGC 129**, which sits about halfway between the 2nd-magnitude stars Caph, or Beta (β) Cassiopeiae, and Navi, or Gamma (γ) Cassiopeiae, and just north of an imaginary line connecting them. The notes on my original observations, made with 7×50 binoculars, read, "compact, many stars, rivals M103 under dark skies." If conditions are good, by using 10×50 binos you may be able to spot a nice, even triangle of 9th-magnitude stars set off a bit to the south of the cluster's center. Our second target, **NGC 225**, glows at 7th magnitude a little more than 2° northeast of NGC 129. To me, the stars at the cluster's center look like a cup or a chalice, with fainter lights glittering within. A pleasingly symmetrical arc of 9th-magnitude stars sits just east of the cluster.

Of the two objects, NGC 129 looks bigger and brighter, so it's tempting to perceive it as being closer to us. But, in fact, at 5,300 light-years it lies more than twice as far away as NGC 225. NGC 129 also looks almost two times as large in diameter (21′ vs 12′), and if it's twice as distant, it must actually be four times the size of NGC 225. Astrophysical measurements bear this out — NGC 225 has a diameter of about 7.5 light-years, whereas NGC 129 is 32 light-years across. It's nice when the math works out so neatly.

I hope that learning more about the objects you observe helps you find connections of your own.

■ Realistically, **MATT WEDEL** is never going to fit all of Cassiopeia in his head, but that doesn't stop him from trying.



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

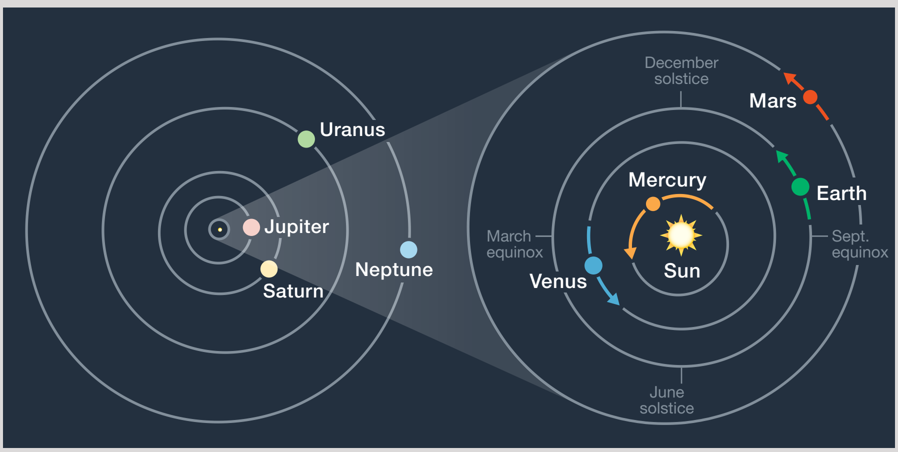
▶ **ORBITS OF THE PLANETS** The curved arrows show each planet's movement during October. The outer planets don't change position enough in a month to notice at this scale.

PLANET VISIBILITY (40°N, naked-eye, approximate) **Mercury** is visible at dawn to the 26th • **Venus** visible low at dawn until the 3rd • **Mars** rises in the evening and is visible to dawn • **Jupiter** shines brightly at dusk and sets before dawn • **Saturn** transits in the evening and sets after midnight.

October Sun & Planets

	Date	Right Ascension	Declination	Elongation	Magnitude	Diameter	Illumination	Distance
Sun	1	12^h 27.5^m	–2° 58′	—	–26.8	31′ 57″	—	1.001
	31	14^h 19.5^m	–13° 55′	—	–26.8	32′ 13″	—	0.993
Mercury	1	11^h 37.6^m	+2° 01′	13° Mo	+1.4	8.9″	16%	0.757
	11	12^h 01.7^m	+1° 44′	18° Mo	–0.8	6.6″	62%	1.024
	21	12^h 57.6^m	–4° 07′	13° Mo	–1.0	5.3″	90%	1.258
	31	13^h 59.6^m	–11° 04′	6° Mo	–1.2	4.8″	99%	1.391
Venus	1	12^h 08.8^m	+0° 36′	6° Mo	–3.9	9.8″	99%	1.708
	11	12^h 54.6^m	–4° 25′	3° Mo	–4.0	9.7″	100%	1.715
	21	13^h 41.0^m	–9° 18′	1° Mo	—	9.7″	100%	1.717
	31	14^h 28.7^m	–13° 49′	2° Ev	–4.0	9.7″	100%	1.715
Mars	1	5^h 15.7^m	+22° 24′	108° Mo	–0.6	11.9″	88%	0.784
	16	5^h 33.2^m	+23° 08′	118° Mo	–0.9	13.4″	90%	0.700
	31	5^h 39.4^m	+23° 49′	132° Mo	–1.2	15.0″	93%	0.624
Jupiter	1	0^h 12.9^m	–0° 22′	175° Ev	–2.9	49.8″	100%	3.956
	31	0^h 00.5^m	–1° 39′	142° Ev	–2.8	47.7″	100%	4.131
Saturn	1	21^h 26.1^m	–16° 29′	131° Ev	+0.5	18.1″	100%	9.170
	31	21^h 24.7^m	–16° 34′	101° Ev	+0.7	17.3″	100%	9.612
Uranus	16	3^h 00.8^m	+16° 43′	155° Mo	+5.6	3.8″	100%	18.775
Neptune	16	23^h 36.0^m	–3° 55′	151° Ev	+7.8	2.4″	100%	29.041

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**.



Autumn's Lonely Southern Beacon

Solitary Fomalhaut shares connections with several bright stars.

Autumn is a very lonely season for bright stars. From mid-northern latitudes, the constellations of spring have three stars of first magnitude or brighter; summer displays four such stars; and winter boasts seven luminaries. But the constellations of autumn have, remarkably, just one: Fomalhaut.

Fomalhaut dominates the otherwise undistinguished constellation of Piscis Austrinus and is even more isolated than the above statistics suggest. Excluding the far southern sky, Fomalhaut is the only first-magnitude star occupying a vast span of about eight hours of right ascension — one-third of the way around the entire heavens.

If you're not sure that the glint near the southern horizon is Fomalhaut, you can confirm your sighting by first locating the Great Square of Pegasus. Extend a line 45° south through the Square's western stars and you'll land right at Fomalhaut's position. But since it has no competition anywhere nearby, unless something's blocking your view, the star should be easy to identify.

▲ **ALONE AGAIN, NATURALLY** Sitting between the glitter and spectacle of the summer and winter constellations are the comparatively faint stars of the autumn sky. The sole exception is 1st-magnitude Fomalhaut, which is shown in the photo above near the lower right of the frame between a pair of trees.

ALAN DYER

Now, here's something else to consider: Fomalhaut might not look as bright as you expect. With a declination of –29.6°, it never rises higher than 20° above the horizon for observers at 40° north latitude. When a star is that low, its light is dimmed by the thick layer of atmosphere it has to travel through. Even on a clear, transparent night, *atmospheric extinction* dims Fomalhaut from magnitude 1.2 down to around 1.6 — slightly below the first-magnitude cutoff of 1.5. Viewers around 50° north latitude never see Fomalhaut higher than 10° and, therefore, never brighter than about magnitude 2.2.

Fortunately, lonely Fomalhaut has some statistical connections to other bright stars, including summer's brilliant Vega. Lyra's alpha star is 25.0 light-years from Earth, while Fomalhaut is just a tiny bit farther, at 25.1 light-years. The two have other interesting connections. About 40 years ago, the Infrared Astronomical Satellite (also known as IRAS) discovered what are probably belts of comets (or Kuiper Belt Objects) encircling each sun. And about 20 years ago, researchers found evidence that Fomalhaut and Vega may also each be orbited by a planet (or planets). The similarities don't end there. Studies also indicate that both stars are members of the Castor Moving Group, which includes some 16 stars that are drifting through space together.

When it comes to brightness, Fomalhaut is a very close match to Pollux, the brightest star in Gemini. Measurements show that Pollux is only 1/50 magnitude fainter — a difference that's impossible to perceive visually.

Finally, there's an interesting connection between Fomalhaut and Capella. At mid-northern latitudes, both stars rise at about the same time. This is remarkable considering that Capella is about six hours of right ascension farther east than Fomalhaut. But that difference is offset by Auriga's luminary being at a declination 76° farther north than Fomalhaut. As an evening star, Capella is viewable over three seasons (autumn, winter, and spring), and for those at around latitude 50° north, it's circumpolar and visible even in summer. By contrast, Fomalhaut is essentially a one-season star, being well placed almost exclusively in autumn. However, even from mid-northern latitudes, you can sight it in the predawn as early as May, and at dusk as late as January.

■ In January 1970, **FRED SCHAAF** located his first comet (Tago-Sato-Kosaka 1969g) low in the southwest, below Fomalhaut.

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

A Month of Lunar Rendezvous

The Moon visits four planets and a bright star in October.

THURSDAY, OCTOBER 6

If you go outside and face south this evening at around 11 p.m., you'll be greeted by the alluring sight of a waxing gibbous **Moon** bracketed by **Saturn** and **Jupiter**. The two planets are nearly 44° apart, and the Moon is roughly in the middle — a couple of degrees closer to Saturn than to Jupiter. But the apparent distances between these worlds presents only a two-dimensional picture. To fully appreciate the scene before you, consider the extreme depth-of-field (to borrow a photographic term) involved. Sunlight reflecting off the lunar surface takes just a touch longer than 1 second (1.23 seconds, to be precise) to reach your eyes this evening. Even though Jupiter has just had its closest opposition in nearly six decades, it's obviously much more distant than the Moon.

This evening the giant planet is far enough away that light bouncing off its cloudtop "surface" takes 1,982 seconds to arrive here. In other words, Jupiter is more than 1,600 times farther away than good ol' Luna. And what about remote Saturn? Here we're talking about 4,616 seconds — more than twice as long as for Jupiter. So, this evening's scene includes light-travel times of roughly 1 second, half an hour, and 1⅓ hours. That's more impressive to contemplate than 44°, isn't it?

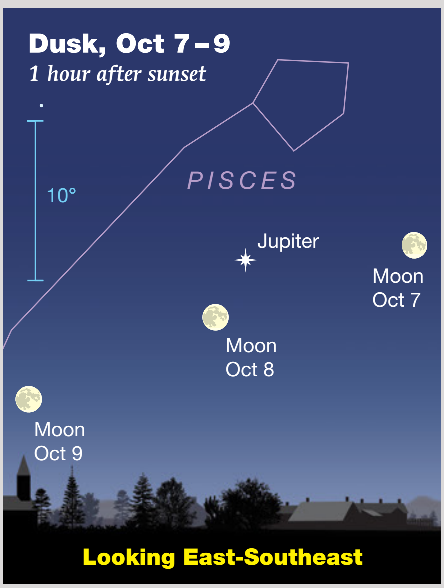
SATURDAY, OCTOBER 8

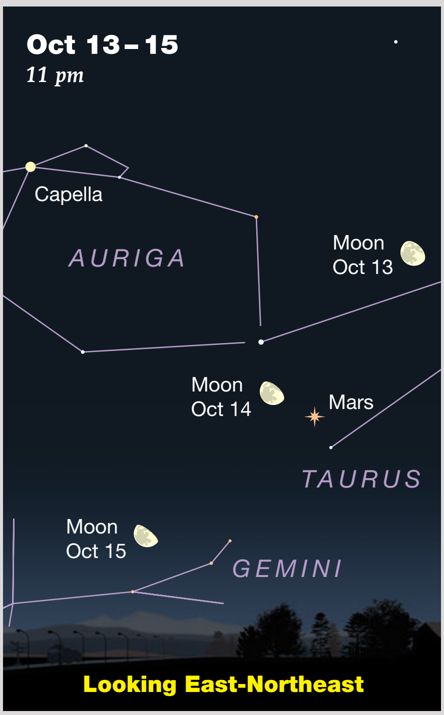
Moving on . . . and that's exactly what the **Moon** does. This evening it leaves Saturn far behind and sits left of **Jupiter**. Because it has already passed Jupiter, the Moon is drifting farther and farther away from the planet. So, the earlier you look, the closer the pair will be. For observers on the East Coast, just a bit more than 3° separates the Moon and Jupiter as twilight dims. However, by the time they rise on the West Coast, that gap has grown to more than 4½°. Even if this isn't the closest Moon-planet pairing of the month (see October 14th), it's arguably the most eye-catching. That's because Jupiter gleams at its peak brightness of magnitude –2.9. This brilliance, plus its proximity to the nearly full Moon, are both indicators that the planet is not far removed from its September 26th opposition.

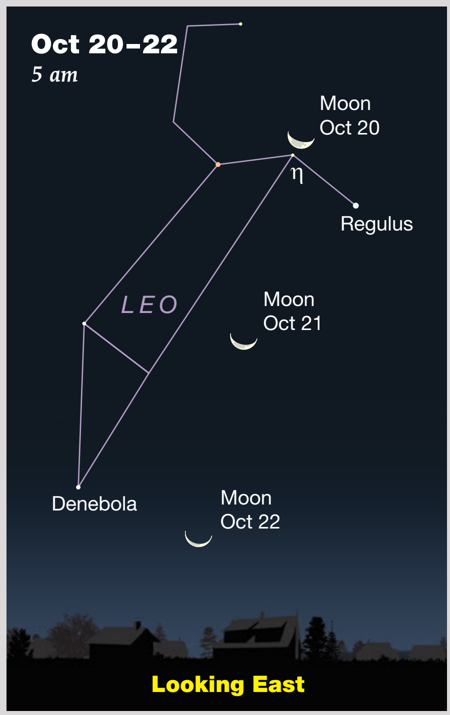
FRIDAY, OCTOBER 14

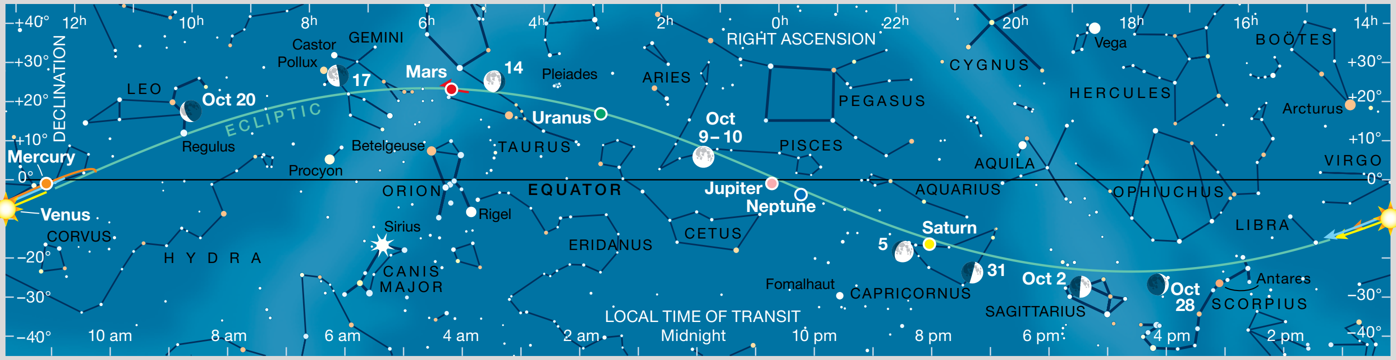
Skipping eastward along the ecliptic, the **Moon** joins **Mars** for its closest October

▼▶ These scenes are drawn for near the middle of North America (latitude 40° north, longitude 90° west).







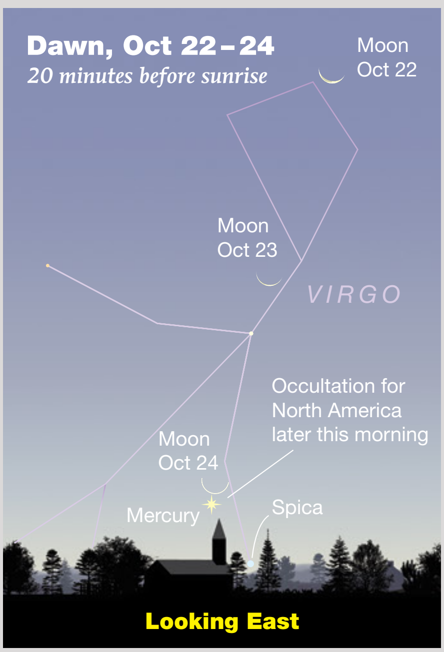


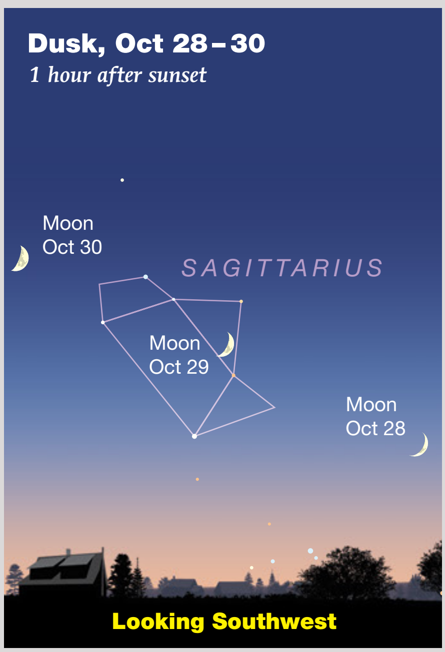
▲ The Sun and planets are positioned for mid-October; the colored arrows show the motion of each during the month. The Moon is plotted for evening dates in the Americas when it's waxing (right side illuminated) or full, and for morning dates when it's waning (left side illuminated). "Local time of transit"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

planetary encounter. Both objects are situated between the two stars marking the tips of Taurus's horns. The Moon is some 3° from the Red Planet, which glows at magnitude –0.9. That's a full two magnitudes fainter than Jupiter, but Mars's orangey hue gives it extra appeal. Indeed, I find that the silvery gray of the lunar disk enhances the color of any nearby star or planet. See if you find Mars's tint extra vivid tonight. Also, the nearby Moon's waning gibbous phase indicates that Mars is still some ways from reaching opposition. It doesn't hit that mark until early December, when it shines at magnitude –1.8 and enjoys its own (very exciting) encounter with the full Moon.

THURSDAY, OCTOBER 20

The **Moon** escapes the horns of Taurus, the Bull, only to find itself in the clutches of Leo, the Lion. As it climbs above the eastern horizon during the predawn hours this morning, the waning lunar crescent is roughly 4½° from **Regulus**. At magnitude 1.4, the regal star is the dimmest member of the zodiac's first-magnitude club. That's why Regulus looks its best when paired with a crescent Moon, rather than a brighter, more overwhelming phase. As dawn breaks across the Americas, the Moon is still approaching Regulus, which means this conjunction slightly favors observers on the West Coast. The real bonus for West-Coasters though will be the occultation of 3.5-magnitude Eta (η) Leonis. The lunar disk will cover the star from roughly 3:47 a.m. to 4:53 a.m. PDT, depending on your location. You'll need binoculars to enjoy this event, however. Turn to page 49 for more.





MONDAY, OCTOBER 24

This month's most interesting conjunction is also the most difficult to observe. During morning twilight, you have the chance to see a very thin (1% illuminated) waning crescent **Moon** hanging just 1° above **Mercury** in the east-southeast. Both objects are near the horizon and rise into a brightening sky. The Moon will be just 10° up at sunrise and, obviously, you'll need to locate Mercury well before that. On the plus side, the speedy inner planet is quite bright, shining at magnitude –1.1. However, given its low elevation and the resulting effects of atmospheric absorption, you'll need to shave a full magnitude off that figure. That's why it's a good idea to pack a pair of binoculars when you go out to observe this close gathering. And since the Moon is approaching Mercury, the later you look, the narrower the gap between them becomes. In fact, if you wait long enough — into full daylight — the Moon will actually catch up to Mercury and even eclipse it for observers at some locations. That event is described in detail on page 50.

■ Consulting Editor **GARY SERONIK** strives to be on time for Moon meetings.

Meteors Brighten October Skies

Fill your Halloween bag with luminous treats from two displays.

▲ More than three dozen Orionid meteors light the sky over the Wulanhada volcano in Inner Mongolia, China, in this composite photo made during the 2017 shower. The meteor streaks point back to the radiant located northeast of the bright, red star Betelgeuse, in Orion. This striking image also features numerous diffuse nebulae, including the C-shaped Barnard's Loop at right.

YIN HAO

Most major meteor showers are associated with comets, but it's usually a case of one comet per display. However, the May Eta Aquariids and October Orionids are exceptions in that they share the same famous parent: Halley's Comet. In May, Earth encounters dust shed by the comet on its outbound path, while on the night of October 20–21 we cross Halley's inbound track.

The shower peaks during the predawn hours of October 21st when observers under a dark sky can expect to see 10 to 20 meteors per hour zipping from a radiant about 11° northeast of Betelgeuse. This year we won't have to sweat the Moon either since the radiant rises late in the evening of the 20th, well before the 17%-illuminated waning crescent clears the horizon at around 3 a.m. local daylight-saving time on the 21st.

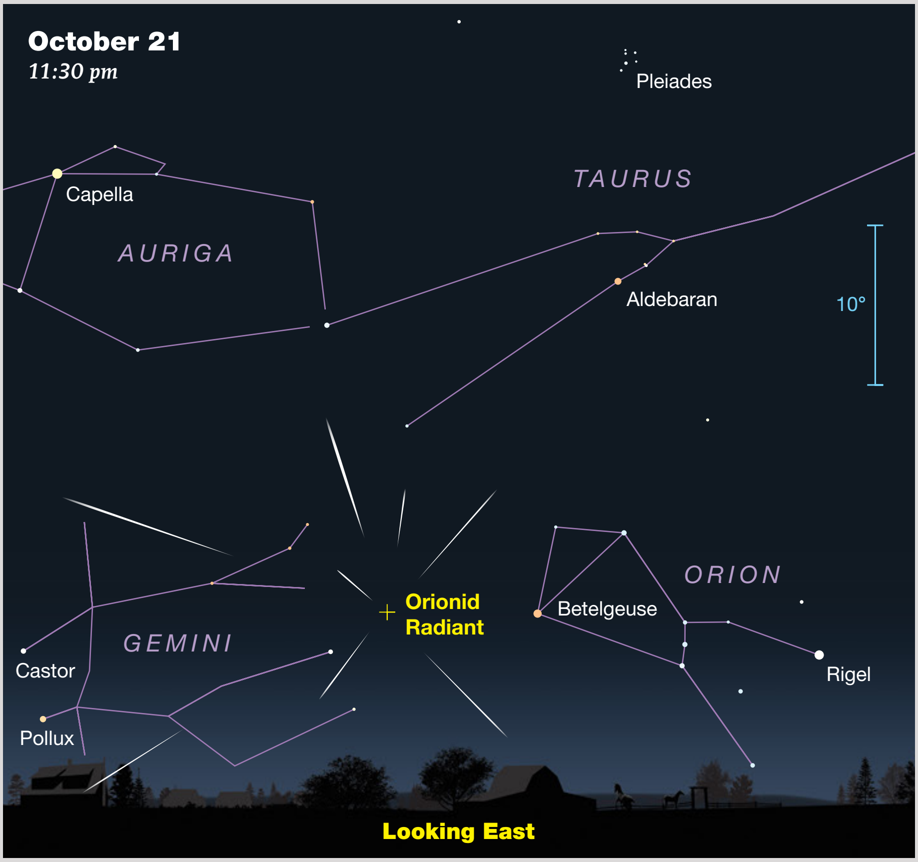
As Earth plunges headlong into Halley's dross, meteoroids will pelt the upper atmosphere at 66 kilometers per second (150,000 mph) — nearly as fast as November's Leonids. Swift meteors add an extra level of excitement to this sparkly sprinkling. Debris spreads out along the comet's orbit with time, broadening the meteoroid stream and increasing the duration of Orionid activity for up to a week centered on maximum.

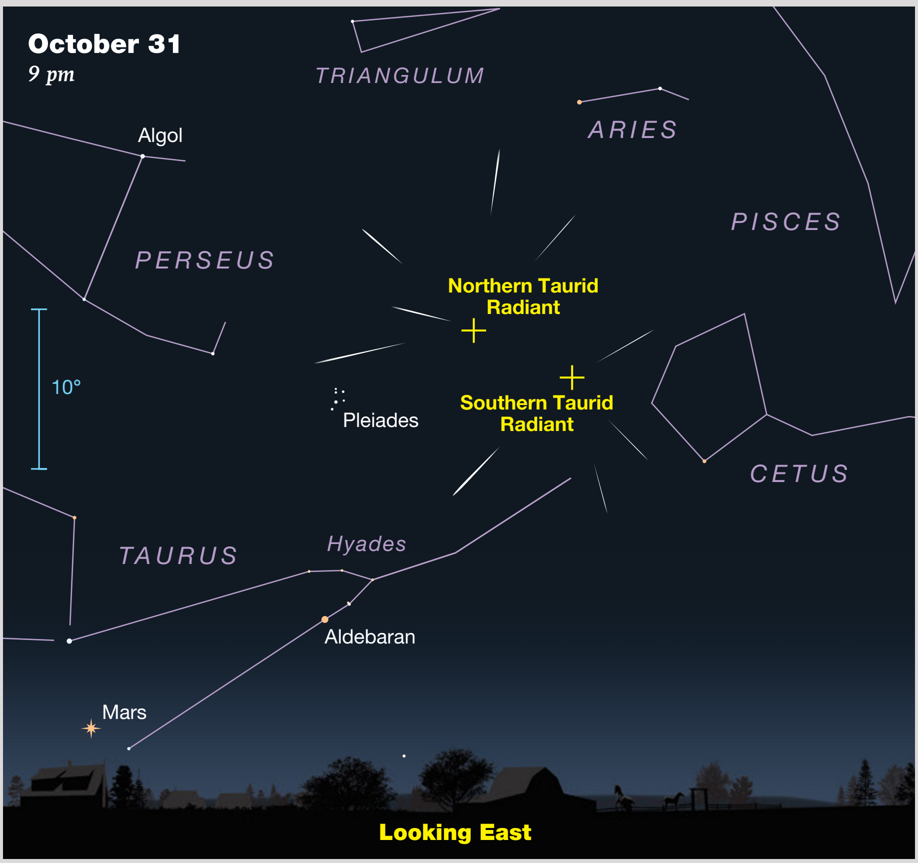
Where's Halley in all of this? Turn your gaze 30° toward the southeast to Hydra. Just a few degrees southwest of the Water Snake's head, the comet glows feebly at 26th magnitude from about 5.3 billion km away as it plods towards its December 9, 2023, aphelion. If you can stick around another few decades, you'll be able see the shower's prolific parent up close when it returns in mid-2061 (*S&T:* July 2021, p. 58).

The Orionids aren't the only October shower. According to the International Meteor Organization, this may be a particularly active year for the Southern and Northern Taurid meteor showers, which could mean an increase in the number of fireball sightings.

This potential uptick in activity is due to the *Taurid resonant swarm* — a concentrated patch of material shed by Comet 2P/Encke, mingled with small asteroids and other solar system debris, in orbital resonance with Jupiter. The swarm completes seven orbits around the Sun for every two by Jupiter. The material passes Earth's dayside in June and July and the nightside in October and November. The most recent nightside swipes occurred in 2012 and 2015.

The last week of October (which also happens to be Moon-free) will be the best time to watch for bright meteors from the display. Both Taurid streams have broad maxima and feature relatively slow-moving meteors (around 30 km per second) at rates typically less than 10 meteors per hour.





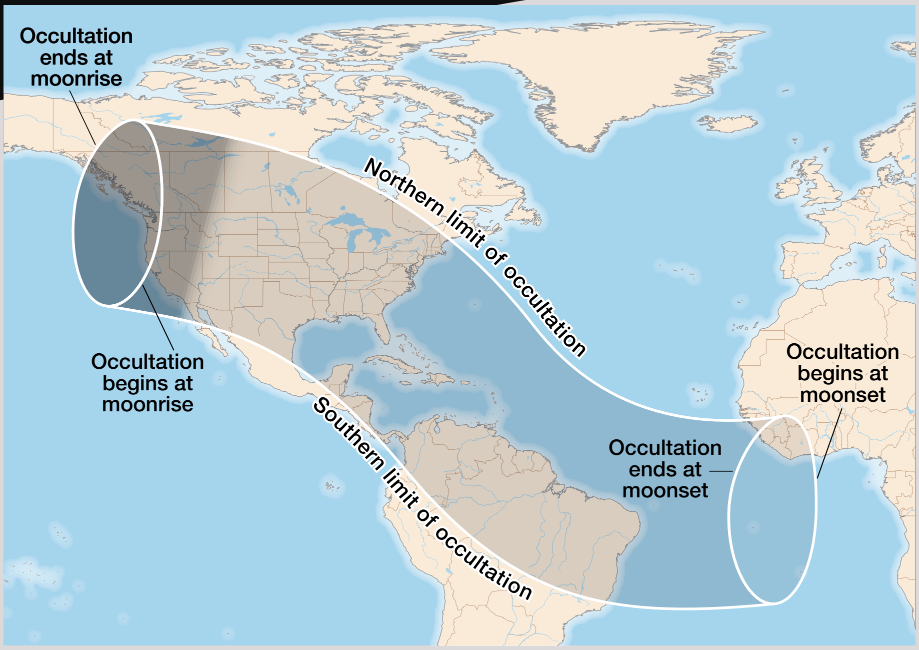
Three Notable Occultations

AS THE MOON MAKES its way eastward along the ecliptic this month, it eclipses two planets and a moderately bright star. The first of these events occurs on the night of October 11–12, when the 94%-illuminated, waning gibbous Moon makes Uranus vanish temporarily for observers across the western half of the U.S. (including Alaska) and much of Canada. The planet's disappearance at the bright lunar limb occurs before midnight (daylight-saving time) on the 11th for the Mountain and Pacific time zones, and shortly after midnight for the Midwest and Great Plains.

Uranus shines at magnitude 5.7 with a disk 3.8″ across that'll require a modest-size telescope to pull from the lunar glare. Its reappearance along the dark lunar limb will be easier to observe. The Moon's angle of approach varies depending on your location. The more oblique its path, the more gradually it'll cover the planet. For example, in Minneapolis, Minnesota, where the southern limb nicks Uranus, the Moon takes about 22 seconds to completely eclipse it. In Seattle, Washington, where the occultation is more central, the Moon covers the planet in about 8 seconds. Some places will see the lunar limb graze Uranus. For a list of disappearance and reappearance times visit **https://is.gd/uranusoccultation**.

Next, in the predawn hours of October 20th, the 24% waning crescent hides 3.5-magnitude Eta (η) Leonis in Leo's Sickle. Once again, the western half of the U.S., along with southern Canada and northern Mexico, are favored. Observers as far east as Ohio might be able to spot the star perched on the Moon's western limb around sunrise.

There's evidence to suggest Eta may have a close companion star, so



▲ This map shows the visibility of the Mercury occultation. Along most of the path the event occurs in daylight, while observers in the dark-shaded region experience a twilight occultation.

be sure to watch for a two-step wink-out, or better, record it on video with your telescope. You'll find more details at **https://is.gd/etaleonis**.

Finally, the Moon's third cover-up is something of a rarity but is also challenging to observe. On the morning of October 24th, observers across much of North America may see the exceedingly thin (0.8% illuminated) Moon cover Mercury's tiny (5.1″) disk. From most places, the event occurs after sunrise.

The good news is that the planet shines at magnitude −1.1, making it visible by daylight in a scope. The bad news is that the Moon will appear as thin as an onion skin and may not be visible at all unless your skies are exceptionally clear. It might look as if Mercury simply vanishes into the blue!

A section of western Canada and the area of southern California-western Nevada will be the only places where the planet will be occulted during morning twilight. At these locations, it might be possible to view the occultation with just a pair of binoculars. The rest of us will need a scope fitted with a safe solar filter and adhere to a careful procedure to view the event. Use a planetarium program to get the coordinates of the Sun and Mercury for that morning. With the solar filter in place on your scope, center the Sun, focus, and then shift the telescope in right ascension and declination to Mercury's position. You can then remove the filter and enjoy the show.

Minima of Algol

Sept.	UT	Oct.	UT
2	21:09	2	9:34
5	17:58	5	6:23
8	14:46	8	3:12
11	11:35	11	0:00
14	8:23	13	20:49
17	5:12	16	17:38
20	2:01	19	14:27
22	22:49	22	11:16
25	19:38	25	8:04
28	16:27	28	4:53
		31	1:42

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**.

Action at Jupiter

JUPITER IS FRESH FROM its September 26th opposition date and nicely placed for telescope observers. Indeed, for those who prefer viewing the planet in the evening hours, the post-opposition months are an apparition's prime time. On the first of the month, Jupiter is already nearly 20° above the east-southeastern horizon at the end of astronomical twilight and reaches the meridian at roughly 12:30 a.m. local daylight-saving time. The feature-rich planet presents a disk nearly 50″ across and gleams brightly at magnitude –2.9. Even by month's end, it's only 0.1 magnitude fainter.

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. Find events timed for when Jupiter is at its highest.

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

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

October 1: 4:03, 13:59, 23:55; **2**:

GREGG DINDERMAN / S&T

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

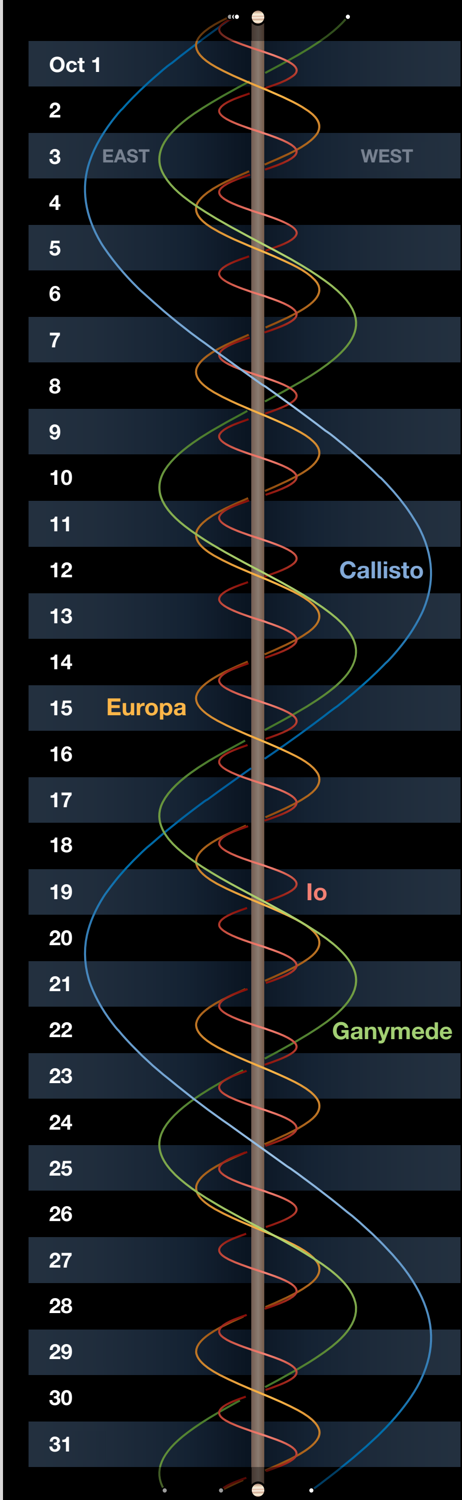
These times assume that the spot will be centered at System II longitude 25° on October 1st. If the Red Spot has moved elsewhere, it will transit 1²/₃ minutes earlier for each degree less than 25° and 1²/₃ minutes later for each degree more than 25°.

Phenomena of Jupiter's Moons, October 2022

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

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

Jupiter's Moons



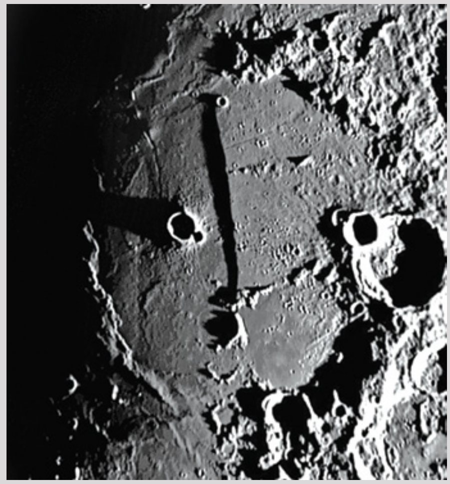
The wavy lines represent Jupiter's four big satellites. The central vertical band is Jupiter itself. Each gray or black horizontal band is one day, from 0^h (upper edge of band) to 24^h UT (GMT). UT dates are at left. Slide a paper's edge down to your date and time, and read across to see the satellites'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

Within Ancient Thebit

The Straight Wall isn't a single, continuous feature.

Is there an amateur astronomer who hasn't enjoyed looking at **Rupes Recta**? Commonly known as the Straight Wall, as the Latin name implies, the 110-km-long (68-mile) feature is relatively straight, and its shadow reveals its nature as a wall, cleft, or scarp. Even small telescopes can show the Straight Wall's shadow gradually diminishing as the Sun rises over the feature. From full Moon on, the Wall reflects the Sun's rays and appears as a bright line etched on the lunar surface. Measurements reveal that the eastern side is about 400 meters higher than the mare-covered western side.

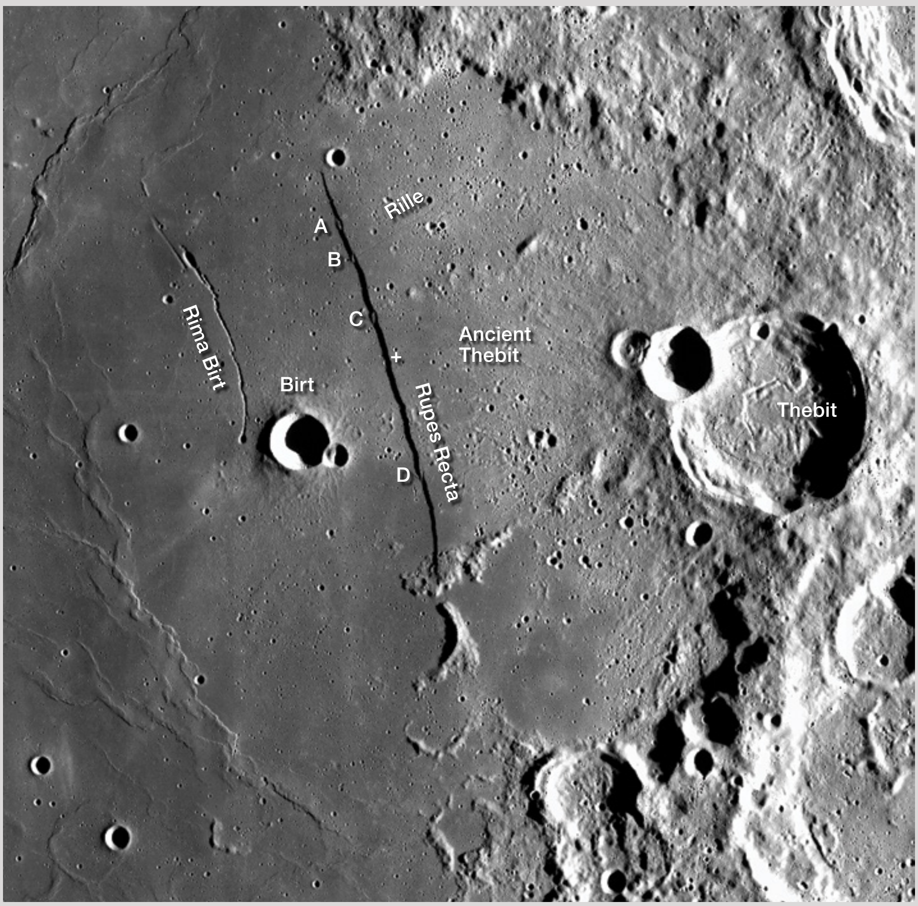
Although correctly interpreted as a fault scarp for many decades, the Straight Wall escaped modern analysis until 2015, when Amanda Nahm (then at the Lunar and Planetary Institute) and Richard A. Schultz (formerly of ConocoPhillips) applied modern techniques developed to study terrestrial faults. Their analysis characterizes the fault orientation, depth, and material strength to help determine the forces and processes that created the feature.



▲ Grazing illumination at sunrise reveals the point west of the Straight Wall where the ancient crater's floor abruptly becomes level.

Nahm and Schultz began by noting that the Straight Wall isn't a single fault but rather five segments, each slightly concave in the direction of the west side. Where the segments meet, there are minor knicks or offsets. Observers with 8-inch or larger telescopes using high magnification can detect these small offsets. Nahm and Schultz labelled them A, B, C, D, from north to south. Lunar Reconnaissance Orbiter Camera images provide closeup views, with offset D being especially interesting. The segment to the north of D ramps down to the base of the fault just where the next segment begins. The ramp would be the easiest place for astronauts to travel from the elevated east side, down 400 m to the west with its access to Mare Nubium.

Craters and large, displaced masses of rock at the segment boundaries along the Straight Wall show only vertical movement, so the scarp is what's known as a *normal* fault. This vertical displacement is verified with readily available height measurements, and the length of the fault requires only a ruler and a scaled photograph to measure. The depth of faulting was obtained by comparing changes in topography across the fault and the



◀ The large, flooded crater seen here is informally known as Ancient Thebit.

LABELLED IMAGE: NASA / GSFC / ARIZONA STATE UNIVERSITY; LOW LIGHTING ANGLE: JIM PHILLIPS surrounding area to a mathematically calculated topography model that uses the fault's vertical height and length as given values.

Nahm and Schultz find that the best fit to the measured scarp length and 400-m height implies that the fault initiated about 42 km below the surface and fractured its way upward. They conclude that the faulting started near the Straight Wall's highest point (marked + in the bottom image on the facing page). Additional fault segments initiated north and south of the main one and grew until they linked together, producing the noted segment boundaries. The estimated 42-km depth at which the fault originated is roughly where the crust meets the mantle, as determined from NASA's Gravity Recovery and Interior Laboratory (GRAIL) orbiter lunar gravity measurements. The crust on the east side of the fault is 35-to-40-km thick and abruptly drops to 25-km thickness west of the fault.

Now let's take a broader look at the region. Notice that the Straight Wall is near the center of a half crater informally known as Ancient Thebit, which is defined by a curved, mountainous rim to the east. The 57-km-wide crater **Thebit** cuts across the destroyed crater's eastern rim. What happened to the western half of Ancient Thebit? When the rising Sun illuminates the area (as the Moon's phase waxes), the buried western rim is revealed as a set of semi-circular mare ridges that extend the truncated northern rim of Ancient Thebit and continue the curved outline back towards the less distinct southern rim. This 220-km crater formed on the edge of Mare Nubium. The Straight Wall marks where the ruined crater's relatively flat floor east of the Straight Wall suddenly drops 400 m and then gradually declines another 450 m westward.

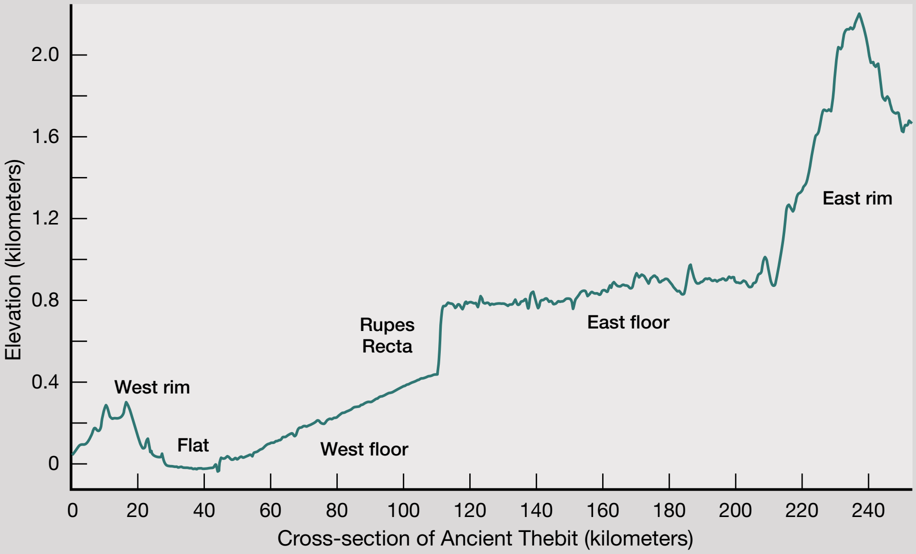
Northwest of the 16-km-wide crater **Birt** is **Rima Birt**. This rille generally mimics the slight curve of the Straight Wall, suggesting that the geologic stress that caused the collapse and created the enormous scarp also allowed magma to fracture its way to the surface, producing a 20-km-wide dome at Rima Birt's north end. In addition to the curve, the Birt rille is also offset at its midpoint, similar to the segment boundaries of the Wall. The rille looks like a series of short faults but has no detectable offset. Rather than moving up or down, it widened and was filled by rising magma at its north end. The 1-km-wide rille contains roughly 30 collapse pits, though none shows evidence of eruptions.

Grazing sunlight photos like the one on the facing page (and confirmed in cross-section measurements shown below) reveal another linear feature that isn't noted in scientific papers. There's a crease where the gradually sloping land 60 km west of the scarp abruptly becomes level. It's unknown how the change in slope occurred.

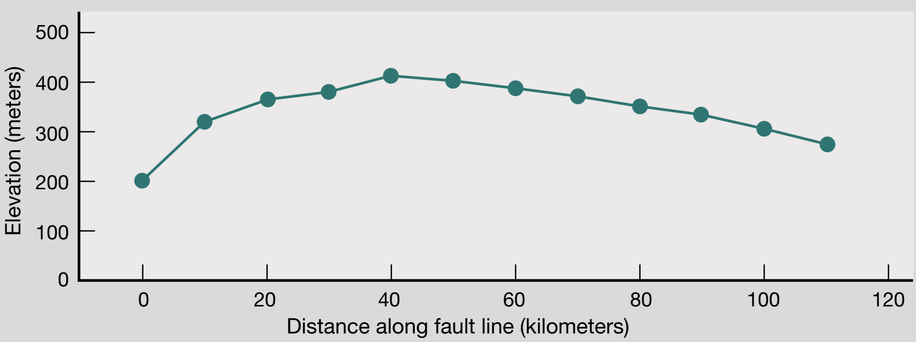
There's one more subtle linear feature within Ancient Thebit. A shallow, inconspicuous rille originates from the northeast and intersects the Wall at B. As with the crease, it's unclear how this apparently older rille relates to the formation of the Straight Wall.

So how did the Straight Wall form? Ancient Thebit was originally carved out of the western rim of the Nubium Basin. Later, the basin was inundated with lava, and the accumulating mass caused the basin floor to subside, triggering a powerful moonquake and the sudden, catastrophic collapse of the western half of Ancient Thebit. The Wall is the dividing line between the two halves.

■ Contributing Editor **CHUCK WOOD** thanks Richard Schultz for an invigorating discussion on this wonderful fault.



▲ The graph above shows the southwest-to-northeast topographic profile across the center of the ruined crater informally known as Ancient Thebit.



▲ This graph plots the height of the Straight Wall from north to south.

NASA / GSFC / ARIZONA STATE UNIVERSITY (2)

Beyond Your Camera's Kit Lens

Go wide or go deep — the sky's the limit when it comes to choosing a second lens.

Most interchangeable-lens cameras come with an inexpensive "kit lens" that works well for everyday photography. In our June 2021 issue, I showed how you can use basic equipment to create some compelling night-sky images. However, as your experience grows you may begin to feel limited by having just the one lens. But with so many options available, how do you choose the best second lens? The answer largely depends on what kinds of photographs you want to make.

Speed Limits

If you're shooting with a camera on a stationary tripod, then a fast, ultra-wide model is a great choice. A "fast" lens (one with a low f-stop number, such as f/1.8) delivers more light to your camera's sensor, which is critical for keeping exposure times to a minimum. The lower magnification of a short-focal-length lens allows you to maximize the exposure time before the stars start to

▶ National Parks and designated dark-sky locations are prime candidates for observing and photographing the Milky Way. The dark skies and high altitude of Bryce Canyon National Park in Utah were the perfect setting for this photo of the Milky Way setting behind a bristlecone pine. A Canon EOS 6D camera was set to ISO 6400 for this 30-second exposure with a Canon EF 15mm f/2.8 fisheye lens at f/2.8.

◀ A Canon 300-mm, f/4 telephoto lens provided the perfect framing for capturing the beautiful Comet NEOWISE (C/2020 F3) as it appeared in the evening sky in July, 2020. This 30-second exposure was recorded with a Canon EOS RP full-frame mirrorless camera set to ISO 3200. An iOptron iEQ30 Pro motorized equatorial mount carried the camera to prevent trailed stars.

trail due to Earth's rotation. You'll also find that the wide field of view increases your compositional options, allowing you to capture more of the night sky (especially the Milky Way) while including an interesting foreground that adds visual appeal to your photos.

If you have access to a motorized equatorial telescope mount, or to one of the many battery-powered sky-trackers, then you have more options. By counteracting Earth's rotation, these mounts allow for longer exposures and the use of greater focal lengths that provide extra detail, all without trailed stars. You can also get away with slower apertures (f/4, for example) while retaining pinpoint star images despite the additional exposure time required.

Either way, you can choose a basic lens since features such as auto focus and image stabilization aren't needed for astrophotography. Quality zoom lenses are versatile but rather expensive compared to fixed-focal-length prime lenses. These so-called *prime lenses* (ones with a single focal length) are likely to be less expensive and readily available on the used market.

A Question of Focus

When checking out a lens in person, pay particular attention to the quality of its manual focus adjustment. That's because the auto-focus systems on most cameras struggle in dim light, and you'll need to use manual focus and "live view" (if your camera has that feature) to achieve sharp stars. This is one of those situations in which you get what you pay for — it's simply easier to focus a high-quality lens than a low-end, budget option. Precise focusing is another reason why a fast lens is desirable. Beyond allowing for shorter exposures, it provides a much brighter live-view image.

Price is also often an indicator of optical quality. When comparing two similar spec'd lenses, the more expensive model is likely to perform better "wide open", that is, at its maximum (lowest f-number) setting. Such a lens will render pinpoint-star images across the entire frame. It's no use buying a fast lens if you have to stop it down to a small aperture to produce acceptable image sharpness. Each increase in f-stop cuts the amount of light reaching your camera's sensor in half — which is why, ideally, you'll want to shoot with your lens wide open.

Of course, no lens is perfect, but some aberrations are more troublesome than others. Image-editing software, such as *Adobe Lightroom* or *Photoshop*, can compensate for faults such as vignetting, geometric distortion, and even mild chromatic aberration. As long as a lens doesn't exhibit severe *coma* (in which stars are stretched out into comet-like streaks in the corners of the image) or *field curvature* (which prevents the entire image from coming to focus at once), it'll perform quite well.

Prime Time

For wide-field, fixed-tripod shots, there are a number of high-quality options available from a variety of different companies. Of course, every camera manufacturer makes (and promotes) its own line of lenses, but these often come at a premium price. If you own a full-frame camera, a budget-friendly option is the Rokinon/Samyang 14mm F2.8 ED AS IF UMC lens, which is available for a variety of common lens mounts. If price is less of an issue, it's hard to beat the excellent Sigma 14mm f/1.8 DG HSM Art lens. For APS-C crop-sensor cameras, check out the Rokinon/Samyang 10mm F2.8 ED AS NCS CS prime lens, as well as the Tokina atx-i 11-20mm f/2.8 CF zoom.

Although fish-eye lenses are somewhat specialized, don't rule them out if capturing super-wide vistas is your main imaging goal. One of my favorites is a discontinued Canon 15-mm model that I picked up used for a good price. Admittedly, it suffers from pretty severe coma, but that's a defect I'm willing to live with given its unique field of view and fast (f/2.8) aperture. For crop-sensor cameras, an 8-mm fisheye lens

▼ Many quality lenses are available on the secondhand market for reasonable prices. Shown here are a few the author has acquired over the years (from left to right): a Canon EF 15mm f/2.8 fisheye, Canon EF 10-22mm EF-S zoom, the EF 50mm f1.4 prime (mounted on the Canon 60D camera), and the author's favorite telephoto, the Canon EF 300mm f/4L IS USM lens.

ALL IMAGES COURTESY OF THE AUTHOR

▲ Despite being quite bright, the northern lights can change rapidly, which means you need very short exposures to record the sight without blurring. The combination of a 15-mm fisheye lens mounted on a full-frame Canon 6D camera was just wide enough to capture this sky-filling auroral display in Iceland. The fast f/2.8 lens aperture, plus a setting of ISO 1600, allowed for a 5-second exposure that effectively froze the action.

would provide similar results.

For those with tracking mounts, there's an almost unlimited number of choices available. This is why it's important to prioritize your astrophotography goals before reaching for your credit card. When it comes to versatility and ease-of-use, I like short- to medium-telephoto lenses (in the 80- to 100-mm range). With these, you can photograph large, individual deep-sky objects, while still enjoying relatively relaxed tracking requirements. Prime lenses in this category are used extensively by portrait photographers, and the same features they value — wide lens openings and tack-sharp results — also make them ideal for astrophotography.

As a Canon camera user, two of my favorites are the Canon EF 85mm f/1.8 USM Lens and the Canon EF 100mm f/2.8 Macro USM Lens. (Yes, a macro lens that's also great for astrophotography — go figure!) Importantly, both these lenses are available on the used market at substantial savings.

While prime lenses typically offer the best performance for your imaging dollar, there are notable exceptions. Many manufacturers offer high-quality zoom lenses in the 70-200 mm range. For example, the Tamron SP 70-200mm f/2.8 Di VC USD G2 Lens is a very desirable option for astrophotography. While these zooms certainly aren't cheap, you can save some money by shopping for older, non-stabilized models such as the Canon EF 70-200mm f/2.8L USM lens. In fact, the slower, f/4 version of that particular model is one of my all-time favorites due to its quality optics, useful zoom range, and light weight. Since this lens is well within the capacity of portable tracking mounts, it's a versatile option for an imaging rig to take along on your next vacation.

▲ If your telescope has a motorized equatorial mount, chances are you can replace the scope tube with your camera fitted with a short dovetail bar. This photo shows a Canon 60D DSLR camera and Canon EF 10-22mm EF-S zoom lens riding on an iOptron iEq30 Pro mount.

Going Long

If photographing individual deep-sky targets is your aspiration, consider prime lenses in the 135- to 300-mm range. Such optics reveal significant detail in many deep-sky objects without needing heavy-duty mounts, though they do require more precise tracking due to their higher magnifications. Check out the Rokinon 135mm f/2.0 ED UMC lens if you are looking for a fast, budget-friendly model in this category. On the used market, the Canon EF 200mm f/2.8L II USM lens can be an excellent value.

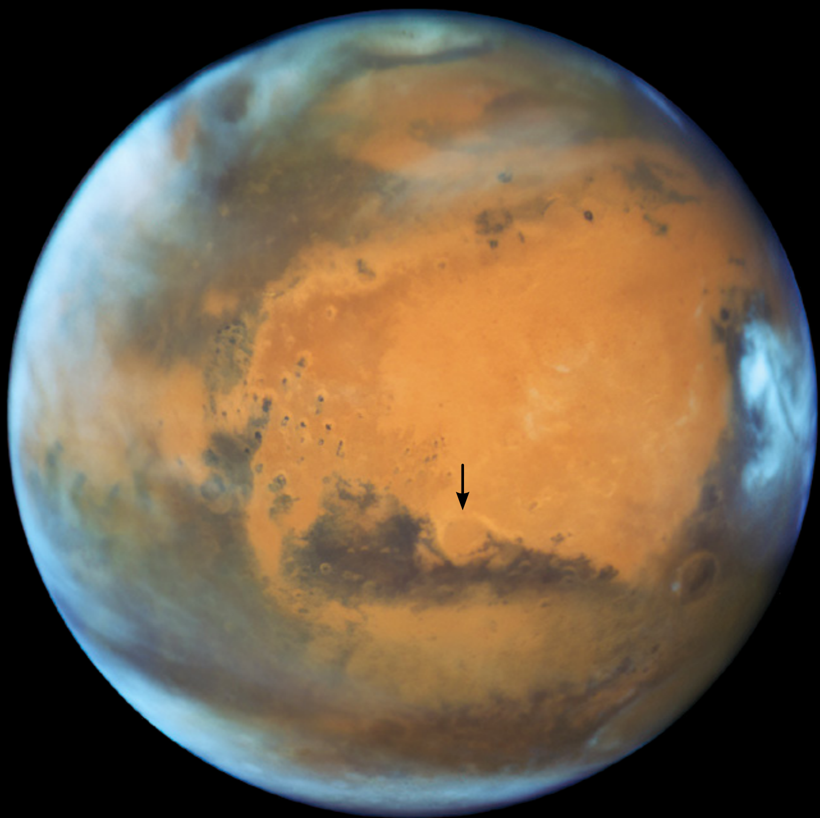
At the top end of the telephoto range you can save a significant amount of money by relaxing the fast f/stop requirement — but only if you're confident your mount can track accurately. There are a number of good options in the f/4 to f/5.6 range available from a wide variety of manufacturers. My go-to lens in this category is the (now discontinued) Canon EF 300mm f/4L IS USM lens.

Beyond these focal lengths, you're probably better off attaching your camera to a small refractor telescope, which typically costs less than the equivalent telephoto options. Just be aware that every increase in focal length requires a larger, heavier, and more accurate mount. If you value simplicity and stress-free imaging, stick with a shorter-focal-length optic.

Each category of lens offers a unique set of capabilities and limitations. So, when it's time to go beyond your camera's kit lens, the biggest decision isn't which lens to buy, it's what kind of astrophotography you want to try next.

■ **TONY PUERZER** is a retired professional photographer and avid amateur astrophotographer living in British Columbia, Canada. He's always on the lookout for a good deal on a new or used lens to enhance his photography.

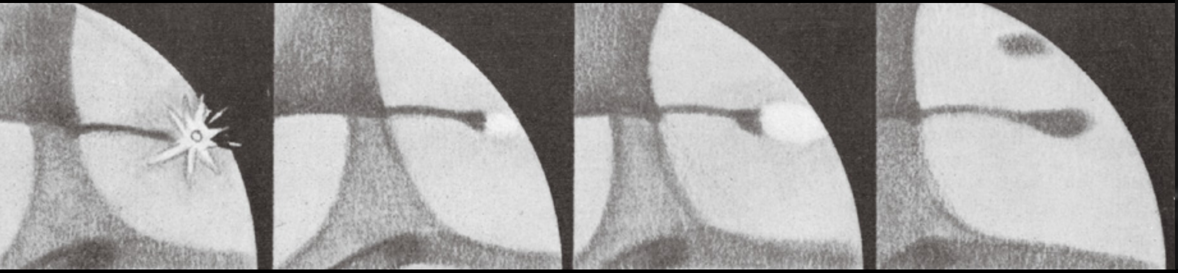
 by Thomas A. Dobbins and William Sheehan



STILL MYSTERIOUS In this 2016 Hubble Space Telescope image of Mars, Edom Promontorium (marked) basks in midday sun while the planet's morning limb and polar regions are shrouded in clouds.

Martian Flares

Observers have a chance to see a rare phenomenon for the second time this century.



In many ways, robotic exploration of Mars has relegated amateur astronomers to the status of telescopic tourists. NASA's Mars Reconnaissance Orbiter has mapped nearly the entire surface of the Red Planet at a resolution of 6 meters (20 feet) or better. Five landers and six rovers have sifted Martian soil and sniffed Martian air. In the span of a single generation during the closing years of the 20th century, "the very character of the scientific questions changed as the planets went from being astronomical objects to geological objects," notes William K. Hartmann of the University of Arizona's Planetary Science Institute.

Yet a few mysteries from the era of earthbound planetary exploration still linger. Prominent among them are Martian "flares" — gleaming points of light that suddenly appear and persist for a few seconds to several minutes before fading from view.

Anomalous Observations

The earliest report of these rare phenomena dates from 1896, when the British amateur John Milton Offord described a "brilliant scintillating star-like point" appearing briefly in Hellas, the vast ochre tract in the planet's southern hemisphere, which we now know as an ancient impact basin. During the following century, however, most flare sightings would be reported by Japanese observers, who came to regard spotting them as something of a specialty.

While observing Mars on the evening of June 4, 1937, Sizuo Mayeda saw an intense, flickering point of light near the morning limb at 55° north latitude. Far brighter than the polar cap, it vanished after about 5 minutes.

MARS: NASA / ESA / HUBBLE HERITAGE TEAM (STSCI / AURA), J. BELL (ASU), AND M. WOLFF (SPACE SCIENCE INSTITUTE); SKETCHES AND INSET: TSUNEO SAHEKI (3)

Redux?

◀▼ *Left:* Tsuneo Saheki's sketches show the development of the December 8, 1951, flare at Tithonius Lacus. *Right:* The 1954 event at Edom Promontorium drawn by Saheki was uncannily similar in both location and appearance to the phenomenon recorded in 2001. *Inset:* Tsuneo Saheki at the eyepiece of his venerable 8-inch f/10 Newtonian reflector.

On December 8, 1951, Tsuneo Saheki, one of Japan's leading planetary observers, was examining Mars through an 8-inch reflector at 400× when he saw ". . . a sharp, bright, glaring spot" suddenly appear at the eastern end of Tithonius Lacus, a dusky feature in the Martian tropics. Decidedly brighter than the polar cap, it disappeared after five minutes.

On July 1, 1954, Saheki saw a second flare, this time at Edom Promontorium, a bright feature on the Martian equator tucked into the nook formed by the junction of the dusky features Sinus Sabaeus and Sinus Meridiani. Its slightly elliptical outline corresponds to the ramparts of an ancient impact crater 460 kilometers wide that now bears the name Schiaparelli Basin. Lasting only a few seconds, this fleeting event was less spectacular than the 1951 flare and wasn't as bright as the polar cap.

Just 23 days later, Clark McClelland at Pittsburgh's Allegheny Observatory witnessed a far more impressive flare at Edom Promontorium. He reported that a white spot abruptly appeared and rapidly grew brighter until it equaled a first-magnitude star before fading from view in under a minute.

Japanese observers reported another outbreak of flares during the 1958 apparition of Mars. On November 7th, Sigeji Tanabe saw a spot on the southwest edge of Tithonius Lacus that grew as bright as the polar cap and faded from view after four minutes. Four days later, Sanenobu Fukui witnessed a spot as bright as the polar cap located between Tithonius Lacus and nearby Solis Lacus that persisted for about five minutes. On November 21st, the eminent Mars observer Ichiro Tasaka saw flares at two widely separated places on Mars, Edom Promontorium and the northern edge of Hellas. They faded after a few minutes, only to brighten again 15 minutes later before vanishing.

Saheki wondered if the flares might be volcanic eruptions, but University of Michigan astronomer Dean McLaughlin pointed out that they were far too luminous for that explanation to be correct. At the distance of Mars, McLaughlin estimated that the fire fountains of the most violent eruptions ever experienced on Earth would appear thousands of times fainter than Saheki's 1951 flare and would be invisible on the sunlit disc. "If these Martian flares were volcanic," he wrote, "they would indicate that Martian volcanism is characterized by occasional great outbreaks of incandescent gas a few kilometers in diameter and

with temperatures very far above those known in terrestrial volcanism."

McLaughlin offered a very plausible alternative, suggesting that "Perhaps it would be worthwhile to explore the possibility of a solar reflection from oriented ice crystals suspended in the Martian atmosphere. . ."

Earthly Analog

Ice crystals high in Earth's atmosphere form hexagonal shapes resembling thin slices cut from a pencil. They slowly descend like falling leaves, their faces aligned parallel to the ground by aerodynamic drag. A layer of millions of these horizontal plates can act as a giant mirror, producing a dazzling specular reflection known as a *subsun*. Resembling the glint off the surface of a calm body of water, subsuns are often seen from aircraft flying above a deck of cirrostratus clouds. These thin, translucent veils of ice crystals form at altitudes above 6,000 meters and can often cover the sky before the passage of a warm front.

In 1969, Victor Davydov of the Sternberg Astronomical Institute in Moscow published a pair of papers supporting McLaughlin's hypothesis that flares might be reflections of sunlight off layers of aligned ice crystals floating in the Martian atmosphere. He attributed their fleeting duration to the planet's rotation, which displaces a reflector by about 3 km every minute. Davydov's list of flare observations included sightings by Soviet astronomers in 1924 and 1956, helping to dispel the widespread impression that Japanese observers had a virtual monopoly on seeing them.

Prediction and Validation

Knowing that specular reflections appear halfway between the sub-Sun and sub-Earth points on Mars, we conferred in late 2000 with a group of dedicated planetary observers to

◀ **LATER SIGHTING** Noted planetary observer and telescope maker Ichiro Tasaka witnessed a pair of flares during the 1958 apparition of Mars.

analyze the Mars-Earth-Sun geometry of historical flare observations.

Our calculations indicated that the flares at Edom Promontorium sighted by Saheki and McClellan in 1954 occurred near zero phase angle illumination, with almost vertical angles of incidence and reflection. At Edom Promontorium the Sun was near the local zenith, separated from the position of Earth in the Martian sky by less than two degrees — ideal geometry for producing a reflection from a horizontal surface like a layer of atmospheric ice crystals.

The Mars-Earth-Sun geometry of other flares suggested reflectors with a modest but appreciable tilt. All but one of the flares at Tithonius Lacus required a highly inclined reflector, but this scenario wasn't difficult to envision because the area is a maze of branching canyons with steep walls.

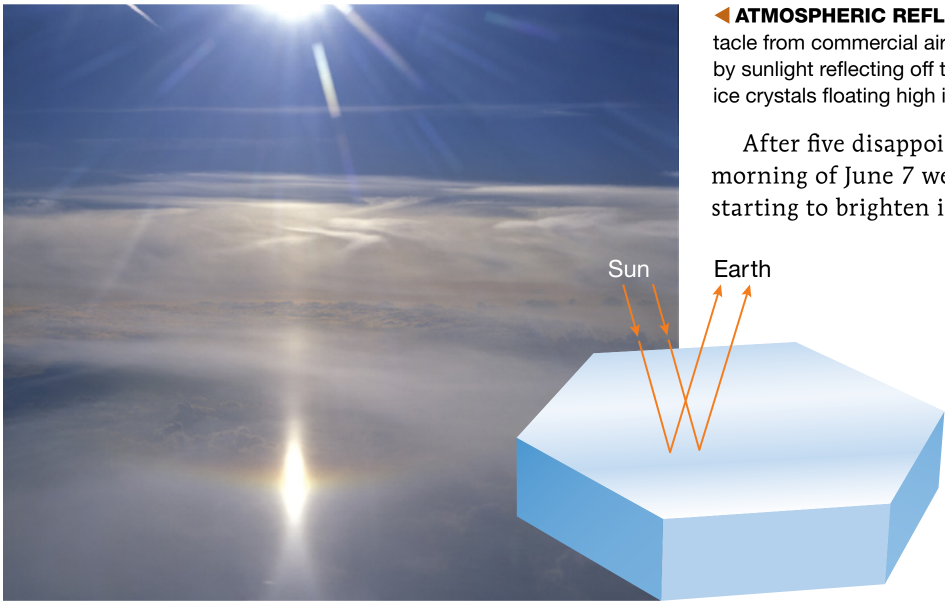
We also realized that for a few days early in June 2001, when Mars would be near opposition, the Mars-Earth-Sun geometry would be almost identical to when flares appeared at Edom Promontorium in 1954. The sub-solar and sub-Earth points would virtually coincide at Edom Promontorium and cross the center of the Martian disc when the planet would be at a reasonable altitude above the horizon for observers in the eastern and central United States.

Our findings were published in the May 2001 issue of *Sky & Telescope*. We urged readers to monitor Edom Promontorium early the following month and organized an expedition to observe the event from a site in the Florida Keys that promised clear skies and steady seeing. Our team included luminaries Don Parker, Matt (Tippy) D'Auria, Don Troiani, and Richard Schmude of the Association of Lunar and Planetary Observers, editors Rick Fienberg, Gary Seronik, and Carolyn

Martian-Flare Sightings

Date	Time (UT)	Observer	Location
June 4, 1937	19:44	Mayeda	Sithonius Lacus
December 8, 1951	21:00	Saheki	Tithonius Lacus
July 1, 1954	13:15	Saheki	Edom Promontorium
July 24, 1954	4:32	McClelland	Edom Promontorium
November 7, 1958	15:03	Tanabe	Southwest edge of Tithonius Lacus
November 11, 1958	15:05	Fukui	Northeast of Solis Lacus
November 21, 1958	13:35 and 13:50	Tasaka	Edom Promontorium and Northern Hellas
June 7, 2001	6:40	Florida Expedition	Edom Promontorium
June 8, 2001	7:00 and 7:53	Florida Expedition	Edom Promontorium

TAKESHI SATO



◀ **ATMOSPHERIC REFLECTOR** Brilliant subsuns are a frequent spectacle from commercial airliners. As illustrated below, they are produced by sunlight reflecting off the flat, mirror-like surfaces of hexagonal water ice crystals floating high in the atmosphere.

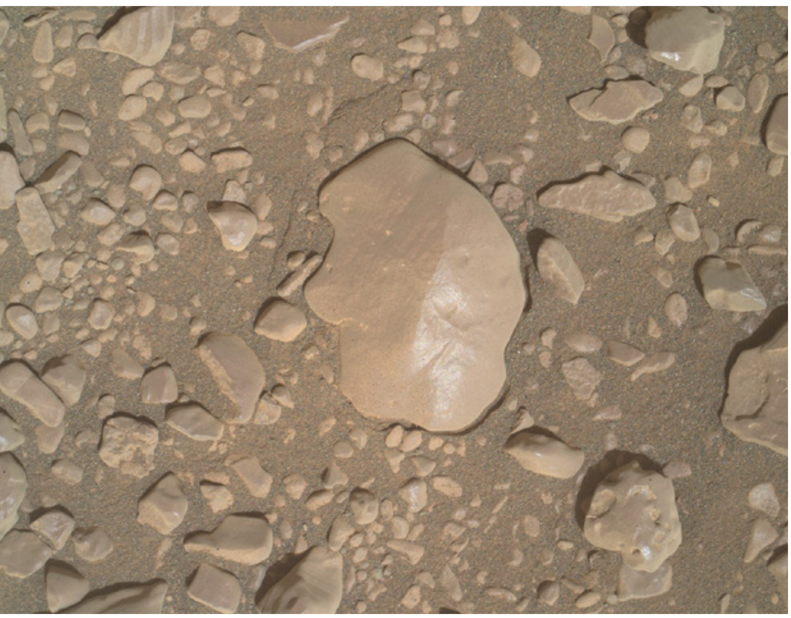
Collins Petersen of *Sky & Telescope*, and planetary geologist Timothy Parker of the Jet Propulsion Laboratory.

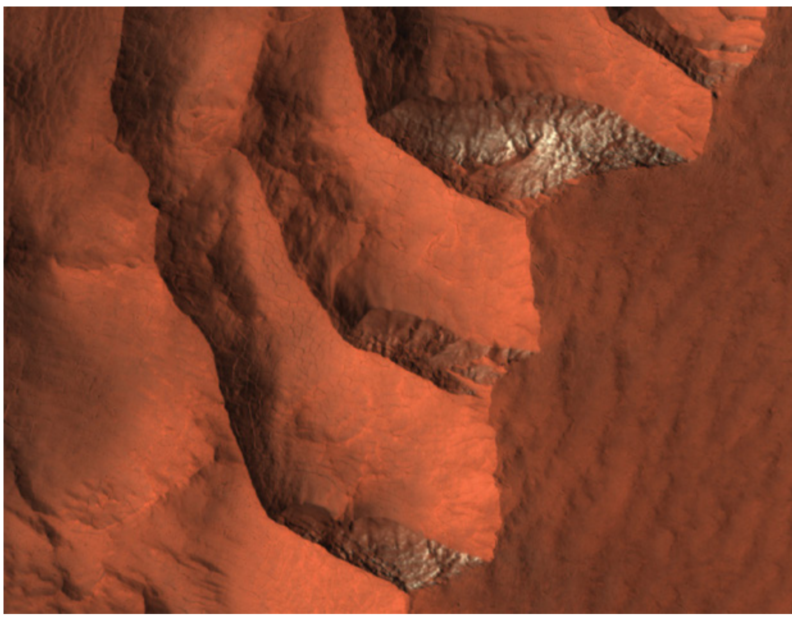
Our vigil began on the night of June 2. As luck would have it, we enjoyed clear or partly cloudy skies every night while most of the eastern and central United States was clouded out. We stayed glued to the eyepieces of our telescopes, pausing occasionally to apply bug repellent, stretch our legs, and inspect the grapefruit-sized image of Mars displayed on a television monitor fed by a video camera at the focus of a 12-inch telescope.

After five disappointing nights, in the wee hours of the morning of June 7 we noticed that Edom Promontorium was starting to brighten in the image on the television monitor. Dramatic brightness pulsations of two to three seconds duration soon began to occur at intervals of 10 to 15 seconds, lasting for 50 minutes. Seeing was very good at the time, so these fluctuations were not the result of atmospheric turbulence. At its brightest the flare surpassed the hoods of clouds over the polar region and the Hellas basin near the evening limb. Seronik described the event as "the most exciting planetary show since Comet Shoemaker-Levy 9 slammed into Jupiter in July 1994."

On the following night the flares reappeared in the same location, but this time in two discrete waves. The first wave, lasting for 20 minutes, consisted of a series of 3- to 5-second pulsations that were very similar in intensity to the previous night's phenomena. After a hiatus of half an hour, a second series began that lasted for another 31 minutes. Theory suggested that June 9 would be the date of the most favorable Mars-Earth-Sun geometry, but no flares were seen on that date or on June 10.

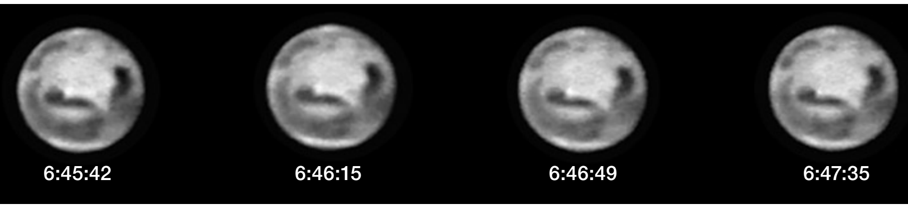
▼ *Left:* NASA's Curiosity rover recorded this image of the shiny surfaces of flat rocks in Gale Crater. These features, known as *ventifacts*, were polished to a sheen by windblown sand. *Right:* The Mars Reconnaissance Orbiter's HiRISE camera captured this image of water ice peeking out from beneath layers of sediment on cliffsides in Milankovic Crater on November 2, 2021. Could similar exposed outcroppings of ice be responsible for the Tithonius Lacus flares of 1951 and 1958?





SUBSUN: JOSEF PÖPSEL; ILLUSTRATION: GREGG DINDERMAN / S&T; ROCKS ON MARS: NASA / JPL-CALTECH / MSSS; WATER ICE: NASA / JPL-CALTECH / UNIVERSITY OF ARIZONA

PHOTOGRAPHIC PROOF This sequence of video frames captures the alternating brightness maxima and minima of the pulsating Edom flare on the night of June 7, 2001.



Measurements of video still frames revealed that the epicenter of the flares was located along the northern edge of Edom Promontorium at 0° latitude, 10° east longitude. On both nights the flares appeared earlier than predicted by our model, which was based on a horizontal reflector tangent to the planet's globe like a deck of cirrostratus clouds. The early onset indicates reflectors that slope upward from east to west roughly 10° to 20°.

To University of Nebraska astronomer Martin Gaskell, the pulsations implied a series of discrete reflectors on the surface of Mars conveyed by the planet's rotation:

> *Since the Martian reflectors are inclined to the horizontal a fair bit, this strongly rules out clouds. It's got to be on the surface. The range of inclinations can be readily explained by a range of slopes on the surface . . . The size of region needed to explain flashes of a few seconds duration is only a few times bigger than a football field. I think the faces of sand dunes is an interesting possibility. Flashes would only be seen on days when frost happened to cover the dunes.*

Although Gaskell's conjecture handily accounted for the pulsating brightness of the flares, it failed to explain why we didn't see them when the opposite slopes were facing us. Far more troubling was the fact that no dune fields appeared in high-resolution images of the flare site taken by the Mars Orbiter around the time when the flares were seen.

San Diego State University astronomer Andrew Young suggested: "If you need a surface inclined by more than a couple of degrees, you'd be better off trying to do this with aligned mineral grains. On Earth, it's not uncommon for minerals like feldspars to be highly aligned in igneous rocks, and faulting sometimes exposes fairly large surfaces with nearly specular reflections."

During the last two decades, two of the principal instruments aboard the orbiting Mars Odyssey spacecraft, the Thermal Emission Imaging System (THEMIS) and Thermal Emission Spectrometer (TES), surveyed Mars at high resolution in several wavelengths spanning the visible and infrared region of the spectrum. These data enabled investigators to construct detailed mineralogical maps of the Martian surface.

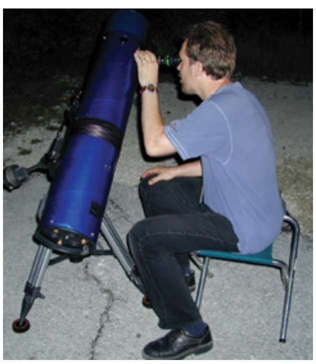
The two sites that account for the majority of flare sightings, Edom Promontorium and Tithonius Lacus, are very dissimilar in appearance and topography. It's only when they're examined in wavelengths invisible to the human eye that their special character becomes evident. Both sites are unusually rich in the feldspars known as plagioclase and pyroxene.

In a 1954 article about the possibility of observing specular reflections on the Moon, D. W. Rosebrugh recalled an observation that he made along the shores of Lake Huron that may explain the properties of the reflectors on Mars:

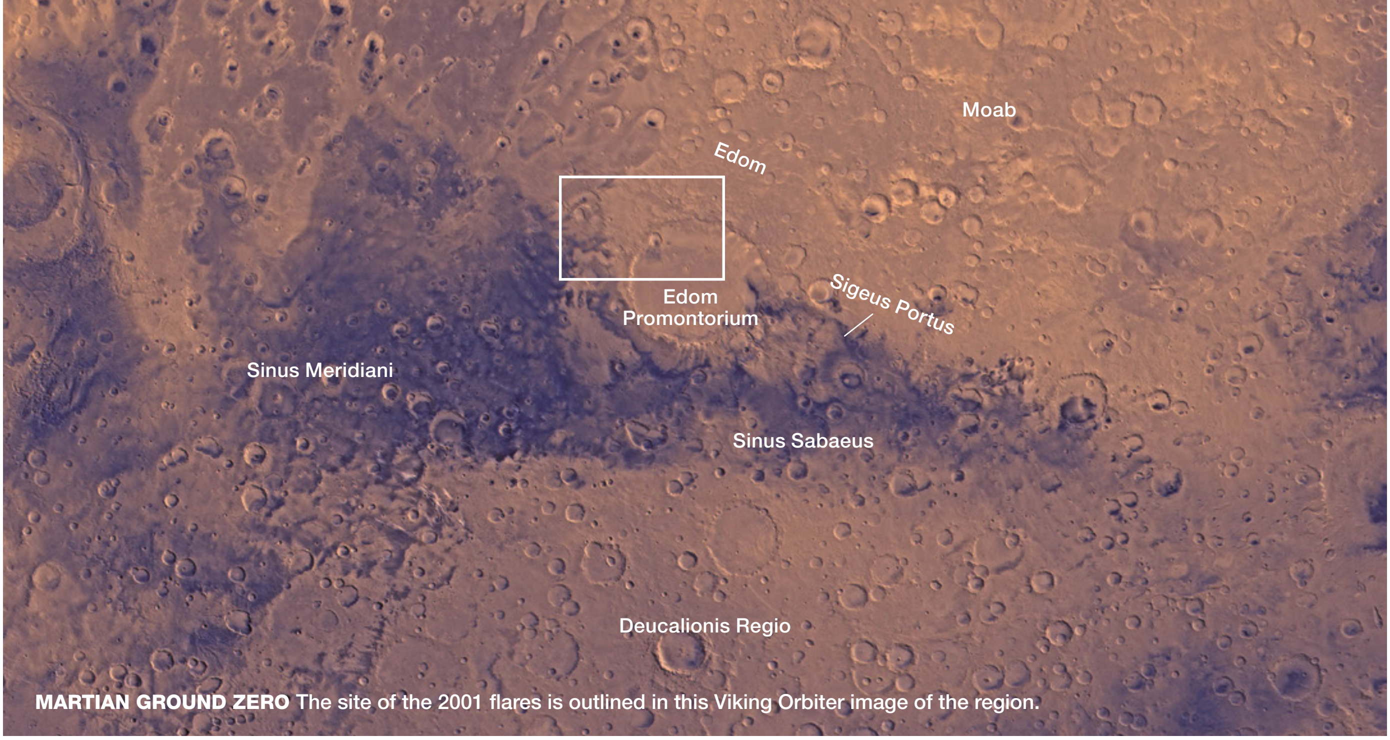
> *The coast is quite rocky and there are many feldspar faults, perhaps 30 feet wide and hundreds of feet long in the granite and gneiss surface rocks which form most of the bare rocky shores. These feldspar faults are quite shiny if viewed from a suitable angle, but if viewed from other angles they appear darker than the surrounding rock.*

▶ **VIDEO SETUP** Tippy D'Auria at the controls of the 12-inch Schmidt-Cassegrain used to record Mars on videotape.

▼ **OBSERVING VIGIL** *Left: S&T*'s Gary Seronik maintains a vigil at the eyepiece of his homebuilt 6-inch Newtonian on the informal 2001 Mars Flare Expedition. *Right:* Don Parker, Don Troiani, and Carolyn Collins Petersen await their turn at the eyepiece as Tom Dobbins takes in the view.



VIDEO FRAMES: DAVID MOORE; OBSERVERS: RICK FIENBERG, GARY SERONIK / *S&T*; VIDEO SETUP: GARY SERONIK / *S&T*



MARTIAN GROUND ZERO The site of the 2001 flares is outlined in this Viking Orbiter image of the region.

At one time the writer picked up a small boulder of feldspar. From every direction but one it was a dull, dirty pink, but when held in a certain way it shone like a mirror. It was a little hard to see why; but an examination showed a myriad of tiny facets, all acting like mirrors, all pointing one way . . . these crystals shielded each other in part, so that the whole effect was confined to a narrow angle.

Despite their close-up vantage point, the cameras of spacecraft orbiting Mars are ill-suited for detecting specular reflections because they normally acquire images under mid- to late-afternoon lighting. Landers and rovers have provided tantalizing clues, however. Some rocks at the Viking Lander sites showed bright specular reflections from facets of feldspar and glossy coatings that resemble the "desert varnish" found on weathered rocks in Earth's most arid environments. Furthermore, NASA's Curiosity rover has recorded sun-glints from isolated shiny rocks on several occasions.

December Prediction

During the first week of December the alignment of the Sun, Earth, and Mars will be very similar to June 2001 when flares appeared in Edom Promontorium, presenting a singular opportunity to shed more light on the Martian flares mystery. The Sun and Earth will be about 6° farther south in the Martian sky than they were in 2001, so the sub-Sun and sub-Earth points on Mars will lie along the southern rather than the northern edge of the Schiaparelli Basin. This will be a good test of the sensitivity of flares to small changes in the angles of incidence and reflection. Fingers crossed that a Martian dust storm doesn't spoil the view.

Edom Promontorium crosses the central meridian of the 17-arcsecond-diameter Martian disc 36 minutes later each night. Western North America and the central Pacific (Hawai'i) will be the most favorable locations. For example, observers in Los Angeles will see Edom Promontorium cross the central meridian at 2:27 a.m. on December 5th when Mars is 56° above the horizon. From Honolulu this will occur at 12:27 a.m. when the planet is only 4° from the zenith.

If flares do appear, the vast improvements in imaging technology during the last two decades promise images of far better quality than we obtained in 2001 using a black-and-white analog video camera. High-resolution images and videos will help to pinpoint the exact location of these transient events. Accurate timings by visual observers will also be valuable. Observers and imagers are encouraged to take advantage of this chance to enjoy a rare spectacle while making a modest contribution to planetary science. Let's hope the weather cooperates — on Earth and on Mars!

Predicted Edom Promontorium Flare Events for 2022

		Martian latitude	
Date (December)	**Time (UT)**	***sub-Earth***	***sub-Sun***
3	9:15	−4.2°	−5.0°
4	9:51	−4.4°	−4.7°
5	10:27	−4.6°	−4.5°
6	11:03	−4.9°	−4.3°
7	11:39	−5.1°	−4.1°

▲ **NEXT OPPORTUNITY** This table shows the times when Edom Promontorium is best placed to repeat the flare events of 2001. Observers located along the west coast of North America and on the Hawaiian Islands have the best chance to witness flares if the Martian atmosphere remains free of dust.

■ Contributing Editors **TOM DOBBINS** and **BILL SHEEHAN** have authored dozens of articles seen in these pages throughout the past three decades.

NASA / JPL / USGS; 2022 MARS EPHEMERIDES COURTESY JEFF BEISH

Vixen's New Polarie U Camera Tracker

This compact mount from Vixen has a familiar name and a lot of new features for today's astrophotographers.

▲ Vixen's Polarie U is a compact and lightweight camera tracker that will support moderately heavy cameras and lenses and features extremely smooth and accurate tracking.

ALL PHOTOS BY THE AUTHOR

Vixen Polarie U

U.S. Price: $615.95
Explorescientificusa.com

What We Like

Excellent tracking
Compact size
Nice features for time-lapse photography

What We Don't Like

Relatively uncommon adapter plate for tripods

THE POLARIE U IS Vixen's next-generation camera tracker. Its size, shape, and features are so different from the company's original Polarie introduced more than a decade ago (and reviewed in this magazine's March 2012 issue, page 58) that it's unfair to call it an upgrade of the original. It's really a whole new product.

If you've been eyeing the Polarie U for wide-field nightscape, constellation, meteor, or bright-comet photography, read no further. Just get it, since I'm sure you'll be more than satisfied with its performance even if you're shooting with relatively heavy DSLR equipment. It's conservatively rated for a load of 2.5kg (about 5½ pounds) for equatorial tracking and up to 10kg when the rotation axis is mounted vertically for time-lapse panning. But if you're interested in some of Polarie U's advanced capabilities, read on.

First, however, I want to briefly mention camera trackers in general. Their popularity blossomed during the twilight years of emulsion-based astrophotography. Color films had reached the point at which they could capture constellations and hints of the Milky Way with a few seconds' exposure, a fast lens, and a tripod-mounted camera. Trackers allowed extending these exposures to a minute or more, which would result in pinpoint stars over a perceptible landscape depending on moonlight or local illumination. It ushered in a new era when simple photos could realistically show the sky as it looks to the naked eye.

Jump to today and I can make similar images with the camera in my handheld smartphone. Furthermore, modern, tripod-mounted digital cameras can capture starscapes with just a few seconds' exposure that show more than the naked eye can see. Mix in special image-processing software (for example, *Sequator*, described by Sean Walker in the August issue, page 66), and you might ask why anyone now needs a camera tracker to create impressive starscapes. The answer is, with a fast lens and a recent digital camera, you don't. But a tracker still provides photographers with a creative edge to turn impressive starscapes into stunning masterpieces. The Polarie U can do that and more.

Fit and Finish

Roughly fist-size, the Polarie U is smaller and lighter than most of the lenses I routinely have in my camera bag, so it's an easy accessory to carry. There are threaded sockets on one side (for equatorial mounting) and one end (for lime-lapse panning) that attach to tripods with either a ⅜ × 16 or (using the included adapter) a ¼ × 20 mounting screw. Each mounting surface also has a thin adapter plate designed to connect with quick-release tripods using the Arca Swiss Standard, which in my experience isn't very common in the U.S. market. There are, however, numerous adapters available from camera stores that attach to any tripod style and accept the Arca plate.

The business end of the Polarie U has a movable mounting block with a ¼ × 20 screw typically used for attaching a user-supplied ball head for holding a camera. Two large thumbscrews allow rotating and locking this mounting block to the Polarie U's motorized shaft. Other external aspects of the unit are shown in the accompanying photographs. The tracker is powered by four, internally housed AA batteries that will run the unit for about seven hours according to the manual and verified twice by my own tests using standard Duracell batteries on mild nights. There's also a USB port that is only used to power the unit from an external source that outputs 4.4 to 5.25 volts DC and is rated for a maximum draw of at least 0.3 amp. It's worth noting that this is a USB Type C port, and while I couldn't find any USB cables with a Type C plug that weren't already permanently wired to 12-volt power supplies among my plethora of USB stuff, you can easily find the right one on the Internet.

One of the first things that caught my eye when unpacking the Polarie U box was the user manual — it's 60 pages long and highly illustrated with

▲ Powered by four AA batteries or externally via its USB Type C port, the Polarie U is easy to operate. The on/off switch also sets the tracker's rotation direction for use in either the Northern or Southern Hemispheres, while the Mode button cycles through the various tracking rates, which are shown on an illuminated display. The ½ rate runs at half the sidereal tracking speed and is favored by some starscape photographers to split the apparent trailing equally between the sky and foreground. C indicates the user-set custom rate for speeds up to 10× sidereal (2½° per minute). The "smartphone" button turns on the unit's Wi-Fi so that it can connect with the app, as described in the text.

▲ The Polarie U is smaller than many of the lenses in the author's camera bag. And while his significantly larger and heavier Takahashi Sky Patrol at left has a declination axis and slow-motion adjustments (and was considered by many to be the gold standard of camera trackers in the 1980s), the Polarie U easily outperforms it for the all-important tracking in right ascension.

▲ The heaviest camera setups tested by the author benefited by using a simple bar such as the one seen here made from scrap aluminum to offset the ball head and better balance the camera on the Polarie U's rotational axis. It was also far easier to polar align the setup with the Sky-Watcher equatorial base, pictured on a small pier in his observatory. Also shown is the cable that operates the camera shutter via the *Polarie U* app.

diagrams, quality photographs, and tables. This seemed like a lot for such a relatively simple device until I realized that 27 pages were devoted to using Vixen's optional polar-alignment scope. This is a $374.95 accessory, which I did not test but which I expect from past experiences with Vixen polar-alignment scopes will work very well.

Another reason for the large manual is that it also offers an introduction to starscape photography with all the basics briefly covered and charming but spot-on advice such as having warm clothing available for cold nights and keeping a plastic bag handy to cover equipment in case of a sudden rain shower.

◀ The ball head mounting block can be removed from the Polarie U to reveal two sets of tapped holes that do-it-yourselfers could use to attach their own custom setups to the drive base.

Heading Outside

Most of my night-sky testing was done with an aging Nikon D700 DSLR camera attached to the Polarie U via a heavy-duty ball head. On my first night outside I mounted the setup on a mid-weight tripod (the Star D clone of the Tiltall for those "veteran" photographers among us), attached a 50-mm lens to the camera, and eyeballed the polar alignment with the Polarie U's peep sight. (This alignment was not as casual as I make it sound here, but more about that in a minute.) Not surprisingly, exposures ranging from a few seconds up to 2 minutes all showed perfectly pinpoint stars — something I'd expect from even the most rudimentary camera trackers. The real test of the Polarie U's tracking accuracy required longer exposures, which aren't practical in my suburban sky. So I switched tactics.

I changed to a 200-mm lens and set the camera's internal intervalometer to shoot 30-second exposures every 5 minutes for three hours. The 36 individual images were then stacked with the freeware program *Startrails* (**startrails.de**) that registers image frames rather than stars to effectively show how much the stars trailed over the course of three hours.

The first result wasn't just good, it was *astoundingly* good. In three hours the Polarie U's tracking was so accurate that stars trailed less than they did in a 15-second exposure made with a stationary camera. This amounted to less than 4 arcminutes of tracking error in right ascension over the three-hour period.

This review isn't about photographic projects, but I suspect that many readers, like me, will dream up interesting things to do with a camera that accurately tracks the sky unattended for an entire night. Following short-period variable stars, for example, or perhaps shooting a time-lapse sequence of a solar or lunar eclipse (the Polarie U has selectable tracking rates for the Sun and Moon as well as the usual sidereal rate for stars).

Polar Alignment

According to the user manual the Polarie U's peep sight has an 8.9° field of view — a value that seems rather precise given that the peep sight is merely a 37-mm-long plastic tube with a 9-mm internal diameter. Furthermore, when I held my eye at the end of the tube I could view the whole 15°-long handle of the Big Dipper, which matches the field of view I calculated with a quick bit of trigonometry. That 8.9° field is accurate if your eye were positioned about 20 mm back from the peep sight — a comfortable distance for someone wearing eyeglasses.

▲ Described in the accompanying text, the peep sight's changing apparent field of view that occurs as your eye is moved back from the sight can be used to advantage in polar aligning the Polarie U.

Nevertheless, this byproduct of changing perspective provides an advantage when polar aligning with the peep sight. Polaris is currently 0.64° from the celestial pole offset in roughly the direction of Mirfak (Alpha Persei). By placing my eye about 400 mm (16 inches) back from the peep sight, the apparent field of view shrinks to 1.3° (twice the offset amount). And if I place Polaris at the very edge of the peep sight's field in the direction of Mirfak, then the field center should be close to the celestial pole. That's what I did on my first night out with the Polarie U, and even I was surprised by how accurate the polar alignment ended up being. It was also beneficial that I did the alignment with my camera already attached to the Polarie U, since most tripods will flex at least a little when a heavy camera is added, slightly throwing off the alignment.

Additional Features

Among the Polarie U's advanced features is an autoguider port that only controls the right-ascension drive. I didn't test it, but with autoguiders becoming smaller and lighter it's not unreasonable that there are applications in which autoguiding will be useful with a tracking mount as small as the Polarie U — when shooting with long telephoto lenses, for example.

The unit also has a 3-mm coaxial port for connecting a camera's shutter release. This port is operated via the *Polarie U* app, which users can download for iOS (Apple), Android, and Amazon Kindle Fire devices. The app connects to the Polarie U via Wi-Fi, and I tested it on my iPhone 11. Camera control only works while the app is actively connected to the Polarie U — you can't program information into the tracker for later playback.

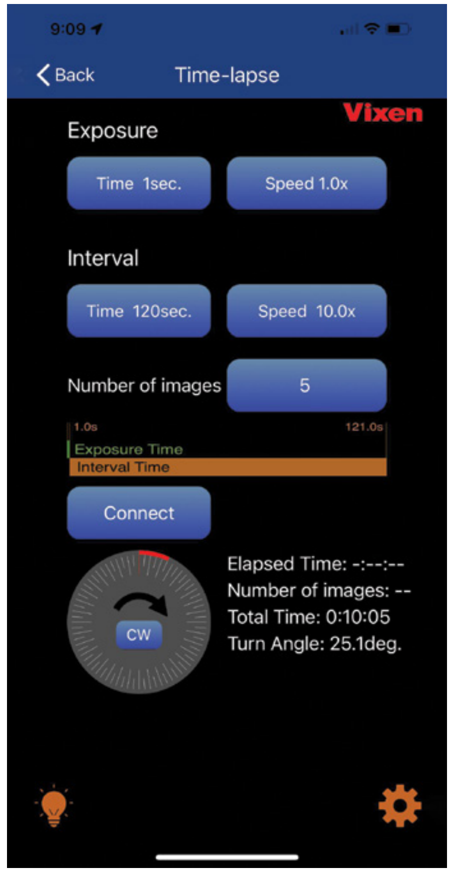
One feature of the app lets you make sets of up to three bracketed exposures at user-set intervals while the unit is tracking. This would be very handy for making a series of time-lapse exposures for, say, a lunar eclipse. My Nikon DSLR cameras have a similar built-in feature, but they are limited to exposures that can be manually set on the camera (in my case no longer than 30 seconds). By setting the camera shutter to Bulb, I can use the *Polarie U* app to automatically make the much longer exposures that are often needed for astrophotography.

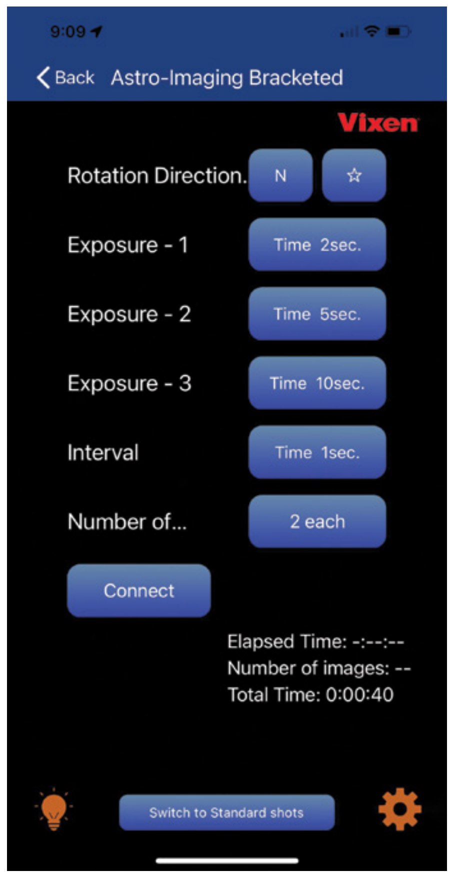
The app also lets you set a custom tracking speed for the Polarie U that ranges from zero to 10× sidereal rate (up to 2½° per minute). This is mostly for photographers who use the Polarie U for panning motion during time-lapse photography. This works by panning the mount and having it stop moving when shooting exposures. Assembling images taken this way into a time-lapse video shows the rotation of the night sky as the scene slowly pans.

The Polarie U can do everything that astrophotographers shooting wide-field images would likely ever want. But its accurate tracking got me thinking about all the excellent photos I've seen lately made with conventional telephoto lenses in the 135- to 300-mm range. With such a setup properly balanced on the Polarie U (like the example on page 65), it would be easy to make hours' worth of short exposures that could be stacked to create deep images. As an afterthought (and to prove this point to myself), I combined the exposures made for several of my tracking-accuracy tests mentioned earlier with the freeware program *DeepSkyStacker* (**deepskystacker.free.fr**). This produced surprisingly deep images (albeit of a nondescript star field surrounding Arcturus) given they were made from my backyard with a camera and settings that I had never intended to record faint stars.

The Polarie U proved to be a first-rate camera tracker for wide-field astrophotography, but I also think that people who own one will start coming up with a lot of projects that go well beyond simple starscape photography. It's a sweet little device.

DENNIS DI CICCO lives under the ever-increasing light pollution of Boston's western suburbs.





▶ The smartphone app described in the text can control a camera's shutter as well as the direction and speed of the Polarie U's rotation.

▲ BIG ASTROGRAPH

Orion Telescopes & Binoculars introduces its new line of observatory-class telescopes, beginning with the Orion 14″ f/8 Truss Tube Ritchey-Chrétien Astrograph (starting at $6,499.99). This 14-inch reflector features low-expansion, quartz Ritchey-Chrétien optics designed to produce coma-free images. The mirrors have enhanced aluminum coatings to provide 96% reflectivity. Its Serrurier-style truss tube assembly is manufactured from thermally stable carbon fiber to reduce temperature-induced focus shift, and, with the aid of three built-in cooling fans, the optics reach thermal equilibrium quickly. The telescope comes with a 3-inch, Crayford-style focuser that includes a dual-speed (10:1) fine-focus knob and both 2- and 1¼-inch accessory adapters. The instrument weighs 30 kilograms (66 lb) and connects to heavy-duty mounts via a Losmandy D-style mounting bar.

Orion Telescopes & Binoculars
89 Hangar Way, Watsonville, CA 95076
831-763-7000; telescope.com

▲ PREMIUM APO

Stellarvue adds a new model to its extensive line of SVX apochromatic refractors with the SVX90T ($2,695). It's a 90-mm (3.5-inch) f/6 triplet apochromat with a FCD100 super-low-dispersion center element housed in a fully collimatable lens cell. The telescope weighs 3.6 kilograms and is 37½ centimeters (14¾ in) long with its dew shield retracted. The SVX90T comes with a 3-inch-format, dual-speed focuser that includes both 2-inch and 1¼-inch eyepiece adapters fitted with non-marring compression rings. Each purchase includes a pair of CNC-machined mounting rings, two dovetail finder mounting bases, and a heavy-duty, padded C-20 travel case.

Stellarvue
11802 Kemper Rd., Auburn, CA 95603
530-823-7796; stellarvue.com

▲ ULTRA-COMPACT GO TO

Mount manufacturer iOptron unveils its latest miniaturized telescope mount, the SkyHunter Portable AZ GOTO System ($488). This new alt-azimuth mount squeezes many high-end Go To features into a small, convenient package that weighs 1.3 kg. The SkyHunter can be attached to any tripod that uses ⅜ or ¼ × 20-threaded connections and, despite its small size, is rated for payloads of up to 5 kilograms. The mount uses dual-axis DC motors with optical encoders for precise slewing and pointing to objects at up to 4½° per second. Its drive rates include sidereal, 0.5×, solar, and lunar tracking speeds for operation in both hemispheres. It's controllable via an optional Go2Nova 8410 hand controller or, thanks to its built-in Wi-Fi, the *SkySafari* iOS or Android smart-device apps. The SkyHunter accepts Vixen-style dovetail bars and is powered by an internal, rechargeable battery that lasts up to 10 hours. Each purchase includes a MiniUSB charging cable and a limited 1-year warranty.

iOptron
6F Gill Street, Woburn, MA 01801
781-569-0200; ioptron.com

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

Two Exquisitely Tiny Telescopes

Hisayuki Uto creates a blend of art and functionality.

◀ Hisayuki Uto's 2-inch, f/6 truss-tube reflector, held here by his niece Saya Hattori, incorporates an ancient Japanese craft.

IN OUR MAY ISSUE, I wrote about what might be the smallest Schmidt-Cassegrain telescope in the world. Today I bring you two telescopes that might take the record for the smallest fully functional Newtonians.

Japanese amateur astronomer Hisayuki Uto began his project with an appreciation for urushi lacquer, the millennia-old traditional glossy finish made from the sap of the urushi tree. Hisayuki says urushi-finished items "exude a warmth that has to be handled to be appreciated. Their silky-smooth texture is comforting and inviting." It occurred to him that urushi lacquer would make an excellent finish for a telescope, too, so he set out to build one.

He decided to start small. He purchased an Edmund Optics two-inch f/6 mirror set from **edmundoptics.com**, which made for a tabletop project rather than a large-scale shop project. He used balsa wood, which is lightweight and easy to cut with a utility knife but which becomes very hard and durable after the lacquer is applied.

◀ Hisayuki's gold-mirrored f/4 telescope rides on a tracking mount for electronically assisted astronomy.

Hisayuki went with a truss-style optical tube assembly for his first scope. He used bamboo for the trusses, since it has better tension and bending strength than balsa. By making the tolerances nice and tight, he doesn't need clamps; he can simply push the trusses into their sockets and they stay put.

The primary mirror box uses three points of support, with 3-mm bolts that extend out the rear for collimation. For edge support, Hisayuki uses a small sling.

The secondary cage has two end rings and curved sides with ribs for strength. The secondary spider is made of 1-mm aluminum. I'm proud to say that the focuser uses my "boxy Crayford" design (*S&T:* Feb. 2015, p. 68), beautifully miniaturized to accommodate 0.965-inch Takahashi eyepieces.

Hisayuki opted for a fork mount, also made of balsa. To balance the scope, he put two springs inside the mount and connects them to the base of the mirror box with strings that run through tiny channels in the fork. And in what I think is the perfect extra touch, he added setting circles to the RA and declination axes.

More than 10 coats of lacquer later, the scope was finished. How well does it work? Hisayuki says, "I was pleasantly surprised. At 106×, I got a really nice view with many craters on the Moon. I could see the Cassini Division in Saturn's rings clearly and split Epsilon Lyrae (the Double Double) completely."

The scope only weighs 295 grams (10.4 ounces), including the eyepiece. Hisayuki built a lacquered box to hold the disassembled scope, and he reports that "I always keep this telescope in my business bag. When the sky is clear after my business hour, I go to the park just adjacent to my office and observe the Moon and planets with the telescope on a picnic table."

Last holiday season, Edmund Optics

▶ The truss-tube scope's mirror box and secondary cage fit in a beautiful lacquered box that rests comfortably in a hand.

ALL IMAGES COURTESY OF HISAYUKI UTO

▲ This image of lunar crater Clavius (lower center) taken with the tiny f/4 telescope is nothing short of phenomenal.

put its 2-inch f/4 gold mirror set on sale, so Hisayuki bought one and started building another scope. He made this one fully enclosed, intending to use it for electronically assisted astronomy (EAA). He reasoned that the gold mirror wouldn't reflect as much of the blue light pollution that plagues his home only 15 kilometers (9 miles) from downtown Tokyo, and he was right. The gold coating isn't satisfying for visual observation — it makes the view yellowish, and white/blue stars are noticeably dimmed — but for a camera that's sensitive in the red end of the spectrum it's ideal. Using an ASI462MC CMOS camera, Hisayuki gets great views of deep-space objects like NGC 4244 (the Silver Needle Galaxy) and even Stephan's Quintet.

For EAA, Hisayuki needs a tracking mount, so he puts the gold-mirrored scope on an iOptron SkyTracker equatorial platform. Since he's just doing live stacking of a few dozen frames rather than long-duration photography (see August issue, p. 60), he doesn't even need to align it perfectly.

For telescopes that started out as art projects, these little two-inch reflectors have proven to be very useful, high-quality optical instruments as well as beautiful examples of traditional urushi-lacquer finishing. Hisayuki is very happy with them, and so am I. Projects as exquisite as these make me smile just looking at them.

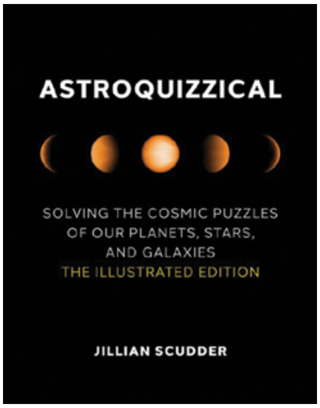
For more information, contact Hisayuki at **dob18a@gmail.com**.

■ Contributing Editor **JERRY OLTION** hopes to see these beautiful telescopes in person someday.

For Inquiring Minds

ASTROQUIZZICAL: *Solving the Cosmic Puzzles of Our Planets, Stars, and Galaxies (The Illustrated Edition)*

Jillian Scudder
The MIT Press, 2022
224 pages, ISBN 978-0-262-04672-5
US$29.95, hardcover



THIS BOOK PROVIDES a superb introduction to astrophysics. The author, astrophysicist Jillian Scudder of Oberlin College, hangs her book on a metaphorical cosmic family tree: Earth as our parent, the Sun and stars as our grandparents, the Milky Way and other galaxies as our great-grandparents, and the universe itself as our great-great grandparent. The idea is to help the reader grasp our unique place in the cosmos, including the ties that bind us to the stars and the universe as a whole.

As the title suggests, the book is structured around captivating questions. Some are straightforward, like why do stars twinkle, and what is a galaxy? Others are a little more pointed: What will happen to Earth when the Sun dies? Why does Jupiter have stripes (i.e., belts and zones), and why are they so stable? If the universe is expanding, how can two galaxies collide?

Scudder intersperses the chapters with thought experiments. Can we, she muses in one, take prehistoric photos of Earth by capturing photons from some natural reflector light-years away in space? (The answer, regrettably, is no.) In another, by way of explaining escape velocity, she asks what would happen if we opened a door directly from the surface of Earth to that of the Moon. Hang on! Because of atmospheric pressure differences, we'd trigger a wind blast, she figures, of 1,480 km/hr (920 mph).

It's clear that much thought and care have gone into creating *Astroquizzical*. (Scudder defines the term as "expressing curiosity in the astrophysical wonders of the universe.) The book offers multiple ways into the content, which can be read equally well sequentially or by jumping around to subjects of greatest interest. Each chapter opens with a compelling question and snippet of context. The main text that follows — the answer to the question — is rich with fascinating facts and explication, and it's pleasingly broken up by callouts, sidebars, and stunning photographs.

The illustrations (see examples at right) deserve special mention. Beginning with a timeline of the universe that comprises, impressively, just 10 entries, the diagrams appear throughout the book and are crisply designed and easy to assimilate. Together with the well-written, jargon-free text, these concise, well-designed illustrations help readers retain details and concepts.

The text supports them well: For example, to bolster understanding of a graphic showing how a star's velocity around a more massive object helps keep the star in equilibrium with the pull of gravity, the author explains how the International Space Station (ISS) stays aloft using the same principle.

Scudder peppers the volume with thought-provoking ideas. How many experienced observers, much less beginners, know that the Moon, if viewed through a gamma-ray telescope in space, would appear brighter than the Sun? Or that the center of our star is effectively transparent to light? As she asserts, "Two invincible friends sitting in the Sun's core would have no more trouble seeing each other than they would through thin air."

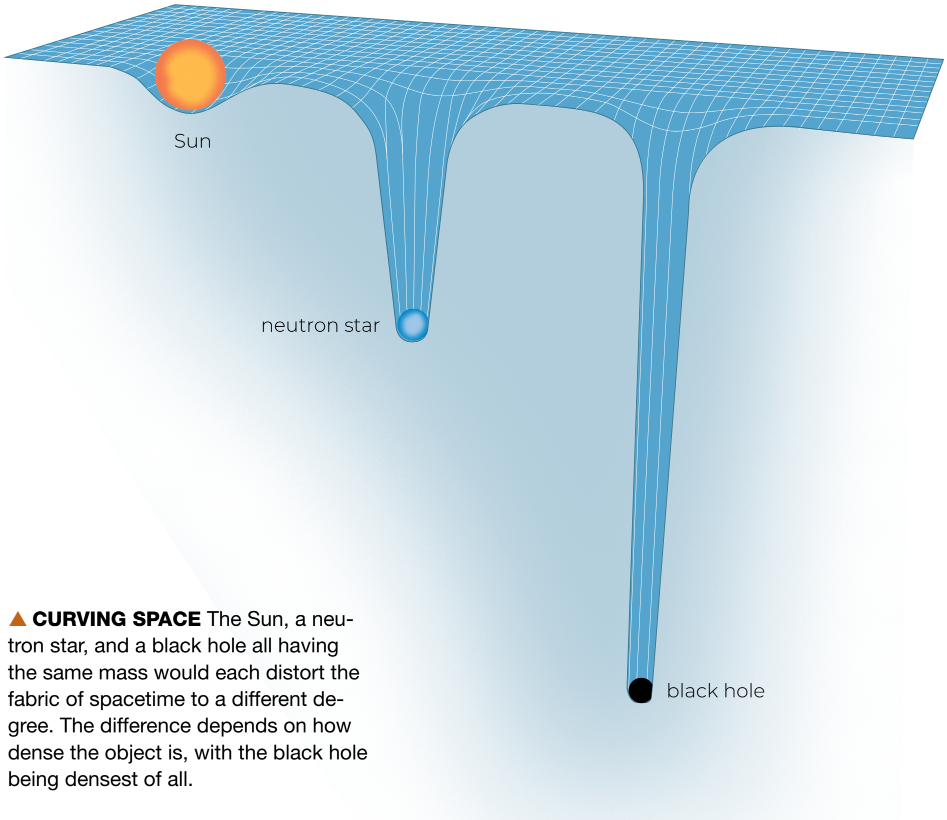
> This book serves as a terrific Astro 101 course for the discerning newcomer.

Astro novices will find succinct explanations of difficult concepts. On *time dilation*, for example, after noting that "the faster you're moving, the slower your clock appears to move, relative to someone who is not moving," she goes on to give an idea of just how small a time difference this can be. If you spent a year on the ISS like NASA astronaut Scott Kelly did, you'd have aged 0.007 seconds less than your kin on the ground. This is a minuscule number, she explains, because the critical factor is how close to the speed of light you're traveling, and the ISS, even though it's zipping around Earth at around 7.7 km/s, is still moving, she says, about 39,000 times slower than the speed of light.

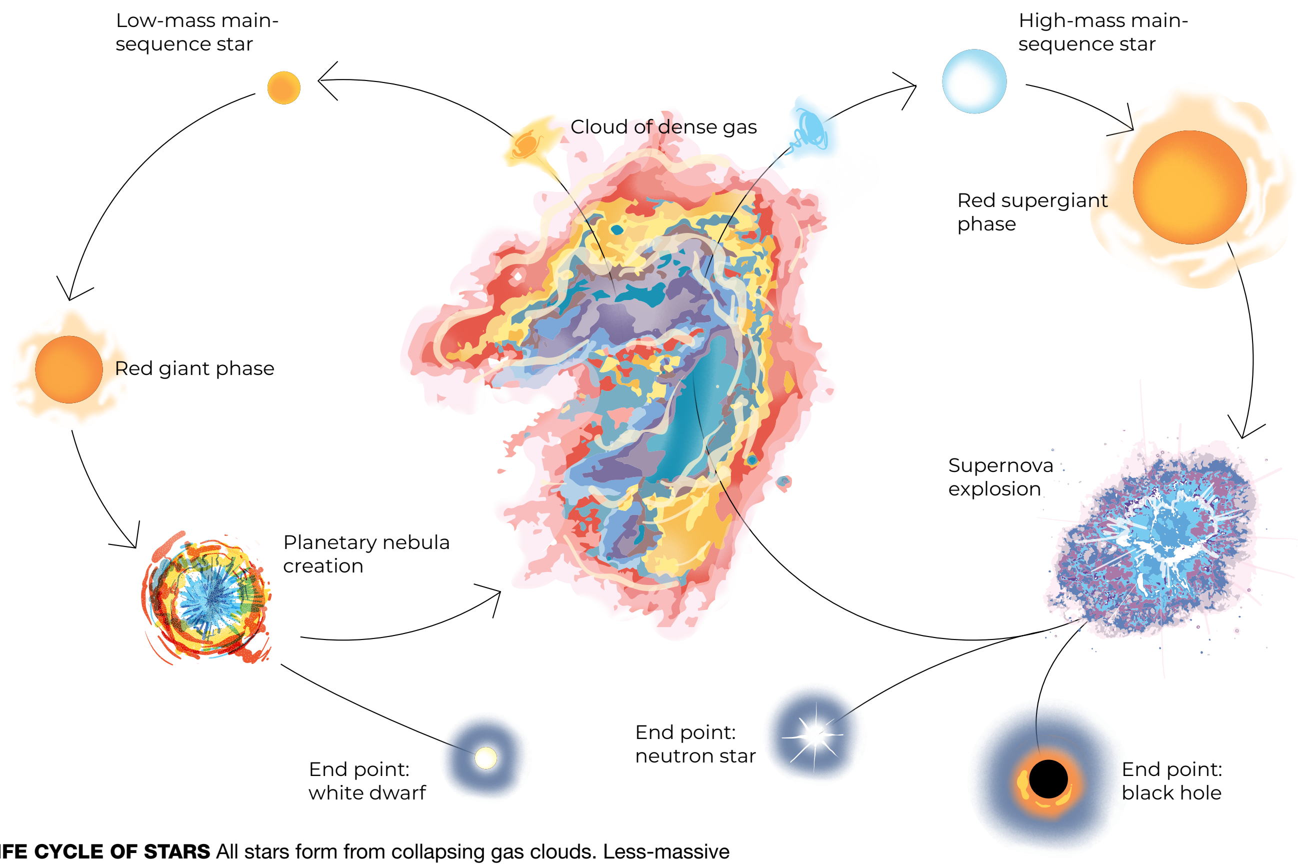
Scudder's prose is lively, with an understated humor popping up here and there. On the notion of looking for live bacteria in the clouds of other planets, for instance, she writes, "Suspicions should immediately turn to Venus, everyone's favorite 860°F (460°C), runaway-greenhouse, volcano-ridden, battery-acid-raining planet." She's also not shy of expressing her opinion. Of the scaled-up frequencies scientists create of gravitational waves so humans can hear them, she says, "This scaled sound is often described as a chirp, but if you listen to one, it sounds much more like a *vwooop*." (Agreed.)

In sum, this book serves as a terrific Astro 101 course for the discerning newcomer. It teaches an enormous amount in a fun way. The book would have benefited from a bibliography or further-reading section; nevertheless, it serves as a robust yet go-down-easy primer to the field. For the astrophysically quizzical of high-school age and up, I highly recommend this.

■ Editor in Chief **PETER TYSON** wishes he had this book to hand when he first became interested in astronomy.



▲ **CURVING SPACE** The Sun, a neutron star, and a black hole all having the same mass would each distort the fabric of spacetime to a different degree. The difference depends on how dense the object is, with the black hole being densest of all.



▲ **LIFE CYCLE OF STARS** All stars form from collapsing gas clouds. Less-massive stars like our Sun follow the lefthand path over billions of years, while massive stars evolve along the righthand route, living out their lives in only millions of years.

ILLUSTRATIONS FROM *ASTROQUIZZICAL* BY J. SCUDDER (2)

What Are Constellations?

EVER SINCE THE DAWN of time, we've looked up into the night sky and imagined stories in the patterns of the stars.

The concept of *constellations*, arbitrary groupings of stars that represent familiar shapes, dates back more than 4,000 years to the ancient Sumerians. The Babylonians took the pictorial concept one step further and listed stars in what might be the first ever astronomical catalog, the MUL.APIN. Surviving copies of this compendium date to the 7th century BC, but they contain references to events several thousand years earlier. Astronomy is an ancient science indeed.

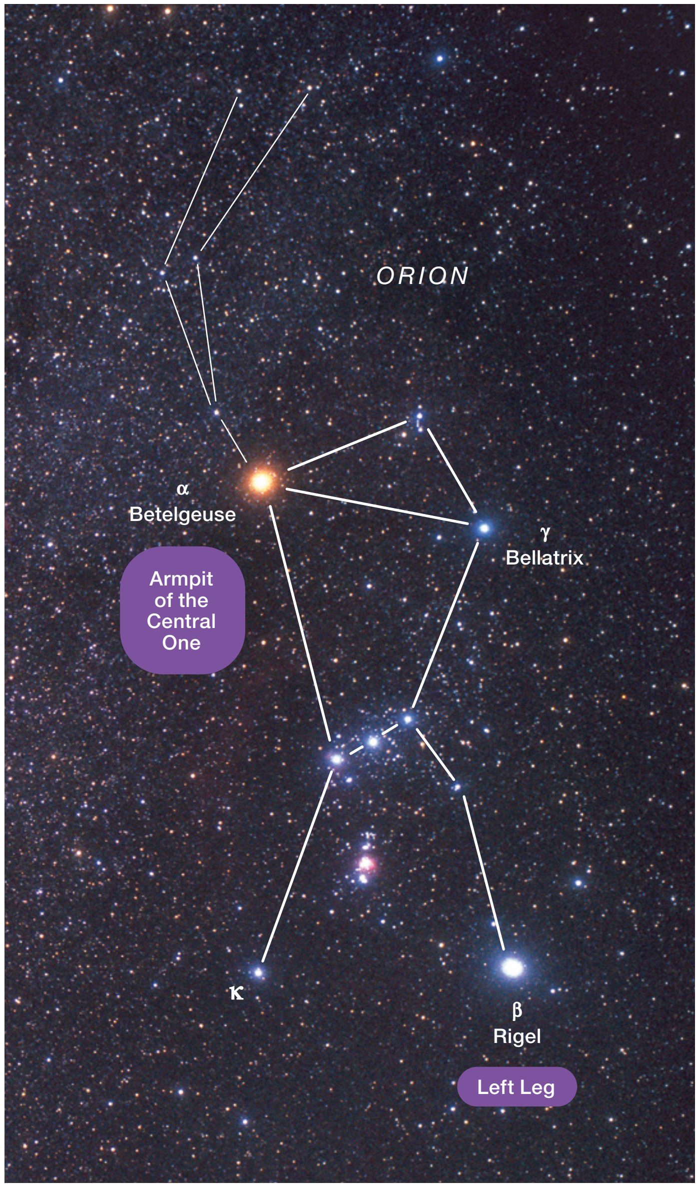
Throughout the ages, civilizations around the globe have imposed their own cultural histories and mythologies on patterns in the sky. But it's Greek traditions that bring us the constellations we're most familiar with today. And the person responsible for this was the great Alexandrian astronomer and geographer Claudius Ptolemaeus, commonly known as Ptolemy. In his *Almagest*, written around AD 150, he listed 48 constellations, all but one of which are still extant today (Argo Navis is split into three). Ptolemy drew upon mythologies pertinent to him. And thus he lofted into the sky the legend of Perseus, the Hero, who rescued Andromeda, the Chained Maiden. (Perseus also lopped off the Medusa's head to bring forth Pegasus, the Winged Horse.)

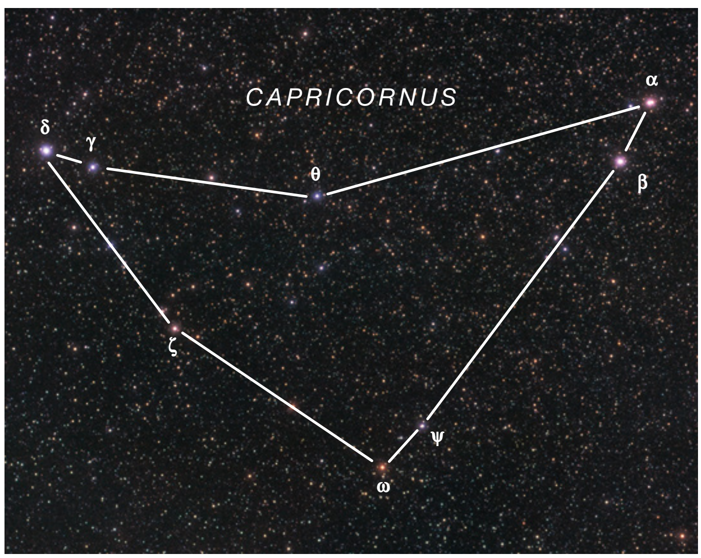
During the Golden Age of Islam, Arab astronomers such as Muhammad Al-Battānī modified and expanded on Ptolemy's scheme. We honor their legacy today in that we still refer to many of the brighter stars by their Arabic names.

A Plethora of Patterns

For hundreds of years, the Ptolemaic system's status quo held. Then the 15th century ushered in the Age of Exploration. European navigators and adventurers sailed the globe in search of trading routes, treasures, and spices. In so doing, they opened up the Southern Hemisphere skies to astronomers who headed to locations such as the Cape of Good Hope and established observatories. Their exuberant explorations of the southern skies yielded constellations honoring exotic creatures, such as Tucana, the Toucan, and Piscis Volans, the Flying Fish (today known simply as Volans).

After a period of relative soberness during which celestial cartographers appeared to favor the sciences — as a result





▶ **THE HUNTER AND THE SEA-GOAT** You may need to rely on your imagination to discern the figures the constellations are meant to portray. It's likely easier for you to picture Orion for the hunter he represents than to see a goatlike creature in Capricornus, one of the constellations of the zodiac. We still use the Arabic names for the brighter stars.

ALL IMAGES COURTESY OF AKIRA FUJII

there's Telescopium and Microscopium — we have a foray into the mildly absurd. Enter Globus Aerostaticus, Hot-Air Balloon, and Machina Electrica, Electric Machine, to name but two.

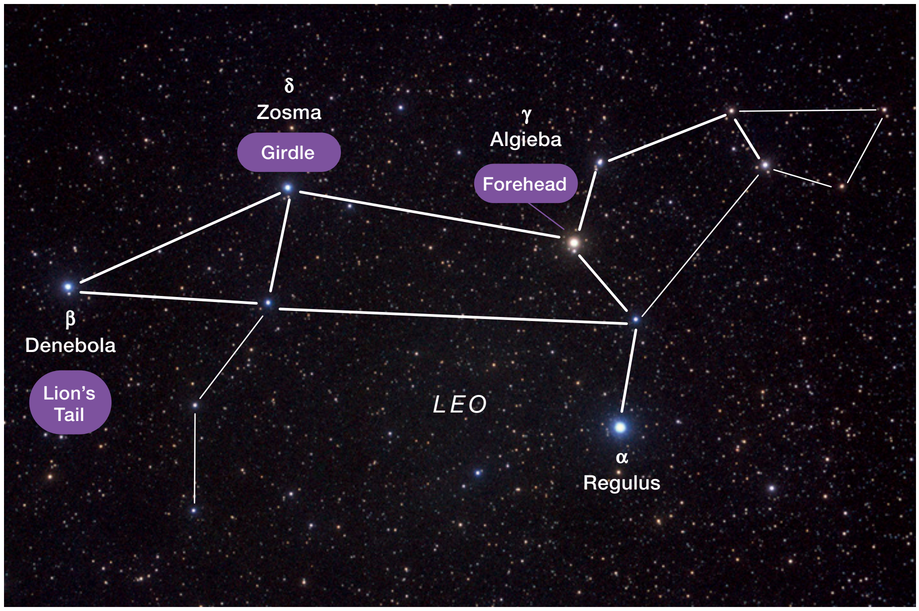
In the first half of the 20th century, with stellar atlases brimming with myriad constellations, the newly founded International Astronomical Union put its foot down and proceeded to clean up this profusion of celestial whatnots. Beginning in 1922, they streamlined the constellations to the marginally more manageable 88 shapes and patterns that we're familiar with today. We might not be able to admire Officina Typographica, the Printing Press, much less the Hot-Air Balloon and Electric Machine, but we recall certain defunct constellations in other ways — every January, for instance, when we view the Quadrantid meteor shower, we're reminded of Quadrans Muralis, the Mural Quadrant.

Constellations Around the World

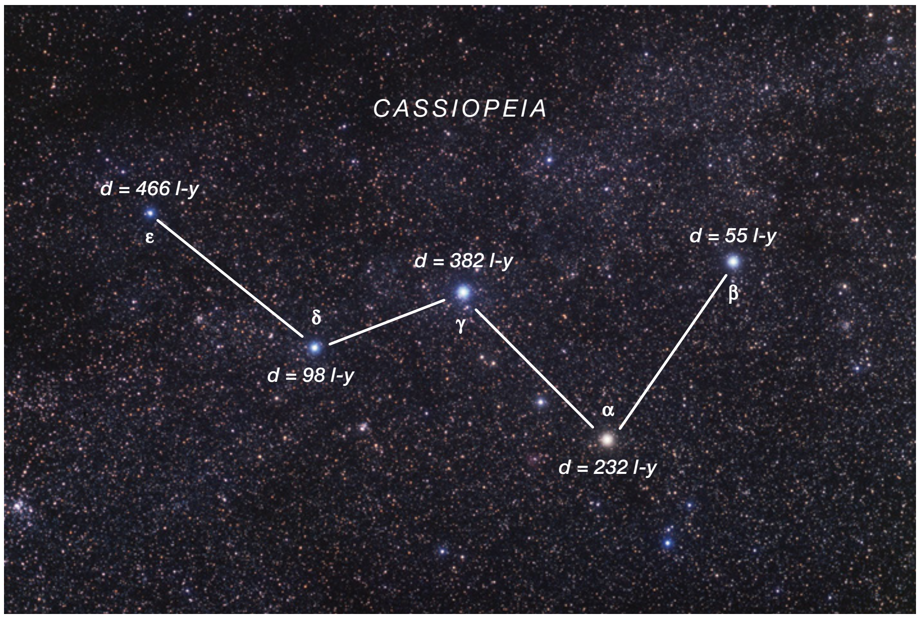
Throughout history, cultures across the globe crafted their own stories of the skies. For example, in the 3rd century AD, the Chinese arranged more than 1,500 stars into a whopping 283 constellations that they called "officials." Obviously, by having that many constellations the patterns were generally much smaller than in the Western tradition.

Not all cultures turned to the bright sparkles in the sky. Several Southern Hemisphere peoples fabricated stories out of the sooty clouds of gas and dust in the Milky Way. And so we have the dark constellations of the Incas, such as Machacuay, the Serpent, and Hanp'atu, the Toad, while in Australia the Kamilaroi gaze upon Gawarrgay, the Emu (*S&T:* Aug. 2021, p. 12).

One of the most notable constellations in the sky is Ursa Major, the Great Bear. Many cultures refer to that particular pattern of stars as a bear, among them the Wampanoag, Lakota, and Mi'kmaq in North America. The legends of the Indigenous Americans' celestial bear predate the arrival of the first Europeans in the Americas.



▲ **ALPHA-BETA** Leo, the Lion, is one of the 12 constellations of the zodiac. In addition to their popular names, stars in constellations are also assigned Greek letters. With some exceptions, the brightest star is designated by the Greek letter alpha (α), the second brightest by beta (β), the third brightest by gamma (γ), and so on. The name of Leo's brightest star, Regulus, is Latin for "little king."



▲ **CONSTELLATIONS AREN'T FLAT** One thing to bear in mind when admiring the constellations is that their stars aren't on a flat plane on the sky — they're all at different distances from Earth. For example, in Cassiopeia, the Seated Queen, the stars' distances range from 55 light-years (l-y) for Beta (β) Cassiopeiae to 466 light-years for Epsilon (ε) Cassiopeiae.

This suggests that migratory peoples crossing the Bering Land Bridge from Siberia brought the mythologies with them more than 10,000 years ago. That constellation has been around for a long, long time.

Maybe you see the same pictures in the sky as others do. Or maybe you see your own. Regardless, next time you're out at night at a reasonably dark site, look up into the sky and set your imagination free. ■

THE GULF OF MEXICO

Patrick Cosgrove

The dark nebula LDN 935 (center) dominates this field in Cygnus and helps define the emission nebulae NGC 7000 (top and left), IC 5067 (right), and IC 5070 (far right).

DETAILS: *Askar FRA400 astrograph and ZWO ASI1600MM Pro camera. Total exposure: 9.33 hours through narrowband and color filters.*

▷ STELLAR METROPOLIS

Chuck Manges

Several hundred thousand stars make up the globular cluster M13. They're so densely packed that stellar collisions can occur, creating giant stars known as *blue stragglers*, which are younger and more massive than the bulk of the ancient cluster's stars.

DETAILS: *Meade 8-inch LX50 Schmidt-Cassegrain and QHY23M camera. Total exposure: 4 hours through LRGB filters.*

▽ CELESTIAL FIREWORKS

Aaron Lisco

Nebulous bubbles blown by young, massive stars within NGC 3576 appear to encircle thick columns of dust that bear a striking resemblance to the Statue of Liberty.

DETAILS: *Celestron RASA 11 astrograph and ZWO ASI6200MM Pro camera. Total exposure: 2.3 hours through narrowband filters.*

◁ SOLAR LIFT

Soumyadeep Mukherjee

Two large sunspot groups, AR 12976 and AR 12975, decorate the Sun on the morning of March 28, 2022, as it rises behind a tower crane in Kanpur, India.

DETAILS: *Nikon D5600 camera and Sigma 150-to-600-mm zoom lens. Total exposure: 1/800 second at f/6.3, ISO 100.*

▽ HANGING ON A STAR

Ron Brecher

Collinder 399, the Coathanger asterism in Vulpecula, is a group of unassociated stars that were once thought to be members of a loose, nearby open cluster. An actual open cluster, NGC 6802, is seen to the right. South is up.

DETAILS: *Takahashi FSQ-106EDX4 refractor and QHY367C Pro camera. Total exposure: 3 hours.*

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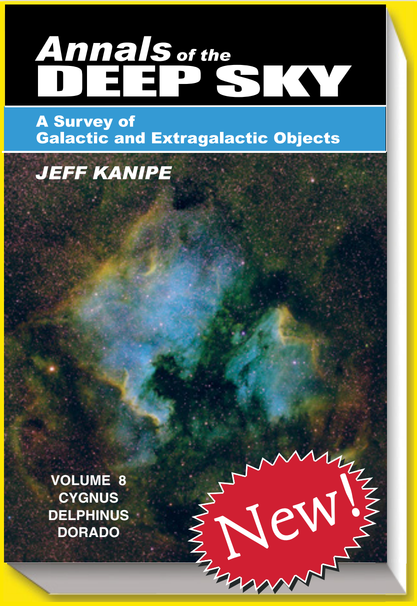

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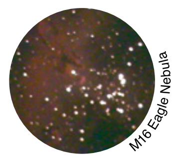

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On the High Seas

Seeking solace, the author finds that and much more while contemplating a distant galaxy.

THE SOUNDS WERE FEW: crickets, an occasional owl, and the clock drive on my telescope, its tiny whirring motor dutifully grinding on, keeping distant galaxies centered in the eyepiece. Even the dogs in the distance had quieted down. My boots gently clomped back and forth on the observing platform as I adjusted some equipment or checked a reference, the gleam of my red flashlight illuminating the star charts.

Wearied by the weight of a turbulent world and fresh out of a friend's funeral, I had spontaneously loaded the scope in the car and made the half-hour journey into the southern Maryland woods to catch some particularly ancient starlight. It seemed a good time for a nightwatch. I needed to unwind.

> Questions of life, death, and mystery hung in the air as I silently mused.

The platform at my astronomy club's observing site became a boat bobbing on a sea of infinity as I peered into the deep. With a hefty star atlas ready at the telescope, I began my search for the elusive galaxy I had in mind at Fomalhaut, the alpha star in Piscis Austrinus, the Southern Fish. My quarry was close: I slewed my scope slightly to the east, following a miniature star pattern outlined on the crisp white chart in my atlas, soon arriving in Sculptor, the Sculptor's Apparatus.

There it was! Glimmering like a tiny ghost, NGC 7507 swam into view. Tens of millions of light-years away, this obscure galaxy winked back at me, the interstellar marveler, peering into the abyss from my imagined speck of a craft. Discovered by William Herschel in 1783, NGC 7507 is a 10th-magnitude elliptical, though it's so distant that it looks like a fuzzy star.

My mind more or less seized up as I pondered this far-off island universe, a wisp of an idea in the eyepiece. Enormous cosmic distances sometimes grab me by the mental shoulders and pin me down, and I have no choice but to stare into eternity, staggered at the immensity. It forces me to relinquish the petty cares that I cling to so tightly.

The sensation can be terrifying, but so is electricity. I feel vaguely like a human phone, plugged into its low-voltage charger, suddenly realizing the existence not only of the powerful current in the wall but of the giant towers that noiselessly carry half a million volts high above the sleeping land. That thrill blows my mind and is precisely the reason I'm here.

The mist crept in from nearby Nanjemoy Creek and began to rise off the field. Questions of life, death, and mystery hung in the air as I silently mused on the vastness overhead.

Later, I packed up my scope and headed back home, to the everyday of "dry land." But I can still feel the swells of the deep if I pay close attention.

■ **JOSH URBAN** is an amateur astronomer and avid galaxy hunter who is occasionally reminded of his place in the universe. He now lives in Lynchburg, VA.

LEAH TISCIONE / *S&T*