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SKY & TELESCOPE

THE ESSENTIAL GUIDE TO ASTRONOMY

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The Inside Story of NEUTRON STARS

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JULY 2017

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You and Your Shadow... Tele Vue-60

Tele Vue-60 Specifications:

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Tele Vue-60 OTA shown with optional equipment.

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Fonemate:smartphone to eyepiece adapter


Sol-Searcher

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TV-85 Eclipse Image by Dennis diCicco, processing by Sean Walker.

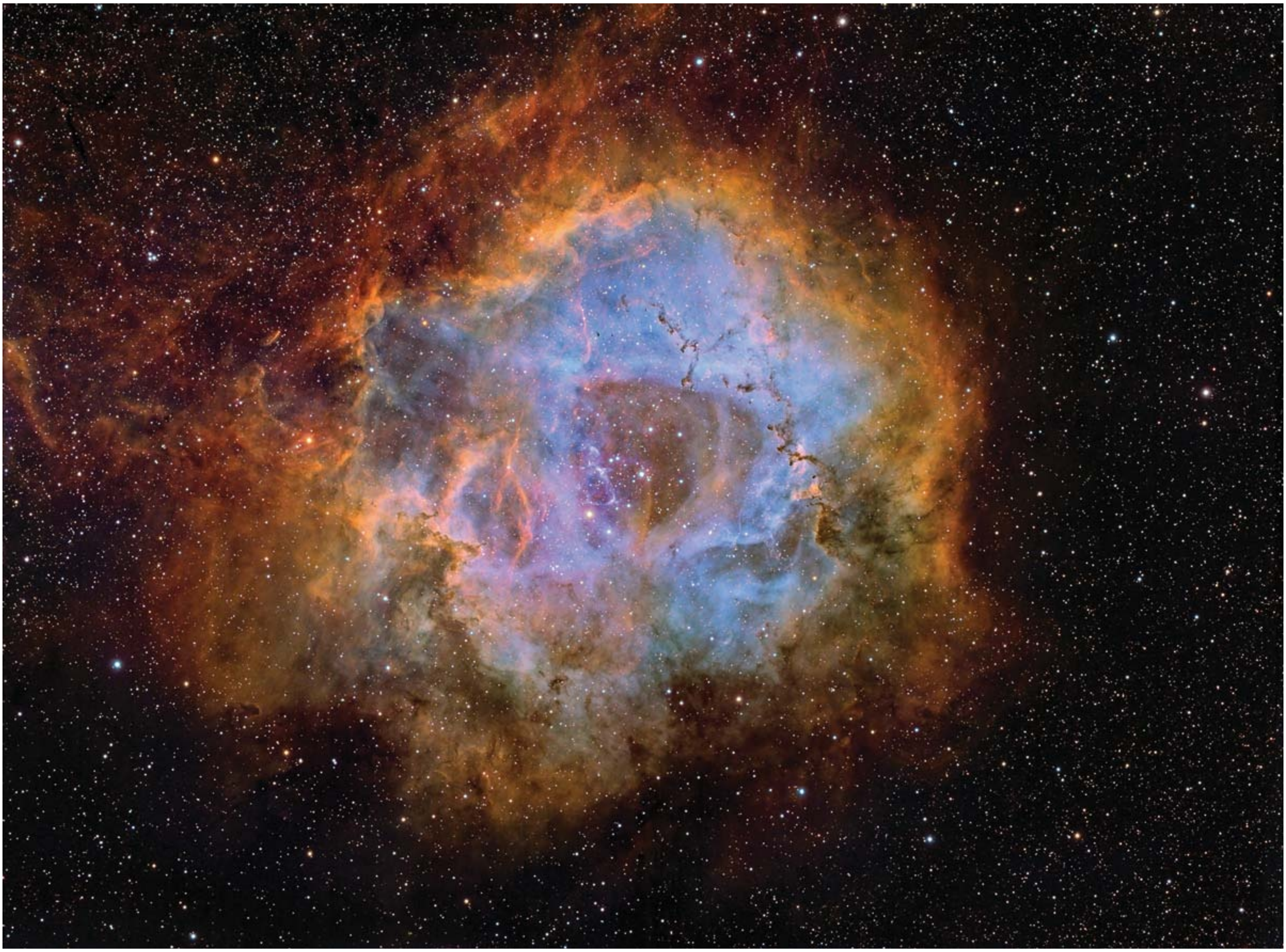

Image courtesy Dr. John Carver (50 megapixel MicroLine ML50100 camera)

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FLI ProLine at Trappist South,
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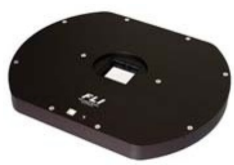

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July 2017 VOL. 134, NO. 1

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GOTO

Decades Later – Bringing New Life

GOTO INC has always loved the excitement of building a brand new planetarium – of bringing the sky to a community in a whole new way. But we also love pumping new excitement into older, existing planetariums through dynamic renovation projects. In 2016, GOTO was proud to have been chosen to revitalize two decades-old planetariums which re-opened to the public in April of 2017.

The 23-meter diameter Saitama City Space Theater originally opened in 1987. The 18-meter Osaki Lifelong Educational Center was built in 1997. One of these planetariums originally chose a GOTO HELIOS star projector, and the other chose a competitor's machine. Unlike today's video equipment which has lifetimes of only a handful of years, opto-mechanical projectors such as GOTO's can be maintained and operated for 30 years or more. And true to form, both Saitama's and Osaki's opto-mechanical planetarium projectors gave decades of solid service, teaching children and families all about the sky.

But finally, it becomes time to retire all old machines and to look for new opportunities with new equipment in total renovations of all domes. This time, both Saitama and Osaki chose the GOTO CHIRON III opto-mechanical planetarium projector to last for their next 30 years. A truly superb sky, the ability to project in tilted or horizontal domes, LED illumination, and intense and accurate sun, moon and planet projectors make the CHIRON III today's choice to be the dependable, solid core of any planetarium.

As part of their renovations, both planetariums chose to synchronize their CHIRON III with GOTO VIRTUARIUM fulldome video systems. The resulting GOTO HYBRID planetarium systems, with their versatile manual control consoles allow both stimulating and educational live programming as well as dynamic and spectacular automated programs.

So whether it's a new planetarium just being born, or an older planetarium that needs a new breath of life, GOTO INC stands ready to provide the equipment and know-how to make your planetarium and its programs come alive!

Saitama City Space theater

Osaki Lifelong Educational Center

GOTO INC

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A Taste of Relativity

"AN HOUR SITTING WITH a pretty girl on a park bench passes like a minute, but a minute sitting on a hot stove seems like an hour." This was Einstein's explanation of relativity for the layperson, and it perfectly captures one aspect of stargazing that I find remarkable: the powerful sense one gets, under certain conditions, of the supremely relative nature of time.

In March I had the pleasure of joining TravelQuest International's Southern Sky Party in Costa Rica. Led by former *S&T* editor Gary Seronik, the trip offered attendees, all of whom live much farther north, the coveted opportunity to view many treasures deep in the southern sky. Early in the evening, Orion hung high in the west, its celebrated nebula glowing invitingly, while Jupiter climbed the eastern sky with its groupie moons. Around midnight the Southern Cross and Eta Carinae regions beckoned irresistibly from above the southern horizon.

My favorite stretch was from the wee hours till dawn. In part that's because the area's scorching daytime heat had finally given way to pleasant temperatures, and also any lingering cumulus clouds from earlier in the evening had largely dissipated.

But it was mostly because of what lay high overhead: the glitteringly rich sky harboring the Sagittarius Teapot, the Scorpion's Tail, and our galaxy's core. The False Comet! The Butterfly Cluster! The Lagoon and Trifid nebulae! There were more Messier objects than you could shake a red flashlight at, and, to top it off, Saturn floated serenely near the meridian. How could one not lose track of time?

The Milky Way's central bulge high above the Gulf of Nicoya

Never while stargazing has time passed so swiftly as during those early-morning hours. It didn't so much go by as vanish in great chunks. On our final night, my journal shows I began a second round of stargazing at 2:06 a.m. At 4:34, as dawn began its inexorable daily vanquishing of the Milky Way, I wrote, "Want night to be longer! How did 2½ hours go by so quickly? Time evaporated like dew on hot stone."

Why *does* time fly in such circumstances? Surely clocks continued ticking at the same rate; it was my grasp of what they measure that had lost all reliability. How? Was it total absorption in a cherished pursuit? Sitting alone at my 5-inch Vixen reflector, with no conversation or other distractions to trigger a sensation of time passing? A release of dopamine? I'll leave possible answers to the psychologists and neuroscientists.

All I know is that on that final evening on Costa Rica's Gulf of Nicoya, the famous "arrow of time" seemed to denote not so much direction as speed, as in a shooting arrow. The hours did indeed pass like minutes.

Peter

Editor in Chief

GARY SERONIK

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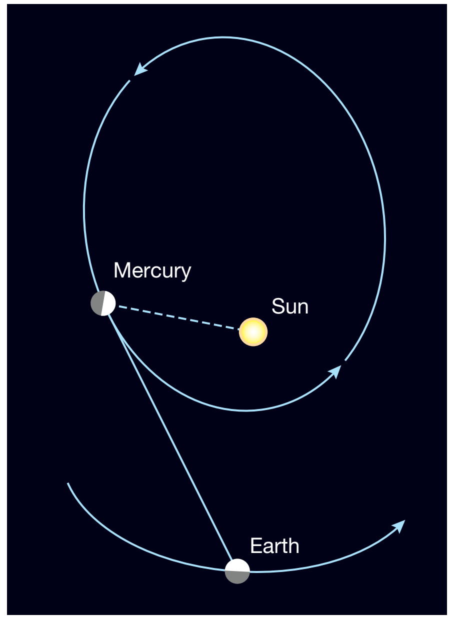

▲ The large eccentricity of Mercury's orbit, 0.21, can cause the planet to appear more than half lit during its greatest elongations from the Sun.

LEAH TISCIONE / *S&T*, SOURCE: JEAN MEEUS

The Schröter Effect: A Closer Look

Another complication in gauging exactly when Venus appears half sunlit (*S&T:* Jan. 2017, p. 52) is that the geometrically calculated moment of dichotomy can vary from the time of greatest separation by up to about 2.6 days regardless of the direction of elongation. This is due to the eccentricity of that planet's orbit.

Thus, observers should also be comparing the *predicted* and *observed* times of dichotomy itself. During the event earlier this year, for example, I calculate that greatest separation occurred at 13^{h} Universal Time on January 12th, whereas dichotomy occurred at 13^{h} on January 14th — two full days later (not earlier, as the Schröter effect would predict). Venus will have its next greatest separation on June 3rd at 12:31 UT with dichotomy the next day at 6:16 UT.

Meanwhile, the term "greatest elongation" is itself ambiguous, as this might mean either the greatest difference in right ascension or the greatest angular separation. For Venus the time difference between the two can be up to 15 hours. Modern observers usually assume it refers to greatest separation in ecliptic longitude, but it's unclear what was used historically.

George Gladfelter
Rapid City, South Dakota

William Sheehan replies: *Clearly, Venus is a special case, and it is only because its orbit is the most nearly circular of all the planets' that observers in the 1950s and 1960s (and presumably Schröter himself) were able to ignore, with relative impunity, the small discrepancy between the times of greatest elongation and dichotomy. As mathematician Jean Meeus points out, the range of illuminated fraction varies at the time of greatest elongation by no more than 1.1%, which visual observers would not have noticed. Presumably, this accounts for some of the variation in the estimates of the Schröter effect. Likely more significant are seeing conditions, sky background (light vs. dark sky), and experience of the observer.*

In any case, it's interesting that during January, as George Gladfelter points out, Venus reached its geometric dichotomy two days after its greatest elongation east of the Sun. And yet, because of the play of light in the planet's upper atmosphere (and what might be called the Mallama effect), Venus still appeared half lit to visual observers before *greatest elongation.*

It's worth noting that similar observations involving Mercury would amplify the kinds of discrepancies that Gladfelter describes (as is evident in the illustration above). I have often noticed, even in small telescopes, that Mercury does not in general appear exactly half lit at the time of its greatest elongations — yet another demonstration, were one needed, of the large eccentricity of its orbit.

Threads Laid Bare

I enjoyed Johnny Horne's review of the ASI 1600MC camera (*S&T:* April 2017, p. 58) but noted one slight ambiguity: Both the article and the manufacturer's specs state that the camera has "male T-threads (often called M42 threads)."

However, readers should be made aware that M42 and T are not compatible when used in lens mounts, even though both have the same throat diameter of 42 mm. M42 (sometimes called P-thread) has a thread pitch of 1 mm, whereas the T-thread has a pitch of 0.75 mm.

The confusion no doubt arises from the use of M42 as metrological shorthand for "metric, 42 mm." But this abbreviation has also come to mean a 42-by-1-mm lens mount.

Because these pitches are so similar, one might be tempted to connect M42-mount and T-thread parts — they will apparently "catch" when you try to couple them together. But this will ultimately damage one or both as they're tightened. Thus the manufacturer's website repeated a common discrepancy conflating the two, and I'm pleased to see that the specs have since been changed to read "Adaptor: 2″ / 1.25″ / M42×0.75."

Aldo Cugnini
Long Valley, New Jersey

"Adorable" Black Holes

Although I have been reading and enjoying *Sky & Telescope* since the mid-1960s, I am hard-pressed to recall an article as personable, literate, and informative as Camille Carlisle's "The First Black Holes" (*S&T:* Jan. 2017, p. 24). Thank you for some pleasurable reading.

I can well believe, as was noted at the article's very end, that she finds black holes "adorable," as her devotion to them becomes clear. I look forward to reading more of Carlisle's articles as well as to her continuing efforts as *S&T*'s Science Editor.

Gary Lazich
Elk Grove Village, Illinois

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Earth Is Not Alone

In Shannon Hall's article on super-Earths (*S&T:* March 2017, p. 22), the graph at the lower right on p. 27 seems to show our Earth as an oddball, with nearly all the discovered planets of our size having orbital periods of less than 50 days. So does this mean we are truly an outlier — or is it just an indication that our detection techniques have low sensitivity to planets in this region of size-vs.-orbit parameter space?

Dan Kuchta
Hilton, New York

Kelly Beatty replies: *The clumping of Earth-size planets toward shorter orbital periods is due to the Kepler spacecraft's observational bias. The mission's scientists required three solid transit detections to assign an object "candidate" status, and those bodies with long orbital periods didn't necessarily reach that detection threshold before the planet-hunting portion of its mission ended. A big part of the problem was that the stars themselves turned out to be less stable — and their light noisier — than had been expected.*

Some Credit Due

In the last paragraph of his article about Supernova 1987A (*S&T:* Feb. 2017, p. 36), Robert Kirshner notes, "Tycho had his supernova, Kepler had his." Perhaps it would have been appropriate to add a mention of my fellow countryman Ian Shelton as SN 1987A's discoverer.

Pat Browne
Mississippi Mills, Ontario

Milky Way's Supermassive Black Hole

Does the black hole at the center of our galaxy have a proper name?

Gordon Nanninga
Covington, Washington

Camille Carlisle replies: *Astronomers call it Sagittarius A*. This was the name of the compact radio source detected at the black hole's position; the * emphasizes its unusual nature. Astronomers struggled to find a good term for the object from its discovery in 1974 until 1982, when, inspired by atomic physicists' nomenclature for excited atoms (He*, Fe*, etc.), Robert Brown coined Sgr A* — he was thinking of it as the "exciting source" of nearby HII clouds. Astronomers have since come to use the name generally for the Milky Way's supermassive black hole.*

FOR THE RECORD

- The Umbrella Galaxy (*S&T:* April 2017, p. 29) is NGC 4651, not NGC 4641 as noted in the caption.
- The load-carrying capacity of the Vixen Polarie Star Tracker (*S&T:* May 2017, p. 70) is 7 pounds.

LETTERS TO THE EDITOR: We love to hear from our readers! Write to: *Sky & Telescope,* 90 Sherman St., Cambridge, MA 02140-3264 or email: letters@skyandtelescope.com. Please limit comments to 250 words.

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

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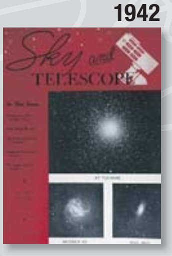

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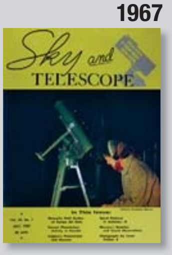

1992

July 1942
Scutum Cloud "This shield-shaped mass of stars is one of the most interesting 'clouds' of the Milky Way.

"In the center of the field is the cluster, Messier 11. . . . Until recently the search for variable stars in the Scutum cloud and its vicinity has yielded few variables. . . . But the open scale of plates made with the Bruce 24-inch doublet at Harvard's South African station is revealing an as yet unlimited number of new variables. . . .

"It is hoped, from this mass of variables, that periods can be obtained for a sufficient number of classical and cluster-type Cepheids to reveal their distances, and consequently, to allow us to decide whether we are dealing with a galactic cloud or a galactic window. In the first case, the Scutum cloud will really be what its name implies; in the second, it will be merely a portion of the Milky Way which is not obscured by dark nebulosity."

When she wrote these words, Margaret Harwood was midway through her 40-year career as director of Maria Mitchell Observatory, much of it tutoring young women in variable-star work.

July 1967
Weapons from Space "The Freer Gallery in Washington, D. C., contains a magnificent collection of ancient Chinese art. Two of the oldest objects are a ceremonial ax and a dagger. . . . These Chou dynasty weapons are puzzling, for stylistic evidence dates them as 10th–8th century B.C., which is before the manufacture of iron in Honan province, where they were found. . . .

"Roy S. Clarke, Jr., of the Smithsonian Institution's division of meteoritics . . . performed mineralogical, X-ray, chemical, and spectrographic tests that detected the presence of nickel. . . . Furthermore, optical examination revealed taenite and kamacite . . . characteristic of iron meteorites."

July 1992
A Spinning Success "April 3, 1992, 4:18 p.m. MST, air temperature 1,160° Celsius and falling. Roger Angel steps out of the control room and crosses the laboratory floor. . . . The glass master's grin is as bright as the crescent Moon. He catches my eye and gives 'thumbs up' with panache. . . .

"A 6.5-meter mirror — having 65 percent more area than Palomar's and, more importantly, being 40 percent lighter — has just been born in a spinning furnace at the University of Arizona's Steward Observatory Mirror Laboratory."

Editor Leif Robinson was on hand for spin-casting of the large mirror that replaced six smaller ones in the Multiple Mirror Telescope on Mount Hopkins. Since 1992, the world-renowned mirror lab has cast four more 6.5-m and seven 8.4-m mirrors.

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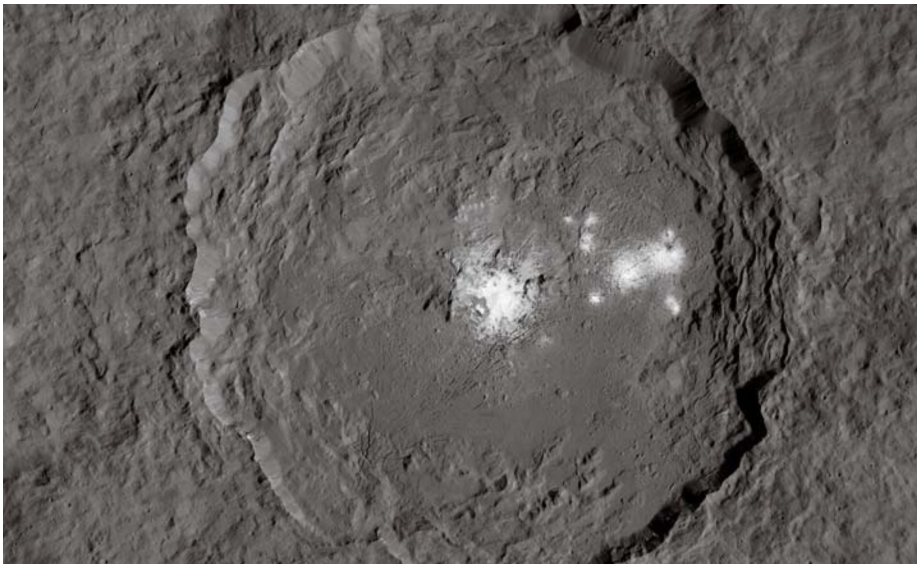
SOLAR SYSTEM

Recent Briny Eruptions on Ceres?



White spots dot the floor of Occator, a prominent crater on Ceres. NASA's Dawn spacecraft has seen haze inside the crater that appears to be linked to the spots.

EVER SINCE NASA'S Dawn spacecraft reached asteroid 1 Ceres in early 2015, mission scientists have been fixated on bright patches inside the 92-km-wide (57-mile-wide) crater Occator (above). The spots, forming a bright area called Cerealia Facula at Occator's center and a complex of secondary spots, collectively called Vinalia Faculae, on its eastern floor, appear to be deposits of carbonate-rich salts — residue from briny flows that gurgled up from a fluid reservoir (perhaps a global ocean) deep in the asteroid's interior.

Occator was gouged into the landscape about 34 million years ago, but the whitish dome at its center is much younger — just 4 million years old. That's the conclusion of a new analysis published in the March 2017 *Astronomical Journal* by Andreas Nathues (Max Planck Institute for Solar System Research, Germany) and colleagues.

The team focused a lot of its attention on the bright, high-standing dome in the crater's center (right). Some 3 km across and 400 m high, it's not the classic "central peak" that many large craters get when they form. Instead, the dome sits within a broad pit, about 11 km across, that's rimmed by fractures.

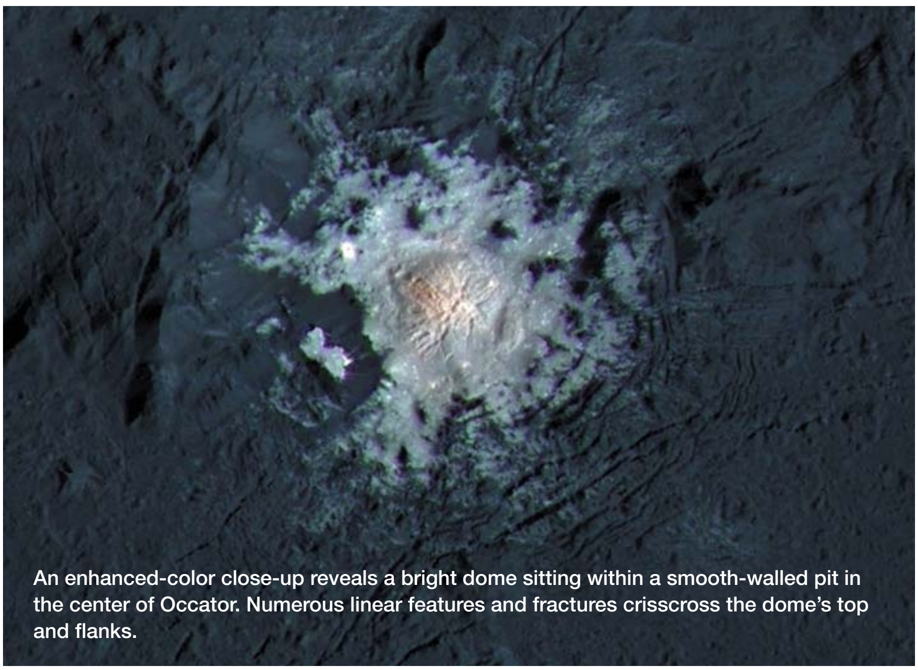
The dome isn't really white, despite what images suggest. It's about 30% reflective — compared to 2% to 4% for the dark surrounding terrain. Last year another Dawn team, using the spacecraft's infrared spectrometer, found infrared absorption bands due to carbonates in Cerealia Facula. The carbonate deposit must be fairly thick, too, because the dome bears a dozen small impacts, 80 to 300 m across, and all are bright like their surroundings.

The dome's relatively young age suggests that cold, briny eruptions, known as *cryovolcanism,* emerged from a liquid reservoir trapped between a muddy icy mantle and a silicate-rich core. Once the slushy stuff breached the surface, exposing it to the cold vacuum of space, the brine would have quickly frozen and its water would have rapidly boiled or sublimated away, leaving the salts behind as a solid residue.

Whether the salts now exist as a stiff layer or as a fine fluffy powder on the surface isn't known. In late April the Dawn project planned to examine the dome with an illumination phase angle of 0° — that is, with sunlight coming from directly behind the spacecraft. Observations made at this special geometry should constrain the grain sizes in the salt deposits.

Nor is it clear how often eruptions might have occurred. "A long-lasting process appears to be prevalent," the team concludes, "whereby periodically or episodically ascending bright material from a subsurface reservoir was deposited, expelled from fractures, and extruded onto the surface, forming the present-day central dome."

■ J. KELLY BEATTY



An enhanced-color close-up reveals a bright dome sitting within a smooth-walled pit in the center of Occator. Numerous linear features and fractures crisscross the dome's top and flanks.

SOLAR SYSTEM TOP: ASA / JPL / UCLA / MPS / DLR / IDA / PSI, BOTTOM: ASA / JPL / UCLA / MPS / DLR / IDA / PSI / LPI

MARS

Atmosphere Lost to Space

NASA'S MAVEN SPACECRAFT has confirmed that the solar wind stripped the Red Planet of its dense, early atmosphere, more than likely through a process called *sputtering*.

Mars was not always the frozen, barren place it is now. Based on the ratio of various gas isotopes, planetary scientists have long suspected that the Red Planet lost anywhere from 25% to 90% of its initial atmosphere, with the estimates favoring at least 50% (*S&T:* Sept. 2014, p. 20). One popular explanation has been that the solar wind stripped it away.

Now, MAVEN scientists have confirmed this hypothesis. Using the spacecraft's measurements, Bruce Jakosky (University of Colorado, Boulder) and colleagues determined the abundances of the noble gas argon-36 and of the heavier isotope argon-38. The latter naturally settles lower in the Martian air, leaving argon-36 enriched in the upper atmosphere.

This differentiation leaves the lighter isotope more susceptible to being torn away by the solar wind. During sputtering, the atmosphere colludes with the solar wind against the planet. Ultraviolet solar photons first knock electrons from atoms and molecules in the uppermost atmosphere, forming ions. The magnetized solar wind then picks up these ions, whirling them around and flinging some of them back into the atmosphere, where they collide with neutral atoms and molecules there — such as argon-36 — and "sputter" them every which way, including out of the atmosphere entirely.

MAVEN's observations show that today's Mars has far too little argon-36, if it started out with a level similar to Earth's and that of other solar system objects. To explain the current ratio, the planet must have lost roughly two-thirds of its atmospheric argon over its history, the team concludes in the March 31st *Science*.

This estimate agrees with previous Mars studies, including a 2013 effort by Sushil Atreya (University of Michigan) and others using Curiosity rover data. The new result incorporates those measurements; MAVEN's contribution is the evidence for how the argon isotopes separate and how the argon is lost.

Other atmospheric constituents would have escaped Mars with argon. Jakosky's team estimates that, based on the argon ratio, Mars has lost at least 0.5 bar (half the atmospheric pressure at sea level on Earth) of its primary atmospheric molecule, carbon dioxide. That's enough to at least partially explain what happened to the planet's ancient warmer, wetter climate.

■ CAMILLE M. CARLISLE

SOLAR SYSTEM

Sun Triggers Ceres' "Air"

SCIENTISTS THINK the Sun may inadvertently create a transitory, tenuous atmosphere around the dwarf planet Ceres — and in an unexpected way.

Since 1991, astronomers have occasionally detected an "exosphere" (an atmosphere so thin it's not worthy of the name) of water molecules around Ceres, the largest body in the asteroid belt. Water ice makes up a considerable fraction of Ceres' makeup (*S&T:* Dec. 2017, p. 16), but it was unclear what process was sending the molecules into space. For example, the handful of detections did not always coincide with the dwarf planet's closest approaches to the Sun, eliminating sublimation as a possible solution.

In 2015 NASA's Dawn spacecraft detected both a short-lived exosphere and a space weather "prequel": an uptick in energetic, charged particles arriving from the Sun. Inspired, Michaela Villarreal (University of California, Los Angeles) and colleagues dove into archival data and discovered that an exosphere appears after a burst of solar wind hits Ceres. The solar wind's high-speed particles presumably knock water molecules out of the surface and into space, creating an exosphere that lasts about a week. The team reports the result in the March 20th *Astrophysical Journal Letters*.

■ CAMILLE M. CARLISLE

SUPERNOVAE

Supernova Erupts in Lupus

SN 2017cbv, in outskirts of NGC 5643

ON MARCH 10TH, Leonardo Tartaglia (University of California, Davis) and colleagues discovered Supernova 2017cbv in NGC 5643. This spiral galaxy lies 55 million light-years from Earth and sits in the far western corner of the constellation Lupus. At discovery, the stellar explosion was only magnitude 15, but two weeks later it had brightened to magnitude 11.5, within easy reach of a 6-inch telescope. Unfortunately, because NGC 5643 lies at declination −44° 08′, only observers south of 36° north latitude could see it. Spectra indicate the explosion was a Type Ia, the aftermath of a white dwarf's death. The discovery is part of the D<40 Mpc Survey, which observes galaxies within a distance of 40 megaparsecs (Mpc), or 130 million light-years, every night down to a limit of about magnitude 19. Read more at **https://is.gd/sn2017cbv**.

■ BOB KING

MAVEN: LOCKHEED MARTIN; SUPERNOVA: JOSEPH BRIMACOMBE

METEORS


Fireball over ALMA

A New Take on Sounds

A BAD HAIR DAY might give you the temporary superpower of hearing meteors. Richard Spalding (Sandia National Laboratories) and colleagues sought an explanation for occasional but persistent reports of observers hearing hisses, pops, or pings from bright meteors. The team's study, appearing February 1st in *Nature*'s *Scientific Reports*, suggests the sounds might be triggered by light's effect on certain materials, including human hair.

In principle, observers should not hear sounds simultaneously with seeing fireballs' flashes. Not only do meteors occur in the tenuous upper atmosphere, which transmits sound poorly, but they're also distant, roughly 80 km (50 miles) up. Any noise would reach you noticeably after seeing the flash.

Spalding's team proposes that the sounds originate much closer to observers. Fireballs' strong, millisecond-long flashes are intense enough to induce radiative heating in dielectric materials such as dry leaves, clothing, or even hair, via what's called the *photoacoustic effect*. The irradiated surfaces heat the air next to them, producing tiny pressure oscillations — in other words, sound. A flickering fireball around −12 in magnitude (about as bright as the full Moon) could induce an audible sound of roughly 25 decibels, slightly louder than a whisper's 10 to 20 decibels.

This scheme even explains why people with frizzy hair are more likely to "hear" meteors. "Hair near the ears will create localized sound pressure, so it is likely to be heard," the authors write. "Also, hair has a large surface-to-volume ratio, which maximizes sound creation."

■ DAVID DICKINSON

On the Web: Learn more and listen to a rendition of "Greensleeves" created using the photoacoustic effect at **https://is.gd/audiblemeteors**.

STELLAR

Runaway Stars in Orion

A RUNAWAY PROTOSTAR in the Orion Nebula suggests a tussle occurred between four stars 540 years ago.

The protostar, labeled Source X, lies in the vicinity of the Kleinmann-Low Nebula, the most active part of the star-forming Orion Nebula complex. By comparing Hubble Space Telescope images from 1998 and 2015, Kevin Luhman (Penn State University) and colleagues found that Source X is moving at more than 55 km/s (120,000 mph) across the sky, away from the same origin point as two other high-velocity stars: the Becklin-Neugebauer (BN) object and Source I. BN and Source I are zooming in opposite directions at 26 km/s and 10 km/s, respectively.

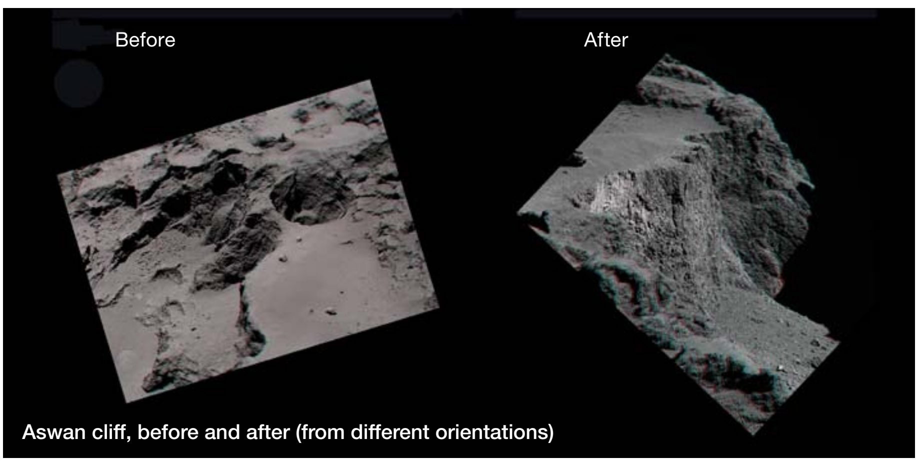
The three objects might once have been part of a four-star system, Luhman's team reports in the March 20th *Astrophysical Journal Letters*. When two of the stars came too close together, they formed a binary or merged (Source I), sending BN and Source X flying. The new measurement of Source X's motion accounts for the system's missing kinetic energy and seals the deal.

■ MONICA YOUNG

COMETS

Rosetta Sees Changing Face of Comet 67P

RESEARCHERS HAVE used data from the European Rosetta mission (*S&T:* May 2017, p. 14) to link outbursts on Comet 67P/Churyumov-Gerasimenko with dramatic surface changes. Comets are notorious for sudden outbursts, even fragmenting, as they near the Sun. Scientists have had only a poor understanding of why. But on July 10, 2015, Rosetta's navigation camera caught sight of a large plume of dust coming from the Seth region on Comet 67P. Five days later, the spacecraft detected a freshly exposed escarpment along Aswan, a cliff face that's 134 m (440 ft) high. The albedo of the exposed material is 40%, the same as dry sand, making it six times brighter than the older, surrounding surface.



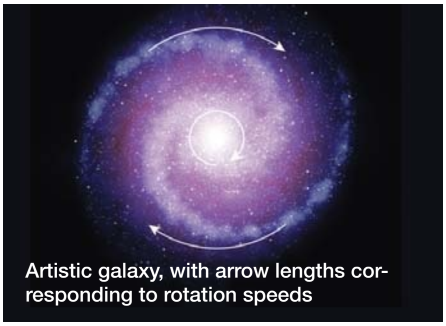
Aswan cliff, before and after (from different orientations)

Based on a visual count of boulders at the cliff's bottom, Maurizio Pajola (NASA Ames) and colleagues estimate that around 10,000 tons of material were involved in the landslide, with about 100 tons released in the plume. The study, published March 21st in *Nature Astronomy*, supports previous speculation that landslides might explain comet outbursts.

■ DAVID DICKINSON

METEOR: ESO / C. MALIN; ROSETTA: ESA / ROSETTA / MPS / UPD / LAM / IAA / SSO / INTA / UPM / DASP / IDA / M. PAJOLA

COSMOLOGY



Artistic galaxy, with arrow lengths corresponding to rotation speeds

Less Dark Matter in Young Galaxies?

A NEW STUDY of six young, star-forming galaxies suggests they're less influenced by dark matter than expected. But the results perhaps say more about galaxy evolution than about dark matter.

One of the main arguments for the existence of dark matter is that galaxies' outer reaches rotate more quickly than expected based on the matter we observe. Now, in March 16th's *Nature*, Reinhard Genzel (Max Planck Institute for Extraterrestrial Physics, Germany) and colleagues report that the outskirts of six distant galaxies do the opposite: They rotate more slowly than the inclusion of dark matter would predict. Averaged data from 97 other (fainter) distant galaxies show the same result.

That's not to say that dark matter is absent — there's just not as much as astronomers expected. The dark matter cushions these galaxies lie in appear to be rather threadbare.

One possibility, says Mark Swinbank (Durham University, UK), who authored an accompanying perspective in *Nature*, is that the dark matter halos of these galaxies are still growing. But that would fundamentally change how we view galaxy evolution: The halos should be largely in place before the gas and stars come together.

Another possibility is that we're simply viewing these galaxies during a crucial era. Genzel's team chose to observe massive, star-forming disk galaxies during *cosmic noon*, the universe's peak in star formation, about 2 to 8 billion years after the Big Bang. Recent computer simulations by Adi Zolotov (Ohio State University) and colleagues show that virtually all such massive galaxies take a fast track toward evolution, their burst of star formation instigated by a single event. As a result, massive, star-forming galaxies will look a lot more compact during this cosmic era than they actually are.

So measuring their rotations won't reveal the influence of the full dark matter halo around them, says simulation coauthor Joel Primack (University of California, Santa Cruz). The dark matter simulations actually predict the Genzel team's result.

■ MONICA YOUNG

• Read more at **https://is.gd/bluenuggets**.

PHOTO OP

Pan: Saturn's Ravioli-Shaped Moon

This close-up shows the bizarre shape of Saturn's moon Pan. The Cassini spacecraft took the image during a flyby on March 7th, when it came within about 24,000 km of the moonlet. A mere 35 km across, Pan is nestled in the Encke Gap within Saturn's A ring, where it kicks up spiral density waves in the ring. Scientists suspect the flange of ice around Pan's equatorial bulge is ring material the moon has swept up and collected as it cruises through the Encke Gap. The skirt of ice towers several kilometers above the surface.

■ DAVID DICKINSON

SPIRAL GALAXY: ESO / L. CALÇADA; RAVIOLI MOON: NASA / JPL-CALTECH / SPACE SCIENCE INSTITUTE

IN BRIEF

NASA Narrows Mars 2020 Landing Sites

Three candidates are now in the running for where NASA's Mars 2020 rover will land: Columbia Hills, the crater Jezero, and northeastern Syrtis Major. All three are near the equator. The latter two are close to each other, on the edge of Isidis Planitia; Columbia Hills was explored by NASA's Spirit rover, which discovered evidence for ancient hot springs there. The sites selected include terrains where water might once have flowed and, just possibly, sustained microbial Martian life. Read more at **https://is.gd/mars2020threesites**.

■ DAVID DICKINSON

Meteorites Date Solar Nebula's Demise

A study of ancient meteorites has refined the date for the dissolution of the solar nebula, the cloud of dust and gas from which the planets formed. Going off snapshots of infant exoplanet systems, astronomers had crudely estimated that the nebula lasted 1 to 10 million years, until the newborn Sun's radiation cleared it away. But by looking at some of the oldest meteorites on Earth, known as *angrites*, Huapei Wang (MIT) and colleagues put the solar nebula's lifetime at 3 to 4 million years. The magnetism frozen into meteorites of various ages dropped more than tenfold in strength between 2 and 3.8 million years after the solar system's formation, the team reports in the February 10th *Science*. The magnetic field would have been associated with the solar nebula.

■ DAVID DICKINSON

Black Hole Gnaws Star

The black hole in the galaxy SDSS J1500+0154 has been eating the same star for at least 11 years — a feast that normally takes one to two years. X-ray observations suggest the object has been gorging itself on the shredded star's remains at what should be an unsustainable rate, called *super-Eddington accretion*, Dacheng Lin (University of New Hampshire) and colleagues report February 6th in *Nature Astronomy*. The detection supports the idea that the universe's first big black holes could grow this way (*S&T:* Jan. 2017, p. 24).

■ MONICA YOUNG

Life Outside the Habitable Zone

Over its history, a planet might host oceans long enough to support life.

WHAT WOULD ALLOW a planet to host life? We often define the *habitable zone* as the distance from a star where water can remain liquid on a planet's surface. Starward of the inner edge we imagine planets in a Venus-like state — broiling hot and dry. Beyond the outer edge, we picture Mars-like worlds, freeze-dried and oceanically deprived.

Since stars become brighter as they evolve, the inner and outer edges of the zone will both move outward, away from the heat, as hot worlds boil and frozen worlds melt. So we often talk about the "continuously habitable zone" hosting planets that remain in this zone over a star's lifetime.

But when we study planetary evolution we learn this simple guideline is inadequate, because without knowing a planet's history, its position doesn't really tell us if it's habitable. What if a planet can be conducive for life, even if its oceans are not stable?

Two recent results illustrate this ambiguity. Some colleagues and I have modeled the history of Venus with an eye toward understanding the inner edge of habitability. We used a 3D climate model to simulate billions of years of evolution under the warming Sun and, when we included the complex interplay of clouds, topography, planetary rotation, and atmospheric motions, we learned something unexpected: As the Sun warms and the oceans evaporate, the clouds arrange themselves to keep the planet cool and slow down the loss of oceans. Thus, although the oceans of Venus became unstable early in its history, the process of actually losing them to space likely took billions of years. Venus, while outside the habitable zone, might have been habitable for much of its lifetime.

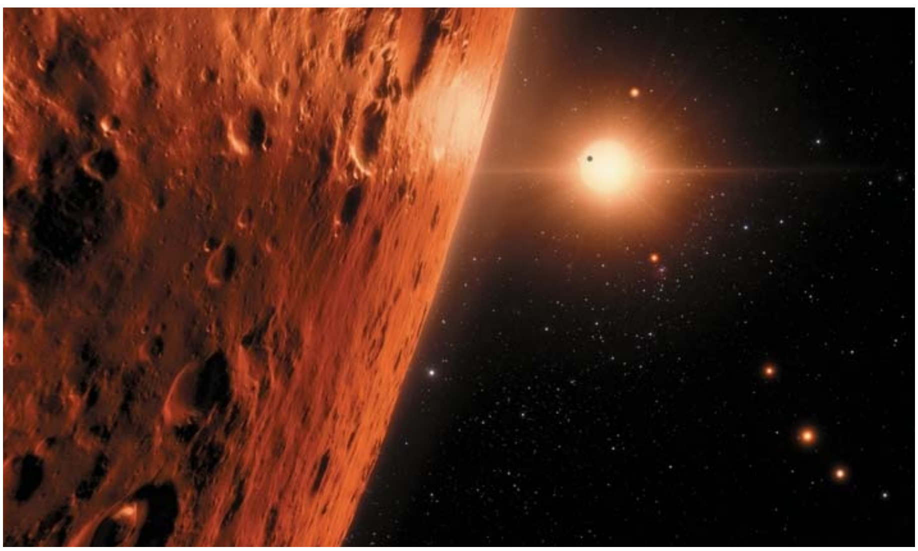
More recently, a group of researchers at the University of Washington has considered the evolution of icy moons, like those of Jupiter and Saturn. As planets migrate inward toward a star — as we've learned young giant planets are wont to do — their icy moons will melt. How long will their oceans last? That depends on size. Oceans on a larger moon, such as Ganymede, might become stable and last as long as its host planet is in the habitable zone. For smaller moons like Europa, surface oceans would not be stable but would instead fully evaporate, though this process could take well over a billion years.

> It's not hard to imagine life following oases of habitability, surviving by hopping from one promising world to the next.

These results made me realize that a planet does not have to be a stable resident of the habitable zone to host life.

We describe a chemical as being "metastable" if in its current conditions it will eventually decompose but the rate of this decomposition is quite slow. Similarly, I think we have to consider worlds that are "metahabitable." If oceans can persist for hundreds of millions or even billions of years, this might be plenty of time for life to flourish on worlds that are not in a stable habitable state.

We don't yet know how long an ocean takes to come alive, but Earth's history hints at less than 100 million years. Since we suspect that microbial life can travel from planet to planet, hitchhiking on meteorites, then a few worlds with metastable oceans may suffice to cultivate and maintain life in a planetary system. Especially now that we know of systems like Trappist-1, around which many planets orbit very close together (*S&T:* June 2017, p. 12), it's not hard to imagine life following oases of temporary habitability, surviving by hopping from one promising world to the next.

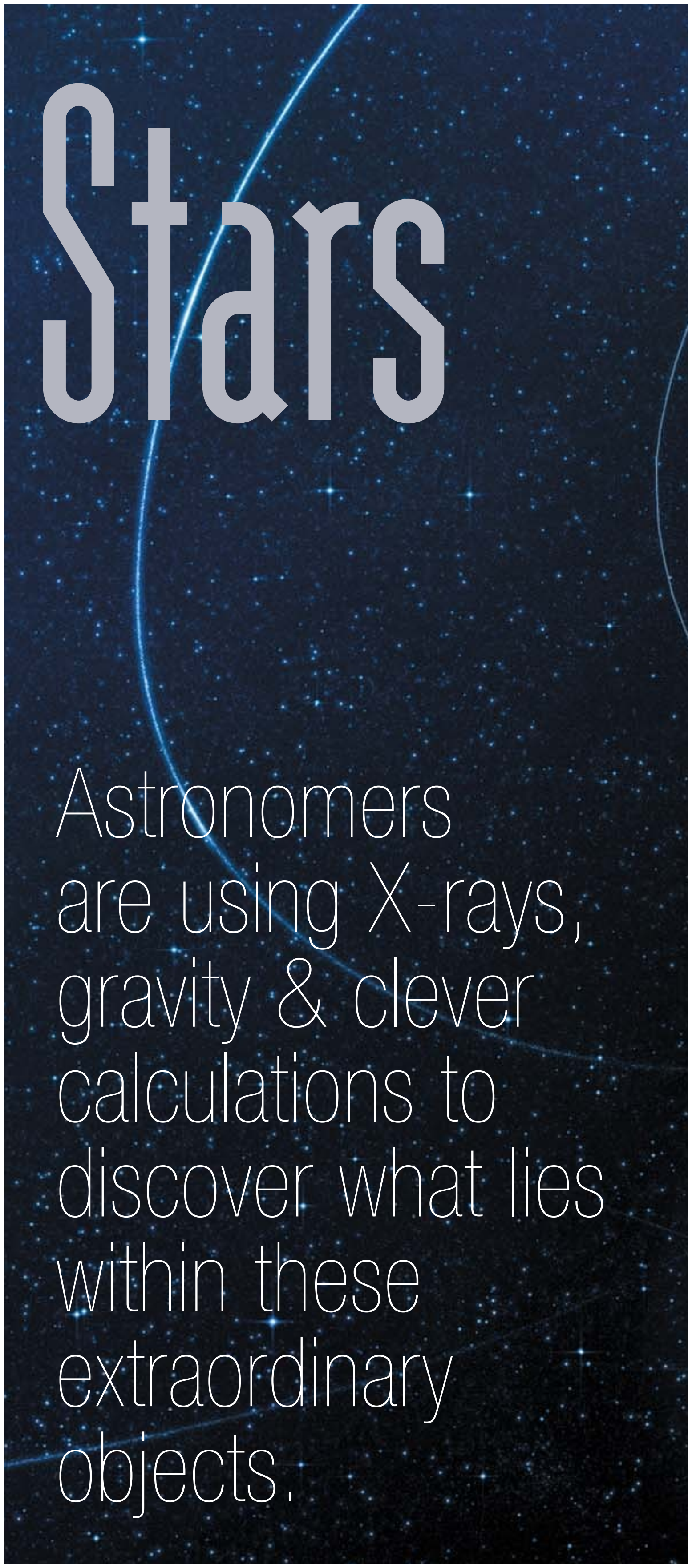


ESO / N. BARTMANN / SPACEENGINE.ORG

▲ An artist's concept of the TRAPPIST-1 system seen from one of its seven known planets, several of which lie within the star's habitable zone.

■ **DAVID GRINSPOON** is an astrobiologist at the Planetary Science Institute. His new book, *Earth in Human Hands*, came out in December.

The Inside Story of Neutron Stars



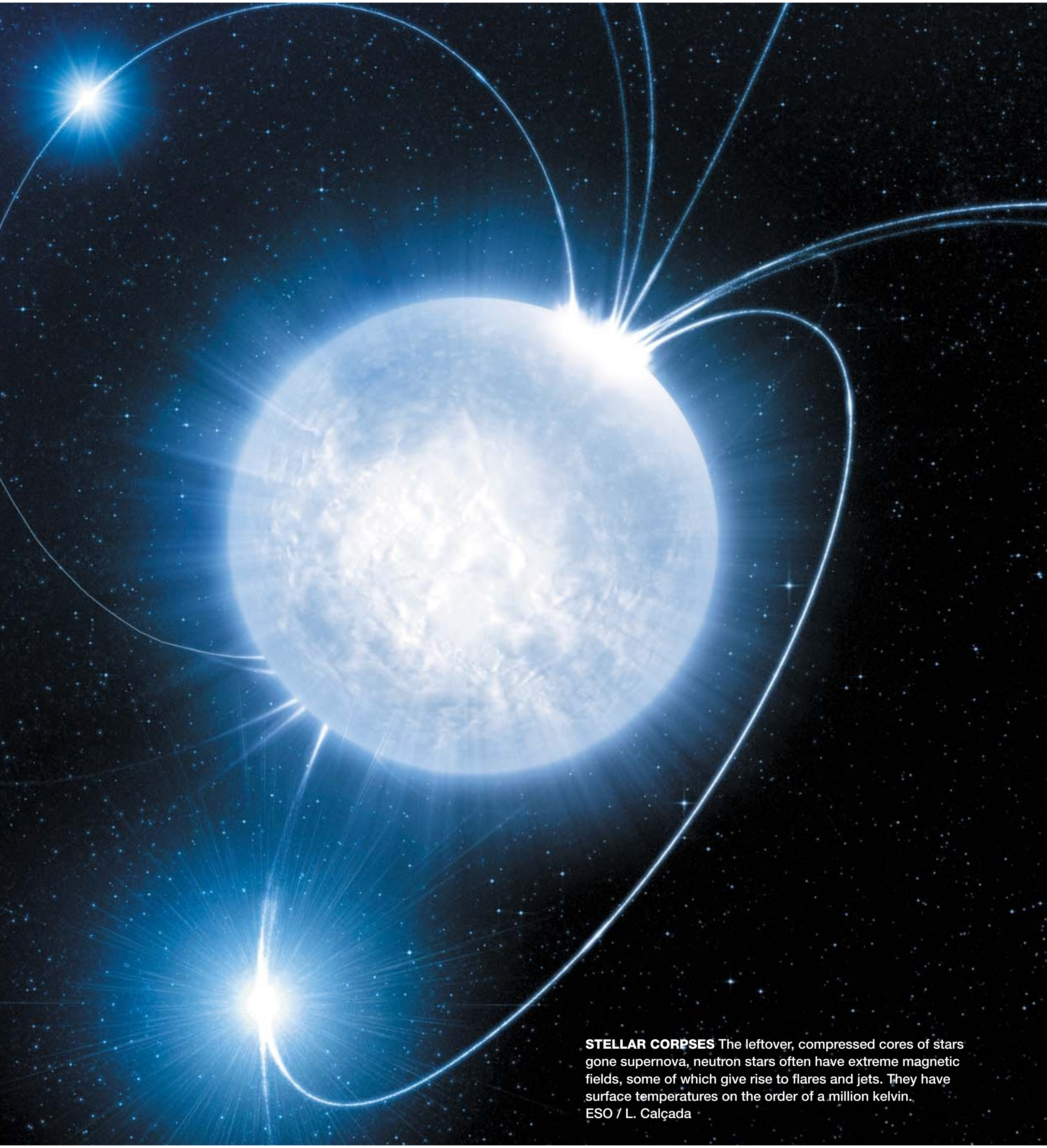
Astronomers are using X-rays, gravity & clever calculations to discover what lies within these extraordinary objects.

It is a rare opportunity when we can use astronomical observations to push the frontiers of physics in a way that is not possible in any laboratory on Earth. Yet neutron stars, the dead, dense remnants of massive stars, provide us with just that opportunity.

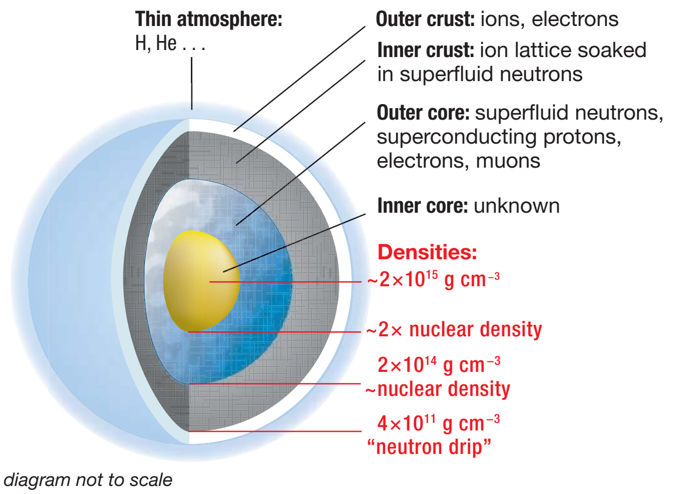
Crushed under the inward pull of gravity once a massive star's fuel is exhausted, the stellar core that becomes a neutron star reaches matter densities that are not naturally encountered anywhere else in the universe. (Black holes don't count: Although they may have infinite energy densities, they hide behind horizons and are inaccessible.) In fact, the matter that makes up neutron stars has fundamentally changed character, taking us into regimes that are still poorly understood in physics. As a result, a lot of recent efforts have focused on probing these stars' interiors with astronomical observations.

To be sure, there are some aspects of that unusual matter that we can confidently predict, based on theoretical calculations and laboratory experiments. For example, during the implosion of the star, the electrons that normally surround the nucleus of an atom in the core get pushed into the atomic nuclei. There, they combine with the protons through *weak interactions*, one of the four types of interactions that take place between particles in the universe. (The other three are strong, gravitational, and electromagnetic.) That combination produces a neutron — thus giving this new star its name — as well as nearly massless, ghostly particles called neutrinos that rapidly escape from the star, carrying with them a large amount of energy. The first observational confirmation of this process happened with Supernova 1987A, observed in 1987 in the Large Magellanic Cloud (*S&T:* Feb. 2017, p. 36), when two neutrino observatories detected a burst of particles around the same time as the supernova's visible light appeared in the sky.

Scientists can't create such neutron-rich matter. Simply smashing nuclei together and squeezing them to high densities in heavy ion colliders, such as the RHIC experiment in Brookhaven National Laboratory, doesn't work. First, collisions in accelerators create very hot matter, which behaves



STELLAR CORPSES The leftover, compressed cores of stars gone supernova, neutron stars often have extreme magnetic fields, some of which give rise to flares and jets. They have surface temperatures on the order of a million kelvin.
ESO / L. Calçada



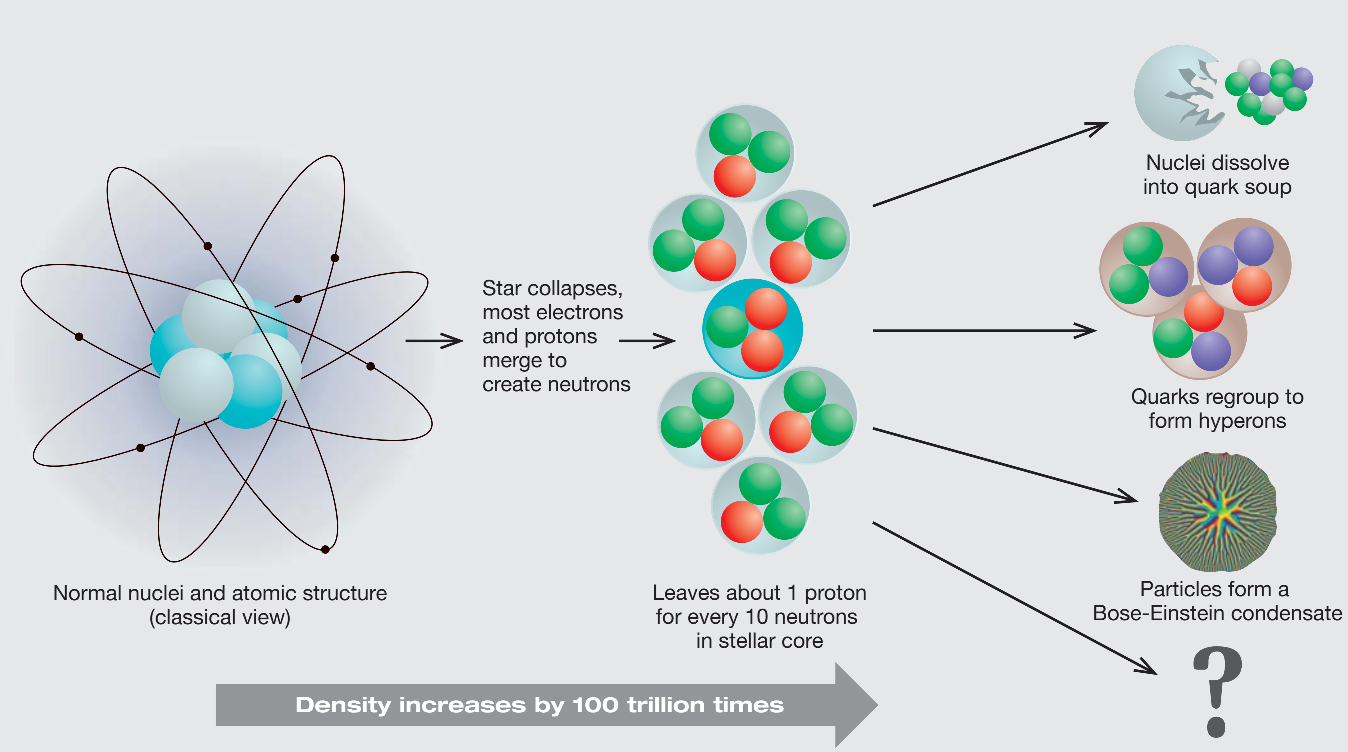
WHAT LIES WITHIN Here is one approximation of what a neutron star's interior might look like. The "neutron drip" boundary is the density at which no more neutrons can be added to nuclei; the few nuclei that exist at the neutron drip density have 20 to 40 times more neutrons than protons and sit in a vast sea of free neutrons. Inside that boundary the density skyrockets, surpassing the maximum packing ability of neutrons and potentially creating exotic matter phases. The predicted density in the core is 100 trillion times greater than lead at room temperature.

differently than the cold matter inside a neutron star. (It's "cold" not because the temperature is low, but because the thermal energy is so small compared to the energies of other internal interactions that it's unimportant.) Second, the weak interaction acts over a relatively long time scale, much longer than the time that particles have to interact with one another when crushed against each other in a collider. Imagine that a plane were flying nearby, in the opposite direction to yours. You might have time to catch a glimpse of a passenger on that flight, but you certainly wouldn't have time for a hearty handshake — even if it were physically possible.

Still, if the creation of neutrons during the implosion were all that could happen to the core's atomic nuclei, astronomers would by now consider the question of what lies inside a neutron star a solved problem. But transforming run-of-the-mill atoms into a super-dense soup of (almost) entirely neutrons turns out to be only the beginning of the particles' journey.

The Fate of Collapsing Matter

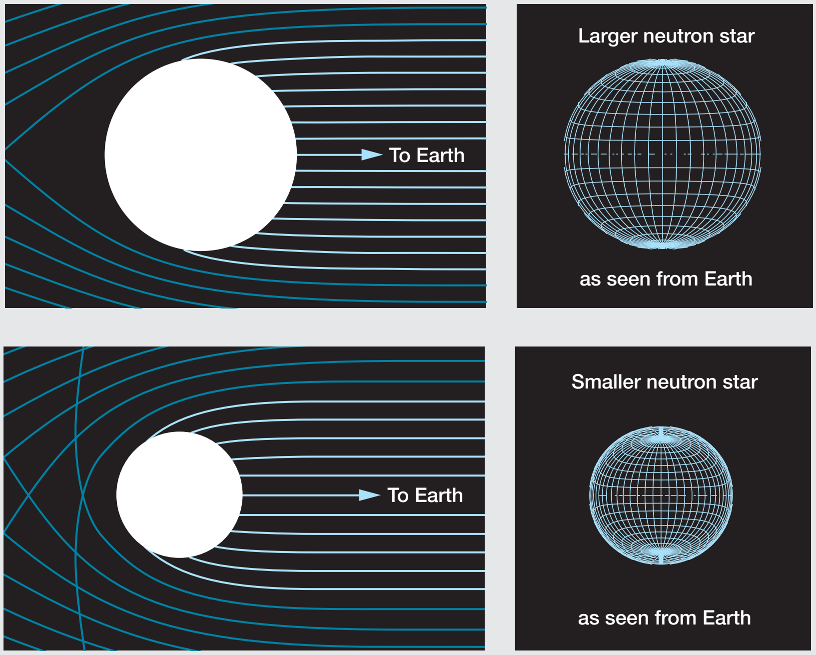
As neutrons become squeezed further together in neutron star cores, they reach densities that are difficult to fathom. While the star's crust may look more or less like normal matter, the core can reach densities that are a hundred trillion(!)

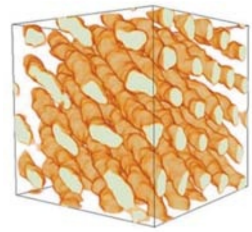


FATE OF COLLAPSING MATTER When a star collapses to form a neutron star, the atoms in the core (*left*) are crunched together, with the majority of the electrons and protons combining to form neutrons. Protons and neutrons are each made of three subatomic particles called quarks (*center*). But under such incredible densities, these nuclei might transform further (*right*): The protons and neutrons could dissolve into a quark soup; the quarks could change and regroup to form particles called *hyperons*, which contain at least one *strange quark*; the nuclei could unite in a single quantum state, called a *Bose-Einstein condensate*; or something else that we haven't imagined could be created.

INTERIOR: B. LINK (MONTANA STATE UNIV.) / NASA; COLLAPSING MATTER: COMPOSITION: GREGG DINDERMAN / *S&T*; BOSE-EINSTEIN CONDENSATE: OIST

AROUND THE BEND
Because they're so compact, neutron stars distort the spacetime around them (possible paths in turquoise). Outgoing starlight is redirected accordingly. A telescope would normally only detect light from the hemisphere of a star that's facing it. But the more compact the star, the farther around the star the telescope "sees." Shown are the paths (light blue) of light emitted by two neutron stars of the same mass (1.6 Suns) but different sizes: The larger star has a radius of 14 km, the smaller one of 8 km.





NUCLEAR PASTA
At the bottom of a neutron star's inner crust, the density is so high that nuclei may transform into extended tubes (called "spaghetti"), sheets ("lasagna"), and other strange phases of matter. These are called *nuclear pasta*. The pasta layer would have both solid and liquid properties, akin to liquid crystals.

times higher than the densest natural elements on Earth.

Under those conditions, neutrons not only start vehemently repelling one another but also interacting in new ways. This is because neutrons are examples of particles called *fermions*, which require increasingly higher energy to be confined closer and closer together. To counter this rising energy, neutrons may find it "energetically favorable" — basically, less hassle — to dissolve into their even smaller constituents, called *quarks*, creating a quark soup. Alternatively, they may form different combinations of quarks than what normally make up a neutron or proton. Such hyper-nuclei, called *hyperons*, can be created in laboratories but survive only for a short time. In neutron stars, they might be stable.

Yet another possibility is that fermions pair up with one another to form a type of particle called a *boson*. These particles, which behave differently from fermions, can transition into an unusual superfluid state of matter (the same state that is observed in low-temperature helium fluids, superconductors, and some other metals, called a *Bose-Einstein condensate*). This state will have strange properties, such as flowing without friction. If this transition indeed occurs inside the core — and we have good reason to think that it does — it will relieve some of the pressure built up by the high densities that matter experiences there.

But which of these possibilities actually take place in a neutron star's interior? One of the things that complicate this puzzle is that, while we've observed hyperons and many types of bosons as standalone particles in laboratories, a quark has never been observed by itself, in what is called an "unconfined" state. Therefore, predicting and testing the behavior of quark matter becomes very difficult.

But if one could see into the cores of neutron stars and prove that they contain quark matter, it would constitute a major advance in our understanding of these smallest constituents of matter.

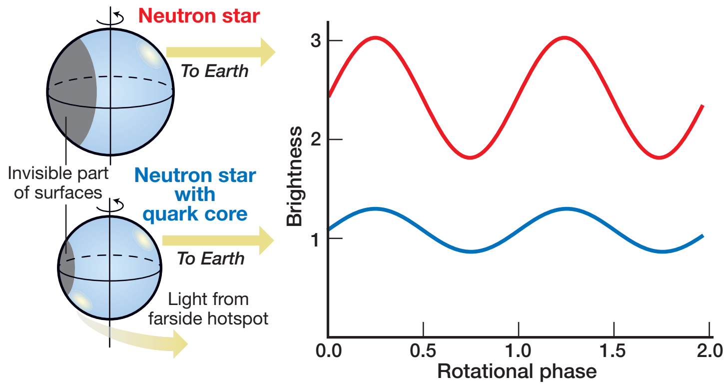
Probing the Invisible

How would astronomers go about probing the deep interiors of not only the densest but also the smallest stellar objects in the universe? At roughly 20 km (12 miles) across, neutron stars are smaller than some of the solar system's asteroids. Yet they pack into that tiny volume up to two times the mass of the Sun. And unlike asteroids, they are hundreds to many thousands of light-years away.

It turns out that measuring the exact sizes of neutron stars, which can be done from a distance, provides the best possible tool for getting a complete picture of their interiors. Our calculations tell us that, if only neutrons remain in the interior, the pressure building up from the repulsive interactions will support a star of a particular size. If any constituents other than neutrons form, their interactions would cause a different amount of repulsion, creating a star of a different size. Thus, astronomers can discover the possibilities in the realm of physics simply by measuring exact diameters of these stars.

Astronomers are used to measuring the sizes of far-away objects by collecting and analyzing the light they emit. Indeed, nearly all our knowledge about the sizes of normal stars comes from measuring both the total light emitted by the star, referred to as its luminosity, as well as the breakdown of that emission into different wavelengths of light, known as its spectrum. The spectrum of the star allows us

GREGG DINDERMAN / *S&T*, SOURCE: FERYAL ÖZEL; SPAGHETTI: M. E. CAPLAN & C. J. HOROWITZ / ARXIV:1606.03646 (2016)



HOTSPOT PULSES A pulsar's strong magnetic field creates a pair of hotspots on the star's surface, one at each magnetic pole. Light from each hotspot spins in and out of view, creating peaks and dips in the star's light curve. But if its interior contained quark matter instead of pure neutrons, the neutron star would be compact enough that light from the farside hotspot would be gravitationally lensed around to the front, contributing to the nearside hotspot's glow and diminishing the overall change in brightness as the star rotates.

to determine its temperature; the hotter the star, the higher the energy of the light that it emits. It's this temperature that regulates exactly the amount of radiation that emerges from each patch of the surface, allowing us to determine the star's intrinsic brightness. Comparing that to the total observed luminosity gives us an exact measurement of the star's surface area.

For neutron stars, the approach we take isn't too different. So far, much of the information we've obtained about their sizes has come from nearly the same methods we apply to normal stars, but with a few complications. First off, it is difficult to see down to the surface of many neutron stars. This is because the majority of neutron stars that have ever been observed are enshrouded by strong magnetic fields (called *magnetospheres*), as well as energetic charged particles that swarm around in these fields like a cloud. These types of neutron stars are exciting in their own right, observable as the beautiful radio and gamma-ray pulsars that spin like lighthouses with exquisite regularity. However, it is difficult to see down to the star's surface without being overwhelmed by the beamed light emitted by this cloud. When looking for the light emitted from the surface of the neutron star itself, we focus instead on those stars that have very weak magnetic fields, which allows the surface's X-ray glow to shine through. Some of these stars are not pulsars at all, while others have very weak pulsar emission.

The second difficulty astronomers encounter in measuring sizes comes from the extremely strong gravitational fields neutron stars possess. Thanks to the vast amount of matter packed into such a small volume, a neutron star strongly bends spacetime around itself, and the path of the light that the star emits becomes significantly distorted. Indeed, the gravitational field is so strong that a neutron star hovers just this side of catastrophe — any denser, and it would collapse into a black hole.

What this means for measuring the size of a neutron star is that an extra step is required to map the observed light through its distorted path back to its origin. This procedure allows us to accurately account for every piece of the surface that contributes to the observed light and obtain a measurement of the entire surface area.

The results we have obtained to date with this method have been pretty striking: Neutron stars turn out to be smaller than what we would predict if they were made up only of neutrons. More precisely, if none of the possible interactions that give rise to new particles or unconfined quarks takes place in their cores, we would expect neutron stars to be 25–26 km (16 mi) across. The measurements point to 20–22 km (13 mi) instead. That may seem like a small difference, but it is in fact large: The central density of two such stars differs by a factor of two. This is enough to have a profound effect on the amount of repulsion the particles experience.

As with all scientific experiments, these results need to be confirmed with independent methods. So far, though, the measurements indicate that neutrons are taking at least one of the possibilities available to them to partially release the pressure valve. Which one, we're still unsure. We need both additional, independent observations and theoretical investigations to find out.

Sextant

◖ NICER's pulsar observations could also further interplanetary exploration. Using the payload's X-ray Timing Instrument, astronomers will undertake the first space demonstration of pulsar-based navigation. The idea is to use the millisecond pulsars that exist throughout our galaxy like GPS satellite clocks, pinpointing the pulsations' arrival times to determine one's position anywhere in the solar system. This mission add-on, called Station Explorer for X-ray Timing and Navigation Technology ("Sextant"), aims to determine the space station's real-time location within 10 km in any direction.

Gravity to the Rescue

One of the powerful techniques that can reveal the size of a neutron star relies on the general relativistic effects that arise due to the star's extreme gravity — the exact same effects that cause complications in surface area measurements. This time, though, they come to our help. We apply a technique known as *pulse profile modeling* to a special class of pulsars. In these sources, the magnetic fields that are anchored on the surface are weak enough that the swarm of particles around the star doesn't overwhelm the light from its surface. Nevertheless, these magnetic fields are strong enough to guide charged particles toward the star's magnetic poles, producing a hotspot where the poles meet the crust. As the star spins on its axis, the hotspots come in and out of sight, generating a characteristic pulse in the X-rays.

COMPOSITION: GREGG DINDERMAN / *S&T*, LIGHT CURVES: FERYAL ÖZEL

Measuring the pulses' shapes allows us to determine the size of the star that emitted them. This is because the amount that the light path bends as it leaves the surface of a neutron star depends on how large the star is. In other words, two neutron stars of the same mass but with different sizes, say 20 and 25 km, would create a different pattern of modulation in the light they emit. These patterns can be calculated very precisely and compared to the observed pulses, revealing the sizes of these pulsars.

We are poised to conduct this experiment with an instrument called the Neutron Star Interior Composition Explorer (NICER), which is scheduled for launch to the International Space Station (ISS) this year. NICER is approximately a meter across and consists of carefully designed optical elements that focus the incoming X-rays onto 56 silicon detectors. After its journey on a SpaceX resupply mission, it will be unpacked and mounted onto its home on the ISS platform. A star-tracker-based pointing system will then allow the high-precision X-ray timing instrument to point to and track pulsar targets over nearly half of the sky.

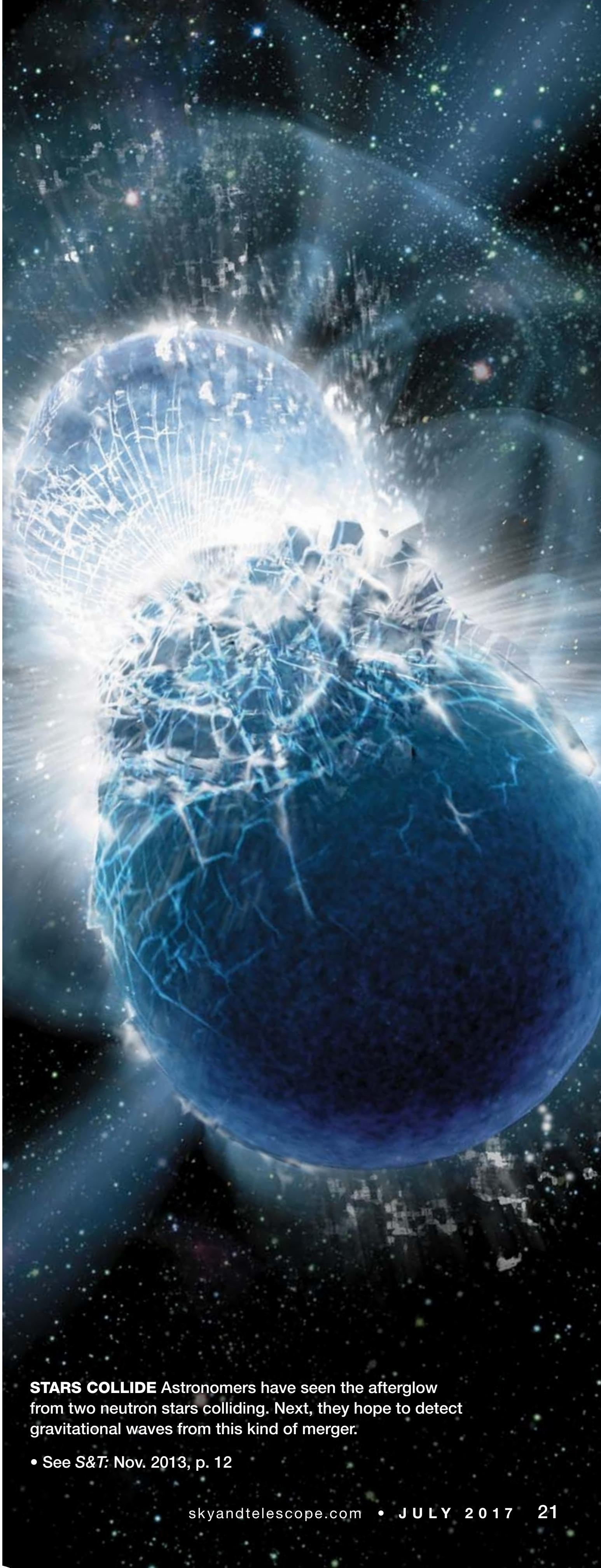
What makes NICER unique is its unprecedented capability to record the arrival times of incoming photons with 100-nanosecond precision. This capability will enable the highly faithful reconstruction of the pulse waveforms for a number of pulsars. The detectors will also capture the pulsars' spectra. Coupled with the precisely determined pulse shape, these measurements will provide all the information necessary for a precise size measurement within a year after its launch.

Another exciting avenue into the neutron star interior will become possible through the detection of gravitational waves with LIGO. Even though the first two events detected by LIGO were coalescing black hole binaries, LIGO is also sensitive to signals from merging neutron stars (*S&T:* Dec. 2015, p. 26). Shortly before the expected coalescence, the pair of inspiraling neutron stars start distorting and pulling each other apart through tidal interactions, obeying the same principles as the Moon's effect on Earth's oceans, but far more severe. How severe it is depends on how deformable the stars are, which in turn depends on their size, density, and interior composition. Remarkably, the distortions caused by these tidal interactions are then encoded into the gravitational wave signals that are emitted throughout the inspiral, offering one more penetrating glimpse into the neutron star interior.

If NICER and LIGO experiments confirm the existing measurements of small sizes, the results would point to new physics that emerges when matter becomes ultra-dense. Or the experiments may offer other surprises — that remains to be seen.

But no matter how small and impenetrable they may seem, neutron stars will not be able to hold onto their innermost secrets for much longer.

■ **FERYAL ÖZEL** is a professor of astronomy and physics at the University of Arizona and a current Guggenheim Fellow. She studies neutron stars and black holes and is a member of the NICER team.



DANA BERRY / SKYWORKS DIGITAL, INC.

STARS COLLIDE Astronomers have seen the afterglow from two neutron stars colliding. Next, they hope to detect gravitational waves from this kind of merger.

• See *S&T:* Nov. 2013, p. 12

Hunting the Galaxy Killer

Half the stars in the universe live in "dead" galaxies, where star formation has ground to a halt. What great force has stopped it in its tracks?

If we could travel back in time 10 billion years, we would experience a universe at the height of fertility. Galaxies underwent tremendous growth spurts as stars formed at prodigious rates: Hundreds or even thousands of them ignited each year in every galaxy. Deep within these galaxies, black holes turned into cosmic lighthouses, gorging on so much gas that the material they were trying to consume grew bright enough to be seen across the universe as quasars.

Since then, there's been a decline. Many black holes have shut off their surrounding lighthouses, while in general the creation of new stars has become less efficient. Our own Milky Way struggles to turn dense clouds containing hundreds of solar masses of molecular gas into a measly Sun's worth of stars each year. But at least our Milky Way is still forming stars. Some galaxies have ceased star formation altogether; they're now composed of stars that are cool, red, and old compared to more massive and short-lived stars. Such galaxies are evocatively described as "red and dead."

▲ **BLACK DEATH** The supermassive black hole ensconced in a galaxy's center may ultimately be responsible for its demise.

Part of the reason for this is that there's less gas available for star formation today than there was 10 billion years ago. Yet three-quarters of red-and-dead galaxies have no shortage of gas — it's just that it's too warm to make stars. These galaxies contain half the stars in the universe yet will make hardly any more — *something* seems to have happened to them. An unknown force, powerful enough to affect entire galaxies, is on a killing spree. Three suspects have been implicated, each with its own compelling means and opportunity.

Death by Blunt Force

Most red-and-dead galaxies are found in clusters, which house ellipticals near their centers and dusty, disk-shaped lenticular galaxies cruising through their suburbs. Could it be that the environment around these galaxies determined their fate?

ESA / ATG MEDIALAB

Red galaxies have been synonymous with galaxy clusters for as long as there have been galaxy clusters. "Ellipticals seem to be in place in clusters quite early in the history of the universe," says James Geach (University of Hertfordshire, UK). "But lenticulars only appear more recently, over the last five billion years."

Lenticular galaxies might have evolved from spiral galaxies. Although they're disk-shaped, they have little, if any, spiral structure. While they've lost most of their gas, they're obscured by plenty of dust and are rich in old, red stars. They also seem to congregate mostly in and around galaxy clusters.

Jeffrey Kenney (Yale University) thinks there's a connection. He spends his time researching the relationship between galaxies and their environments. When the Hubble Space Telescope imaged the face-on galaxy NGC 4921, which features ghostly spiral arms, Kenney noticed something odd on one side of the galaxy's disk. A prominent ridge of gas and dust, thousands of light-years long, appears to be fraying like loose threads on a sweater.

NGC 4921 is currently plunging deep into the Coma Cluster, 310 million light-years distant. Its journey takes it through the hot *intracluster medium*, a thick soup of X-ray-emitting plasma where temperatures soar to more than 10 million kelvin. This plasma acts like a harsh wind, scouring the leading edge of the infalling galaxy and stripping gas into long tails. The frayed filaments are denser, magnetically bound clumps of gas that more strongly resist the stripping pressure as NGC 4921 rams into the intracluster medium.

Right now, this *ram-pressure stripping* is operating tens of thousands of light-years from the galaxy's center, but it won't stop there. "It will eventually eat its way in and probably remove all the gas from the galaxy," says Kenney. "We see lots of disk galaxies in the Coma Cluster that have almost no gas, no star formation. Most of these were likely spiral galaxies that were completely ram-pressure stripped. [NGC 4921] is just the one we've caught in the act; for most of them the action is already over."

▲ **RED & DEAD** Both elliptical (*left*) and lenticular (*right*) galaxies largely contain red, aging stars. Although lenticulars are dusty and disk-shaped, like many spiral galaxies, they're more like ellipticals in terms of their star formation. Ellipticals are often found in galaxy clusters' centers, while lenticulars more often turn up in clusters' outer regions.

Ram pressure's effect depends heavily on the cluster's mass. The Virgo Cluster, 54 million light-years away, is less massive than Coma. Since its galaxies orbit at a slower pace and its intracluster medium is less dense, its ram pressure is consequently lower. Virgo can completely strip its dwarf galaxies of their star-forming gas, but larger spiral galaxies only lose gas on the outer edge. "In Coma," Kenney says, by way of comparison, "almost all spiral galaxies will be completely stripped on their first passage towards the cluster center."

While ram-pressure stripping may produce lenticular galaxies in massive clusters, it cannot satisfactorily explain why every cluster, big or small, contains an ancient, red elliptical galaxy at its hub. "It's not entirely clear what quenches star formation in elliptical galaxies," admits Kenney.

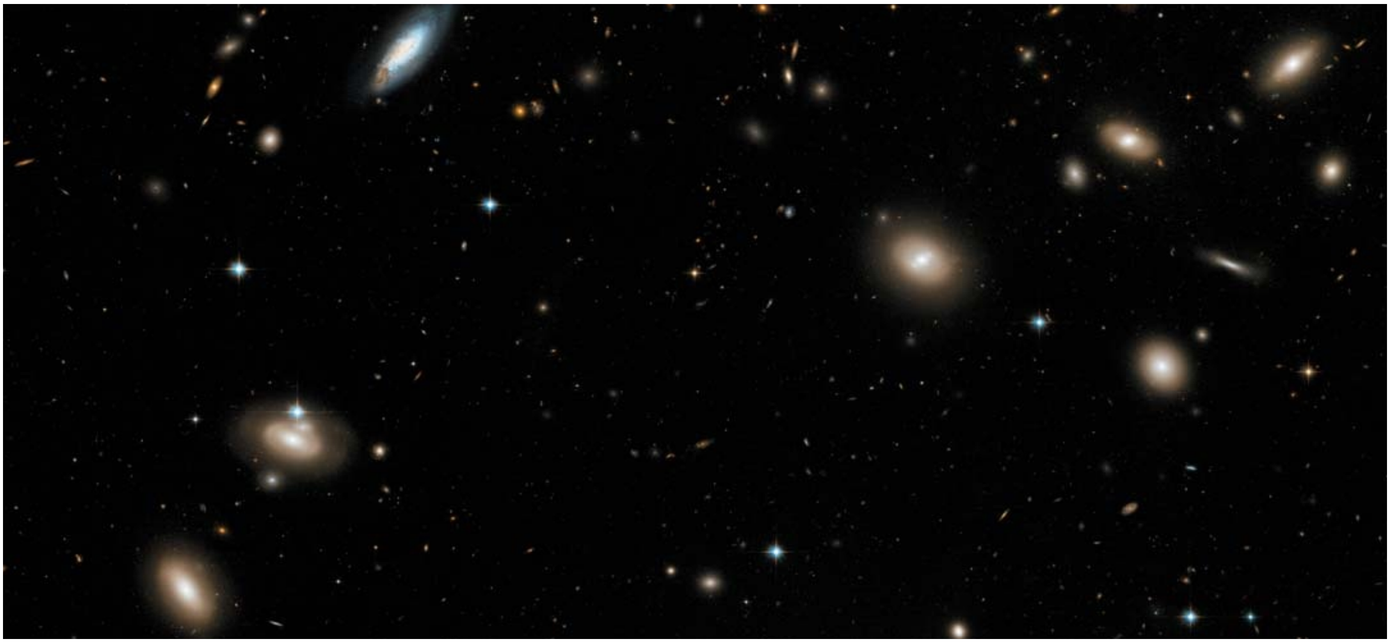
Green Valley Galaxies

Amidst fertile blue spirals and elderly red ellipticals exist a small group of in-between galaxies that aren't quite one or the other. These galaxies lie within the "green valley" on a color-magnitude diagram, which, a bit like a Hertzsprung–Russell diagram, plots galaxies' colors against their luminosities. The green valley is nestled between the swarm of blue galaxies and the curve rich with red-and-dead galaxies, implying that the green galaxies represent a brief intermediate stage.

"The green valley galaxies are where feedback is happening now," Geach says. Something is quenching these galaxies, whether it be black hole feedback, stellar outflows, or ram-pressure stripping. This stage of a galaxy's life might be relatively brief, which explains why green galaxies are so rare. "If you can map out where the green valley galaxies are and what their properties are, it will help pin down that evolutionary transition," says Geach.

▶ **FACING DISSOLUTION** As NGC 4921, a typical "green" galaxy, plunges deep into the Coma Cluster, it rams into thin, hot gas. Gradually, this ram-pressure stripping will tear the gas from its star-forming spiral arms, transforming it into a red-and-dead galaxy.

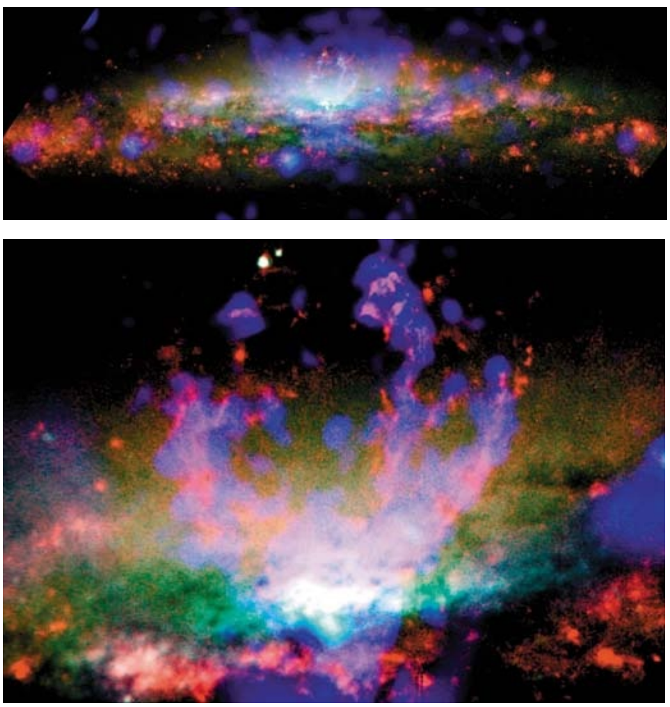
RED & DEAD: ESA / HUBBLE & NASA; FACING DISSOLUTION: HUBBLE LEGACY ARCHIVE / ESA / NASA



▲ **COMA CLUSTER** The hot gas between galaxies in a cluster such as Coma (pictured here) will strip away the gas inside the galaxies that might have formed stars, leaving them aging and sterile.

Stellar Suicide

Suspicion has therefore fallen on other suspects, such as the stars within galaxies. In 2014 Geach and colleagues observed outflows from intense star formation in an extremely compact galaxy. Measuring less than 600 light-years across, this tiny starburst probably arose during a gas-rich galactic merger. Now it's spewing away a third of its gas reservoir.



▲ **GALACTIC FOUNTAIN** A bubble of hot gas rises from the core of a spiral galaxy — perhaps driven by star formation.

Following up with the Institute of Millimeter Radio Astronomy's Plateau de Bure Interferometer in the French Alps, the astronomers observed a Doppler shift in emission lines from ionized magnesium and doubly ionized oxygen, indicating that powerful outflows are blowing gas out of this galaxy at up to 1,000 km/s (2 million mph). Astronomers ordinarily attribute such velocities to fierce winds of radiation from supermassive black holes, but there's no evidence of an active black hole in this galaxy. It must be the stars that are driving the gas out.

In the same way that sunlight can impart momentum to push a solar sail, photons emitted from stars can also drive away gas molecules. The more massive a star, the hotter it is and the greater its *radiation pressure*.

"There's enough energy in stellar radiation pressure to drive quite a lot of gas out of a galaxy," says Geach. He paints a picture where a frenzied burst of star formation converts gas into stars, which in turn produce photon winds that are powerful enough to sweep out the remaining gas and bring star formation to a halt.

So how many stars can a galaxy form before stellar feedback kicks in? It depends how crowded the stars are. Compact galaxies concentrate their star formation rather than spreading it across a large disk, so even a few stars can kick out large amounts of gas. That's not the case for the Milky Way, where the bubbles that individual star-forming regions blow are tiny compared to the scale of our galaxy.

Newborn stars aren't the only ones to create bubbles; dying stars do, too. Intense bursts of star formation produce massive stars that inevitably go supernova. A star cluster might see rapid-fire stellar destruction over the course of just a few million years. While supernova shocks can trig-

COMA CLUSTER: NASA / ESA / HUBBLE HERITAGE TEAM (STSCI / AURA); GALACTIC FOUNTAIN: NASA / CXC / STSCI / UNIV. NORTH CAROLINA / G. CECIL (2) ger starbirth by compressing the surrounding gas, ultimately they heat and clear out gas in *superbubbles* spanning hundreds of light-years. In large galaxies such as our Milky Way, this can create pockets of infertile space. And in smaller galaxies, superbubbles may completely remove all potentially star-forming material, sterilizing the entire system.

If ram-pressure stripping only operates under certain circumstances, and stellar feedback has only limited range in larger galaxies, then only one alternative remains to explain giant, red-and-dead ellipticals: black holes.

Death by Black Hole

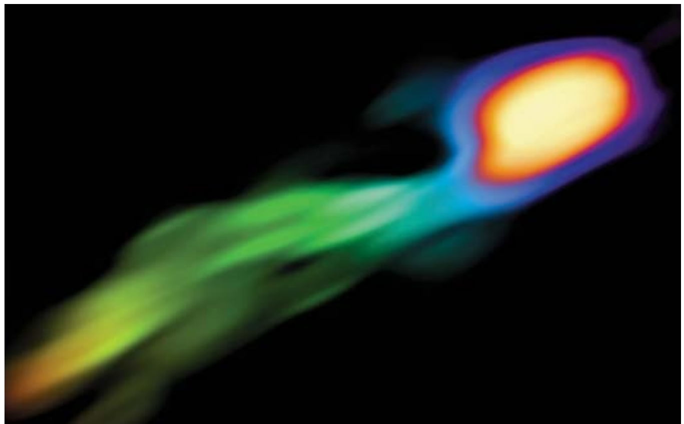
At the hub of most large galaxies is a supermassive black hole millions or billions of times more massive than the Sun. Some are dormant, while others are raging beasts consuming huge amounts of gas. What they don't swallow, they shoot out along magnetic field lines coiled tightly as gun barrels. The material bursts out of the galaxy as powerful jets of charged particles and radiation. While superheated matter spirals inward to await being swallowed or spat out, it settles into a disk, which may launch its own wind. The jets and disk together provide sufficient power to blow a huge bubble into a galaxy's stores of molecular gas — heating or sweeping up gas that might otherwise have formed stars. Molecular hydrogen must be at most a few tens of degrees above absolute zero to condense into stars, so it doesn't take much for the black hole to disturb the gas's delicate thermal condition.

At least, that's the theory. Now, there's some evidence to back it up, from the SDSS project Mapping Nearby Galaxies at Apache Point Observatory (MANGA) that's mapping 10,000 nearby galaxies. Among this immense collection, an international team of scientists led by Edmond Cheung (University of Tokyo) identified a new, rare type of galaxy: *red geysers*. They contain supermassive black holes that are only nibbling on surrounding gas; nevertheless, their low feeding rates are enough to launch a wind that spews into the galaxy.

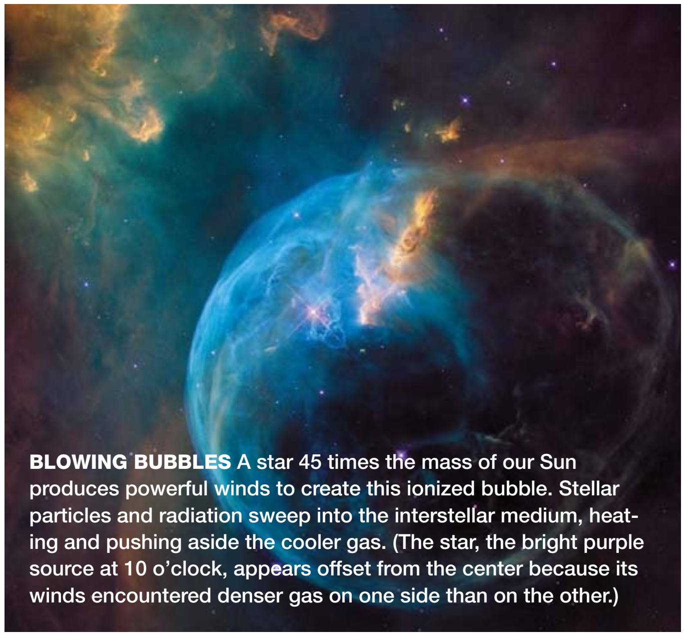
The prototype red geyser observed by Cheung's group, nicknamed Akira, is ripping cool gas from a small companion dubbed Tetsuo. Normally, cool gas would turn into stars, but the red geyser's wind, revealed in velocity measurements of ionized gas billowing out from the central black hole, heats the gas and blows it away, leading the galaxy to turn red.

Many large elliptical galaxies are ensconced within a gaseous halo that, like the intracluster medium, is hot and emits X-rays. Similar halos have been discovered encapsulating spiral galaxies, too — in 2012, for example, Chandra detected an X-ray halo around our Milky Way with a temperature between 1 million and 2.5 million kelvin and a mass between 10 and 60 billion Suns. The halos hold material left over from galaxy formation, as well as gas accumulated from the intergalactic medium. Feedback processes also feed and heat the halos and can maintain a red-and-dead state even after the black hole has become largely inactive.

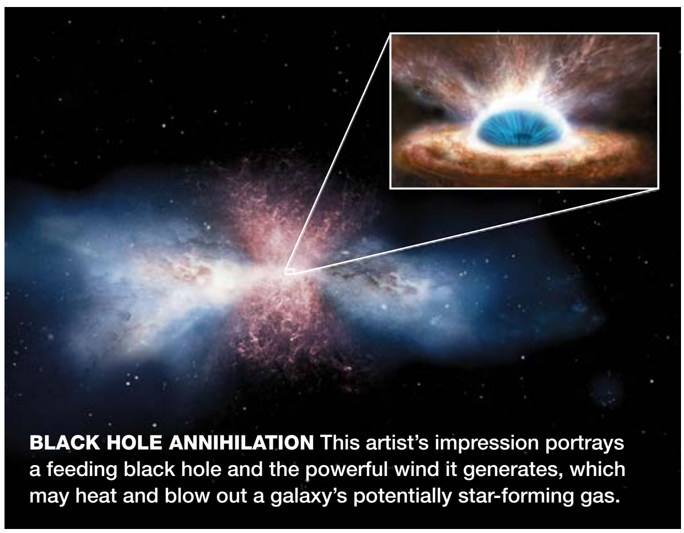
"Once it becomes too strong, the black hole begins to quench its own gas supply," explains Megan Donahue



STARBURST WIND A millimeter-wavelength image from the IRAM Plateau de Bure Interferometer shows cool gas flowing out of a small galaxy at speeds up to 2 million mph. Winds from regions of intense star formation appear to be the culprit.

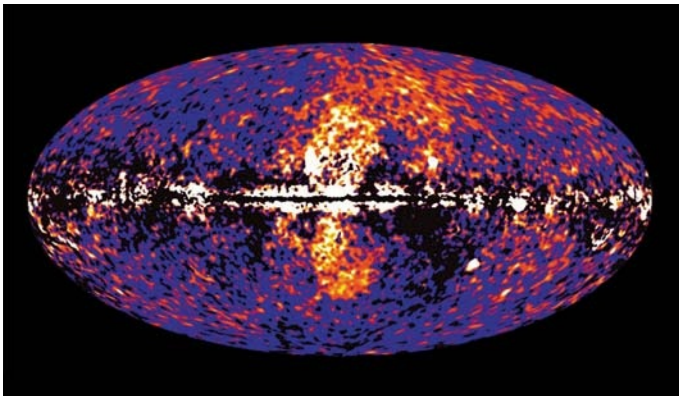


BLOWING BUBBLES A star 45 times the mass of our Sun produces powerful winds to create this ionized bubble. Stellar particles and radiation sweep into the interstellar medium, heating and pushing aside the cooler gas. (The star, the bright purple source at 10 o'clock, appears offset from the center because its winds encountered denser gas on one side than on the other.)



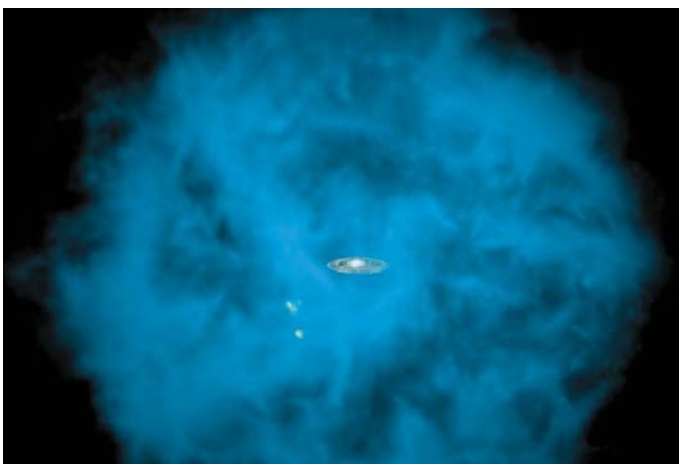
BLACK HOLE ANNIHILATION This artist's impression portrays a feeding black hole and the powerful wind it generates, which may heat and blow out a galaxy's potentially star-forming gas.

STABURST WIND: J. GEACH & R. CRAIN; BLOWING BUBBLES: NASA / ESA / HUBBLE HERITAGE TEAM (STSCI / AURA); BLACK DEATH: ESA / ATG MEDIALAB



FERMI BUBBLES Two giant bubbles on either side of the Milky Way's disk, seen in microwaves, X-rays, and gamma-rays (pictured here), point to a violent event in our galaxy's past: either the ancient antics of the now-quiescent supermassive black hole or a previous burst of star formation and stellar feedback.

SPEEDING STARBIRTH Astronomers found stars forming within the galactic wind pouring out of the galaxy IRAS F23128–5919, depicted here in an artist's conception. The stars, forming at a rate of 15 Suns' worth per year, are flying out of the galaxy along with the outflow, though at a somewhat slower pace.



HOT HALO A huge X-ray-emitting halo of gas surrounds the Milky Way Galaxy and many other spiral and elliptical galaxies.

(Michigan State University), who has a particular interest in how black holes influence star formation.

Cheung estimates that up to 10% of galaxies with quiescent black holes are red geysers — indeed, even our own Milky Way Galaxy fits the bill. Two gigantic cavities above and below its disk, called the Fermi bubbles, are ancient geysers that might be relics of our black hole's rollicking past (*S&T:* April 2014, p. 26).

Astronomers have witnessed similar behavior in elliptical galaxies using the European Space Agency's retired Herschel Space Observatory, which observed the universe at far-infrared wavelengths. Herschel detected cold gas reservoirs in a half-dozen giant elliptical galaxies. Yet the gas wasn't able to cool enough to form stars. Observations by NASA's Chandra X-ray Observatory show that the central black hole was agitating the gas.

The Galactic Phoenix

But Donahue had suspicions that there was more to the story. She began to apply for time on Hubble to search elliptical galaxies for ultraviolet light from hot, young stars.

Her requests for Hubble time were politely turned down. "It was hard," she says of her attempts. "The received wisdom was that [elliptical galaxies] are red and dead, so why would you waste time pointing an ultraviolet telescope at them?"

As it happens, the Cluster Lensing and Supernova Survey with Hubble (CLASH) was studying how 25 massive clusters act as gravitational lenses, magnifying the light of much more distant galaxies. The CLASH project was interested in these magnified galaxies and so observed each cluster — and the ellipticals within them — through 16 different filters, including ultraviolet.

"I was extremely happy because I could have proposed for years and never gotten that kind of coverage," says Donahue. It was worth the wait. Hubble's observations of many of the *brightest cluster galaxies* (BCGs), the most luminous, largest, and exclusively elliptical galaxies at the center of each cluster, revealed a delightful variety of ultraviolet-emitting knots and filaments. Stars are forming at a rate of up to 80 solar masses per year — in galaxies that were presumed to be red and dead — and simulations suggest the central black holes are contributing to the rebirth. Like a phoenix arising from the ashes, the galaxies were being brought back to life. So were they ever really dead, or were they just faking it?

"Quenching [of star formation] might be too simplistic a concept," Donahue acknowledges.

Instead she describes a scenario in which feedback engages in a subtle interplay with a galaxy's gas reservoir. Whether feedback comes from an active black hole or from newborn and dying stars, it may act as a galactic thermostat. First it heats surrounding gas, preventing it from falling onto the black hole or condensing into more stars. But as activity shuts down, the gas has a chance to cool and fall inward, which in turn re-ignites the black hole's activity or forms stars (or both). And so on.

FERMI BUBBLES: NASA / DOE / FERMI LAT / D. FINKBEINER ET AL.; SPEEDING STARBIRTH: ESO; HOT HALO: NASA / CXC / OHIO STATE UNIV. / A. GUPTA ET AL. / M. WEISS

That's what Donahue observed in the BCGs: With feedback stalled, the gas was able to cool and fall back onto the galaxy, some of it forming new stars, the rest heading towards the black hole where it will kick off the next round of activity. Furthermore, although this rebirth was only observed in the BCGs, Donahue suspects that it's at work in other galaxies, too, though harder to observe.

"The physics of cooling, precipitation, infall, and the creation of cold molecular gas is not unique to clusters. It's just that we can see it all in a cluster," she says. "We have all the pieces of the puzzle in front of us."

Perhaps rather than being truly dead, many galaxies instead enter a state of hibernation. Or it may be even more complicated than that: Some forms of feedback may actually resuscitate galaxies rather than kill them. Recent evidence from the European Southern Observatory's Very Large Telescope in Chile has shown new stars born within the very winds that ought to halt their formation. Observing a galaxy collision 600 million light-years away, Roberto Maiolino (University of Cambridge, UK) and colleagues found evidence of infant stars in cold gas that had been swept up by outflows moving through one of the colliding galaxies.

Different feedback mechanisms are also important for different galaxies, so looking for a single cosmic killer may be the wrong way to go about things. In smaller galaxies, stellar outflows and supernovae play a dominant role, and black holes only have to step in once in a while, says Donahue. In larger galaxies, stellar feedback isn't enough. "The black holes have to step up almost all the time."

So are external processes, such as ram-pressure stripping or interactions with other galaxies, ever important? To answer that question, astronomers surveyed 70,000 galaxies in the Cosmological Evolution Survey (COSMOS), where some of the most powerful telescopes on Earth and space have imaged a 2-square-degree patch of sky in the constellation Sextans. The COSMOS team found that internal processes, such as black hole and stellar feedback, quenched most star formation until about 8 billion years ago. Since then, external forces have come to the fore. This result isn't surprising, since star formation and quasar activity were reaching their peaks in the early universe, whereas most clusters took longer to fully form and influence galaxies.

Further evidence for the importance of internal feedback processes in the early universe comes from research led by Sandro Tacchella (Swiss Federal Institute of Technology, Zurich) in 2015. Using the Hubble Space Telescope and the Very Large Telescope, Tacchella and colleagues mapped the distribution of old and new stars in 22 young elliptical galaxies that existed about 10 billion years ago, discovering that their star formation was ending from the inside out, rather than being brought to an end by external processes.

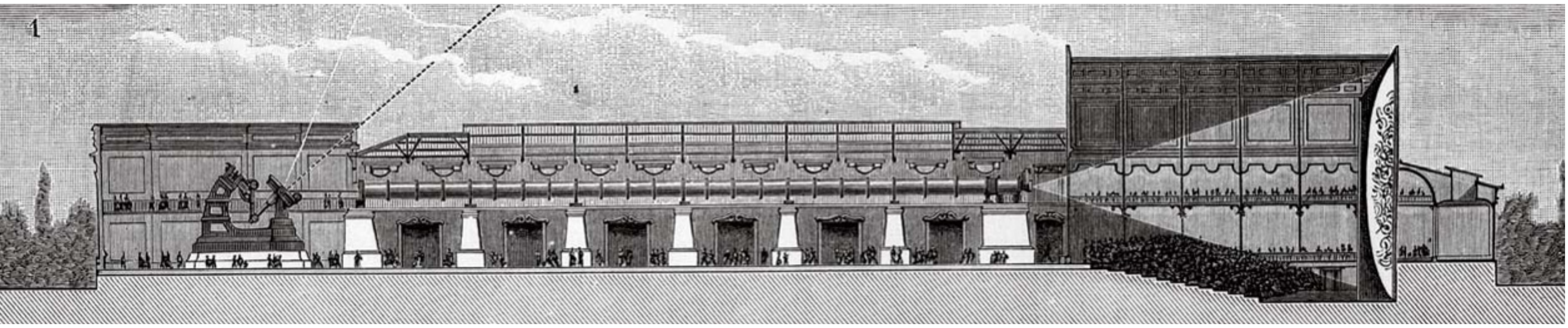
While the identity of the galactic killer may vary in time and space, it's the galaxies themselves that get the last laugh: They're capable of coming back to life, albeit in subdued fashion, hundreds of millions of years after the cosmic crime has been committed. The interplay between quenching mechanisms is going to be crucial to a greater understanding of how galaxies evolve.

■ **KEITH COOPER**, a British freelance science journalist, was editor of *Astronomy Now* magazine from 2006 to 2015. You can follow him via **@21stCenturySETI** on Twitter.

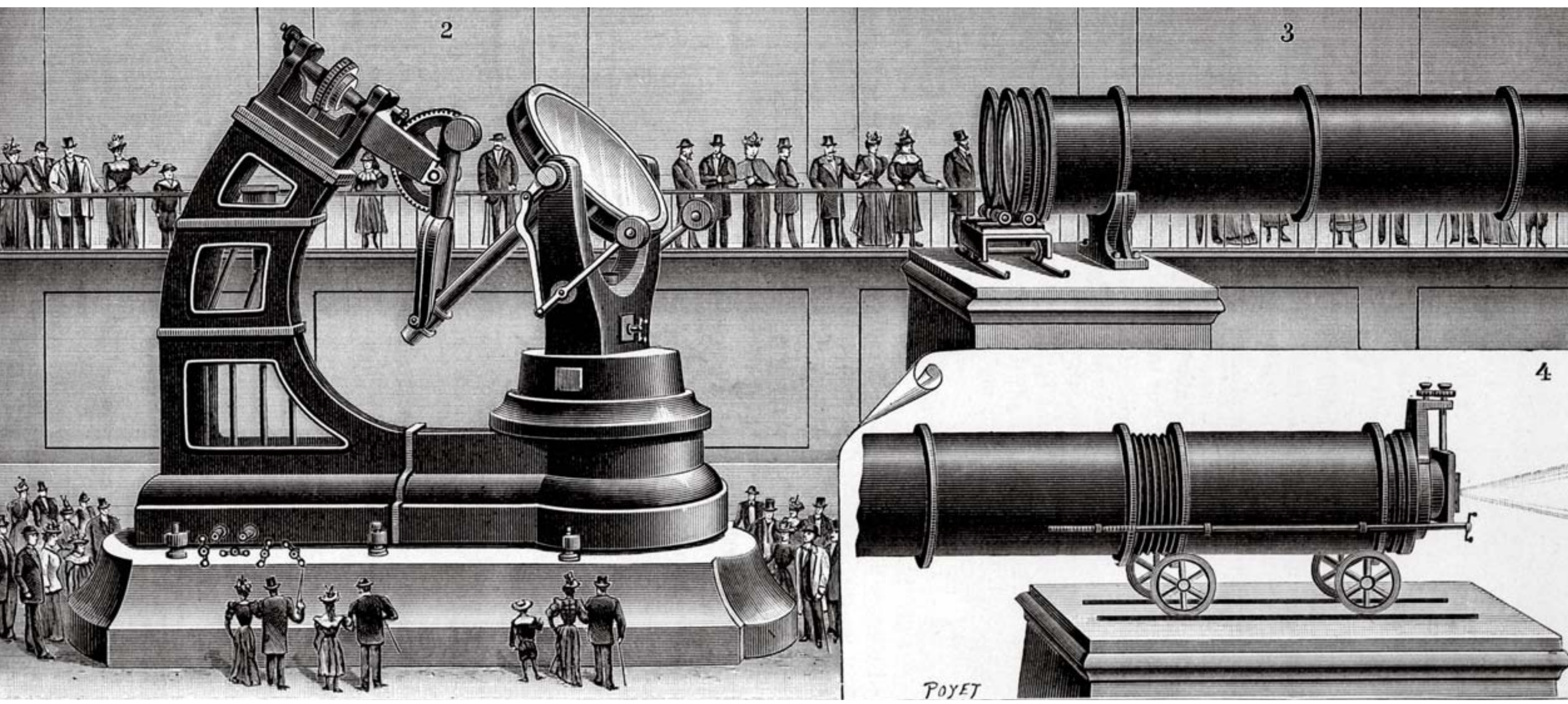
NRAO / AUI / NSF / D. BERRY / SKYWORKS / ALMA (ESO / NAOJ / NRAO)

REBIRTH An artist depicts cold gas clumps that have condensed out of hot intergalactic surroundings to rain back onto a galaxy's supermassive black hole, such as was observed in the brightest galaxy of the cluster Abell 2597. The clumps are fueling both star formation and black hole activity.

 by Jeff Hecht



The Lesson of the Great Paris Telescope



PUBLIC DISPLAY The Paris *Exposition Universelle* of 1900 was meant to be the grandest world's fair of all time, and the Great Paris Telescope was one of its most impressive exhibits. A siderostat mirror followed the turning sky and directed light into a 49¼-inch f/48 refractor, fixed horizontally. Two objective lenses were made, one for visual and one for photographic use. During daytime the Sun could be projected onto an enormous indoor screen in a darkened auditorium, as in the drawing at top.

a new generation of gigantic telescopes should reach first light in the 2020s: the 24-meter Giant Magellan Telescope (GMT), the Thirty Meter Telescope (TMT), and the 39-meter European Extremely Large Telescope (E-ELT). Only then, and after final shakedown and tweaking, will their actual capabilities be known. Their designers and engineers are skating at the edge of 21st-century technology. And in any given era, including recently, the world's most ambitious telescopes have had only a mixed record of reaching their goals (*S&T:* Jan. 2015, p. 60).

So perhaps it's time to remember the largest refractor that was ever built. If you think this was the Yerkes 40-inch, commissioned in 1895 and famous ever since, you're wrong. That was the largest *productive* refractor ever built, and it's still in service (for education and public outreach). The actual largest refractor was the Paris 49-inch, considered a triumph of optics and engineering ... for a while. Its story should be better known.

The 40-inch and 49-inch refractors each came into public view with a grand splash at a world's fair. In 1893 the Warner & Swasey engineering firm displayed the tube and mount for the Yerkes 40-inch at the Columbian Exposition in Chicago. Not to be outdone, at the 1900 *Exposition Universelle* in Paris a French firm debuted an even bigger *working* refractor, with a 1.25-meter (49¼-inch) objective and a gigantic, 60-meter (200-foot) tube. But while the Yerkes telescope became a workhorse, the Great Paris Telescope made only a few noteworthy observations before its owners went bankrupt, no astronomers or institution would buy it, and it was sold off as scrap metal.

What went wrong?

Refractors were already reaching their practical limits. The lenses of the 40-inch were so thick that, it was argued, a larger objective lens would never be worth making, because the increasing thickness of the glass would absorb as much light as the larger aperture would gain. Thinner lenses would require very shallow curves on their surfaces, making the focal length so long that the tube could never be mounted. An ever-longer f/ratio would also be needed to keep chromatic aberration under control.

But at the same time, professional astronomers were wary of gambling on giant reflectors, especially following the disappointment of the Great Melbourne Reflector in Australia. Built in 1868 with a 48-inch speculum-metal mirror, it became widely regarded as an expensive failure.

The Great Paris Telescope was an oddity from the start. It was the brainchild not of an astronomer but a member of the French Parliament, François Deloncle. He wanted to show off French technology and science at the 1900 Paris fair in the grandest manner possible. After talking with Maurice Loewy, director of Paris Observatory, Deloncle decided a record-breaking refractor would be just the thing. (The idea of a 120-inch reflector was considered and rejected.) His quest led to construction of a unique and innovative instrument that initially seemed to work well.

New electric lights blazed across the 1900 Paris Exhibition at night, especially around the Palace of Electricity.

It was the largest refractor ever built, with a 49-inch objective lens. It worked. And then it was sold as scrap.

A Time of Telescopic Transition

Reflectors were the first giant telescopes, Melbourne notwithstanding. As early as 1789 William Herschel had built a 48-inch reflector with a 40-foot focal length for high magnification. But it proved cumbersome to use, and its speculum-metal mirror required frequent repolishing and hence refiguring. In 1845 William Parsons, the third Earl of Rosse, built a 72-inch speculum-metal reflector with a 54-foot tube. His "Leviathan of Parsonstown" gave great views when the weather was good, but that was rare on his Irish estate, and the massive tube was hard to control (it required several assistants pulling ropes while the observer gave orders). And it could only see near the meridian. By 1890 his son had abandoned it for a smaller telescope that was easier to use.

Undeterred by these experiences, the wealthy English amateur Andrew A. Common built a 60-inch silvered-glass reflector in 1890, but he also found its use very cumbersome.

Refractors, however, were in their heyday. Lick Observatory's 36-inch refractor in California set a size record in 1888, and the Yerkes 40-inch in Wisconsin soon surpassed it. Astronomers liked the image quality of refractors; their optics were less difficult to figure well, while early reflector surfaces tarnished quickly and may have scattered more light. But the Yerkes refractor, at 60 feet (18 meters) long and with

LEFT: ENGRAVING BY POYET; ROGER VIOLLET / THE IMAGE WORKS
ABOVE: WIKIMEDIA COMMONS

THE MASTERMIND "The Moon a meter away" reads the caption to a satirical cartoon of François Deloncle and his telescope. The instrument indeed served up impressive lunar views to countless paying visitors. From the *Encyclopédie du Siècle,* published in 1900.

thick lenses even at f/19, seemed to be near a practical limit.

Deloncle had an interest in astronomy, and a desire to put on a Paris fair that would outshine even the 1889 Paris exhibition highlighted by construction of the Eiffel Tower. His dream was to build a telescope with such high magnification that the Moon and planets would look almost within reach.

He found backers to form a company, Société d'Optique, which sold stock to support building a new record-breaker of a refractor — with a 60-meter (187-foot) focal length to magnify images 6,000 times, at least in theory. To build it they chose Paul Gautier, a mechanical engineer whose company had built the mechanical parts for many other French telescopes, including Europe's largest refractor: the 83-centimeter (32-inch) Great Meudon Refractor at Paris Observatory's station in the suburb of Meudon.

A Bold and Different Vision

A magnification of 6,000× would make the moon look only 64 kilometers away, and the extremely long focus would reduce troublesome spherical and chromatic aberration. But astronomers warned that no equatorial mount could handle a telescope 60 meters long. Such an unwieldy tube would flex as it moved, and even if it could be kept rigid the observer would have to move along with the eyepiece at nearly a foot per minute to keep up with the turning of the Earth. Most of all, it would require a 65-meter moving dome that would cost several times more than the telescope itself.

To overcome these problems the group decided to build a novel type of instrument, in which a large movable flat mirror would direct starlight into a stationary, horizontal telescope. The mirroring device, called a single-mirror siderostat, had been invented in 1862 by the French physicist Léon Foucault. A siderostat is a variation on the heliostat, a flat mirror that reflects sunlight in a constant direction as Earth rotates. The siderostat could reflect light from objects in a fairly large swath of sky and keep them fixed in the instrument's field of view.

Foucault's single-mirror design minimizes light loss for faint objects, but in practice it had been most successful for solar astronomy. Gautier likely got the idea from Jules Janssen, the pioneering solar astronomer who discovered helium in the Sun's spectrum; Janssen had built fixed horizontal solar telescopes with siderostats at Meudon.

In the final design, the telescope's key moving element was a flat, 2-meter silvered glass mirror 27 centimeters thick in a fork-mounted siderostat. It directed light into the 1.25-meter, f/48 objective and down a fixed tube.

With astrophotography becoming important, two interchangeable objectives were to be made: one achromatic in the blue-violet wavelengths to which photographic emulsions

BRINGING DOWN THE HEAVENS The 2-meter, flat siderostat mirror rode in an exquisitely smooth equatorial mounting, which could keep an object centered in the eyepiece more than 200 feet away for up for 45 minutes.

CARTOON: AUTHOR'S COLLECTION; PHOTO: © LÉON ET LÉVY / LÉON ET LÉVY / ROGER VIOLLET / THE IMAGE WORKS

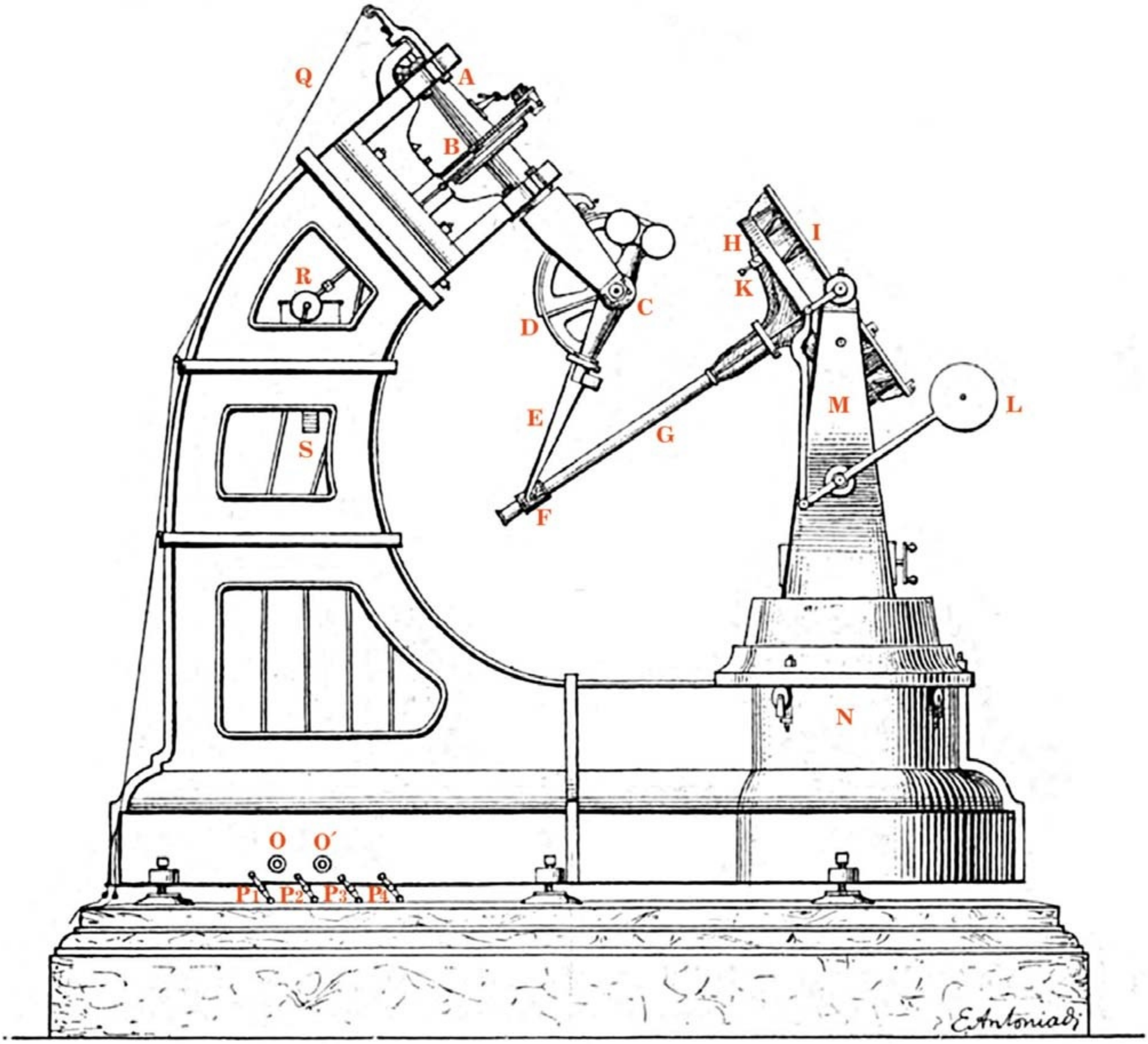


Fig. 2.—The Great Siderostat of Paris, 1900. A, Right ascension axis; B, Right ascension circle; C, Declination axis; D, Declination semi-circle; E, Fork attached to the declination axis; F, Muff held by the fork; G, Brass rod fixed normally to the mirror's cell; H, Cell of the mirror; I, Silver on glass mirror of the siderostat; K, Screw allowing of the mirror being taken out of the cell; L, Counterpoises equilibrating the mirror; M, Great forked support of the mirror; N, Cylinder containing mercury, enabling the floating of the mass M; O, Telescope for reading the divisions of the right ascension circle; O′, Telescope for the declination circle; P_1, Handle for slow horary movements; P_2, Handle for rapid movements in right ascension; P_3, Handle for motion in declination; P_4, Handle for winding the clock; Q, Strings for clamping and unclamping in right ascension; R, Clockwork motion; S, Weight of the clock.

NAMING OF PARTS The astronomer Eugène Antoniadi, famous for his planetary studies, drew this side view explaining the siderostat's components for a magazine titled *Knowledge* (1900). For smooth tracking, the forked mirror support (M) floated in mercury (inside N).

AUTHOR'S COLLECTION

were most sensitive, the other with the usual red-blue correction for visual use. The crown-glass elements of both objectives were to be mounted on rollers so they could be separated from the flint-glass elements for cleaning.

Deloncle also pushed another innovation, encouraging Gautier to use his mechanical skills to develop machines to grind and polish optics to their final shape, without the time-consuming step of final hand retouching necessary for fine astronomical optics (as is still usually required to make fine optics today). This technology, if successful, would promise "an immense step forward" toward refractor objectives as large as 2 meters, wrote the French astronomer Camille Flammarion in a popular article about the Paris Telescope.

Casting the massive, 2-meter siderostat mirror proved difficult. Édouard Mantois, regarded as the world's best maker of large glass blocks, turned down the job as too big. So it went to Georges Despret, director of the Jeumont glassworks. Only one of Despret's 12 casts proved acceptable (ironically, the first). Mantois went on to cast the less unwieldy 1.25-meter flint and crown blanks for both objectives.

Gautier's company had never made optics before and needed nine months to grind the mirror sufficiently flat. Polishing the flat was also time-consuming, because half an hour of cooling was required after every two minutes of

LIGHT PIPE Two hundred feet of steel pipe, weighing more than 10 tons, encircled the light beam on its way to focus. A cloth shroud or even just a few light baffles might have done better; telescope makers have learned to keep as much mass as possible away from the light path to reduce distorting thermal effects. Observers thought that the city air was causing poor images, but the massive, unventilated metal tube could not have helped.

polishing to avoid surface distortions. Grinding the objective lenses also went slowly; only the photographic lens was finished when the telescope was installed for the exhibition's opening in April 1900.

At the *Palais de l'Optique*

The great telescope was the centerpiece of the exhibition's "Palace of Optics," located right by the Eiffel Tower. It also included a giant kaleidoscope, a hall of mirrors, and a hall that could hold more than 3,000 people for lectures on astronomy. A 60-meter horizontal tube was built in the Foucault Gallery, made of 24 cylinders of 2-mm sheet steel 1.5 meters in diameter. Resting on pillars towering 7 meters tall and running the length of a dedicated exhibit space, the tube weighed 21,000 kilograms. Stairs led up to viewing balconies that ran the length of the tube on both sides. The finished photographic objective lens was mounted at the north end. A moveable section of tube at the south end let operators select an eyepiece for visual use or a plate holder for photography. The unfinished visual objective was displayed elsewhere.

The siderostat stood 10 meters tall at the north end of the Foucault Gallery in the Paul Gautier Room, under sections of roof and walls that could be slid to the north and south to expose the sky. The base of the mirror's pivoting fork mount floated in 60 liters of mercury to smooth its motion. A clock drive kept the selected celestial object in the center of the visual field. However, objects rotated around the center as the mirror turned to follow the sky, so photography required another clock drive to rotate the plate holder.

As displayed, the whole telescope cost an estimated 1.4 million francs: roughly $300,000 at the time, or $8.2 million today, and that did not include final installation in an observatory. By comparison, the Carnegie Institution of Washington would spend a similar amount, about $10 million in today's dollars, building the immensely productive 100-inch Hooker reflector in Mount Wilson Observatory. The 100-inch saw first light in 1917 and opened the way for 20th-century astronomy.

About 50 million visitors came to the Paris exhibition. The public lined up to see new types of electric lighting and appliances, talking movies, escalators, and diesel engines as well as the giant telescope. But many astronomers were skeptical of its unorthodox design, particularly after reading exaggerated press reports that it could resolve one-meter objects on the Moon! Deloncle himself tested the telescope on the first clear night when the Moon was observable with the siderostat. He wrote, "On the square ground-glass plate before our eyes [in the plateholder] the moon's image gradually crept up from one corner until it had overspread the glass completely. And there we stood in the centre of Paris examining the surface of our satellite, with all its craters and valleys and bleak desolation! I had won the day!"

Charles P. Butler was quite impressed after an observing session arranged by Deloncle. Even during the exhibition, he wrote in *Nature* (Oct. 11, 1900), the telescope was being used for astronomy every clear night. Opening the roof took six to eight people, he reported, but only two were needed for observations: one adjusting the siderostat and the other adjusting the optics at the eyepiece end. The two communicated over a telephone line. Considering that even the lowest-power eyepiece gave 500× and a field of view only 3 arcminutes wide, Butler wrote "it is astonishing how quickly an object is obtained after the setting of the circles" on the siderostat. Once the object was found, interior lights were turned off for photography or viewing. The siderostat tracked so well that an object would stay in view for 45 minutes.

Butler noted that the Ring Nebula in Lyra, M57, looked better in the telescope than in a conventional 36-inch. It also was bright enough for detail to be seen in the highly magnified image. Observations were possible even with hundreds of people in the building and bright outdoor lighting on adjacent buildings. At midnight when public viewing ended, Eugène Antoniadi of Juvisy Observatory would take over to observe nebulae. Butler praised both the optical quality and the clock drive of the great telescope and hoped that after the exhibit, it would find a new home "at some station out of the city, where the purity of the atmosphere will allow of its power being efficiently used."

A few other astronomers reported making observations. Antoniadi found that the refractor's large aperture made it "wonderfully efficient on nebulae." He also observed Venus. Charles Le Morvan took several photos of the Moon that nearly filled glass plates two feet square. Théophile Moreux sketched the fine details of a sunspot seen by projection.

But overall, the great refractor's scientific output was suspiciously slight. Everyone who used it expected that the seeing would be much better outside the city. But the image quality must surely have been affected by the light passing through 200 feet of steel tubing with no provision for ventilation to prevent slight air-temperature differences ("tube currents," a bane of high-power observing) along the way.

To Flammarion, the telescope's success was further evidence that "the future lies in the development of refracting telescopes rather than reflecting." Yet that was not to be.

Ticket sales at the exposition failed to recover the Société d'Optique's investment. The company put the telescope up for sale after the exposition closed, but no one bought it. Most astronomers remained skeptical of the design and its limitations; for one thing, it could view only part of the sky. It had been built for exhibition rather than for observatory use, so changes would be required to meet astronomers' needs, and success may have seemed uncertain. Then there was the instrument's sheer size. It was one thing to build a world's-fair exhibit for paying viewers unaware perhaps of subtle problems, but another to retool such a giant instrument for professional needs in a working observatory without breaking the bank.

The telescope remained at the exposition site until 1909, when both the Société d'Optique and Gautier's optical firm filed for bankruptcy.

No buyer for the instrument came to the bankruptcy auction. So the tube and other mechanical parts were sold as scrap. The siderostat mirror went to Paris Observatory, where it has long been displayed in the history building. The finished flint and crown elements of the photographic objective went to the observatory cellars, where they lay forgotten in wooden packing boxes until about 2002 when Françoise Launay of the Paris Observatory helped unearth them. The fate of the visual objective remains unknown.

More than a century after it was disassembled, it's hard to assess the great refractor's actual performance. The heavy lenses have not been studied in detail with modern instruments, but Launay wrote in the *Journal of Historical Astronomy* (p. 459, vol. 38, 2007) that the glass looks clear and shows few bubbles. Although the instrument's performance suffered from its location, she says that observations by Antoniadi and a handful of others show that it indeed had astronomical value.

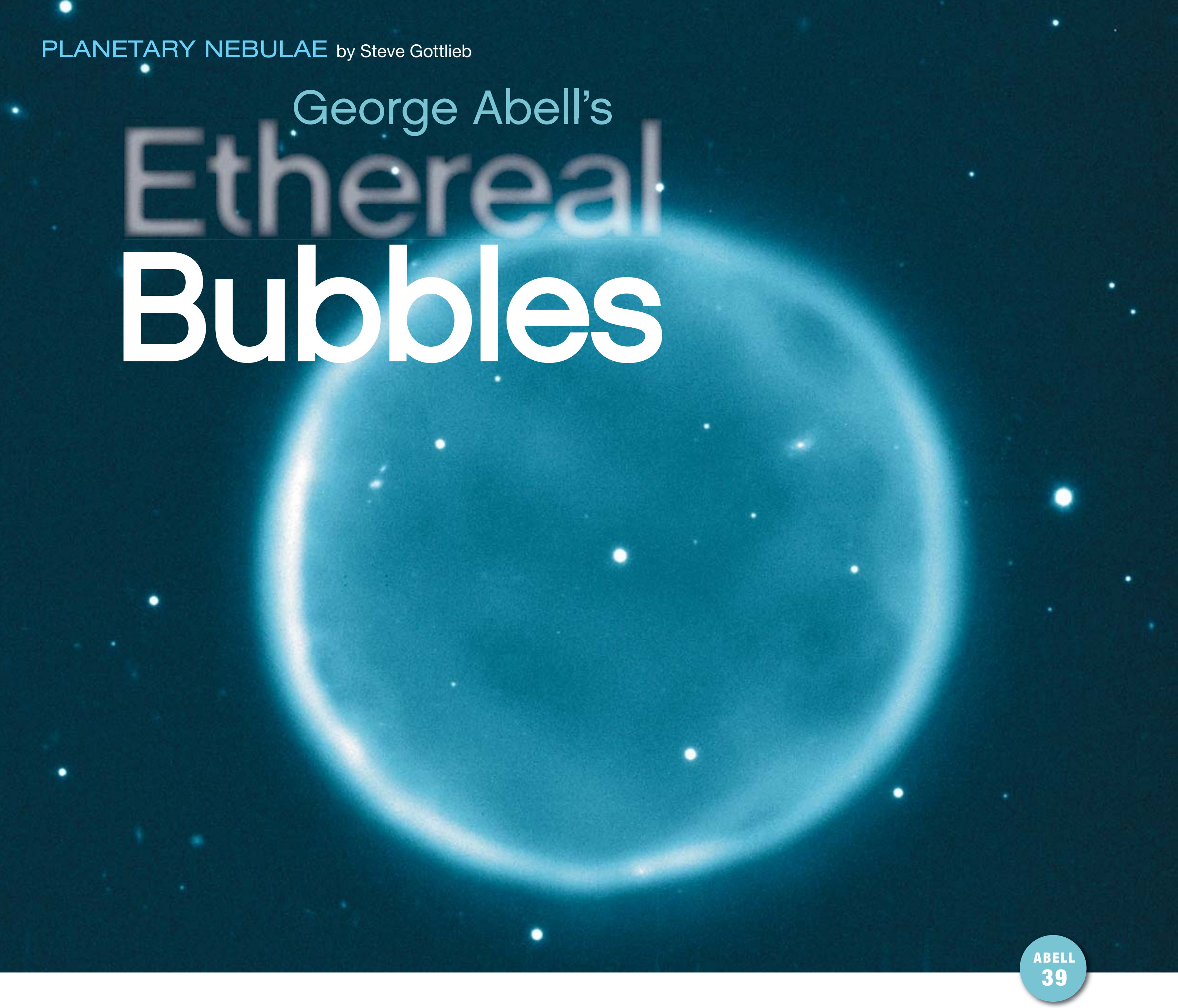
> Perhaps the limits of a technology can be found only by exceeding them.

The Paris telescope proved a technological dead end, the swan song for large refractors. Perhaps the limits of a technology can be found only by exceeding them. By the time it was taken apart in 1909, George Ellery Hale already had a 60-inch reflector operating successfully on Mount Wilson and had begun on the 100-inch — which opened the age of giant reflectors, with never another look back.

■ **JEFF HECHT,** a Fellow of the Optical Society, covers optics and lasers for magazines including *New Scientist* and *Optics & Photonics News.* His books include *Understanding Lasers* and *City of Light: The Story of Fiber Optics.* His father gave him his first telescope when he was 10, and he's been fascinated by light and the sky ever since.

 by Steve Gottlieb

George Abell's Ethereal Bubbles



Are you up for a deep-sky challenge? Start with this list of planetary nebulae.

▲ **SPHERICAL SYMMETRY** This image of Abell 39 was taken with the WIYN Observatory's 35-meter telescope at Kitt Peak National Observatory through a blue-green filter that isolated the light emitted by doubly ionized oxygen at the wavelength of 500.7 nanometers.

GEORGE JACOBY / WIYN / NOAO / NSF

While a Caltech graduate student in the early 1950's, George O. Abell was given a research assistantship to work on the renowned *National Geographic Society–Palomar Observatory Sky Survey* (POSS), taking blue- and red-sensitive plates with the 48-inch Schmidt telescope. Before the photographic plates were sent down to Caltech for approval, Abell made a preliminary check and quickly jotted down notes on new low surface brightness planetary nebulae and globular clusters.

In 1955 he published a list of 73 "Abell" planetaries. He followed this list up with a comprehensive study titled "Properties of Some Old Planetary Nebulae," which he published in the *Astrophysical Journal* in 1966. Abell's final catalog included 86 objects north of –35° declination. A few turned out to be plate flaws and imposters (galaxies and nebulae). Another four had been previously discovered visually and already carried NGC or IC designations, but hadn't been recognized as planetary nebulae.

But why had William and John Herschel, along with other keen-eyed 19th-century visual observers who scoured the heavens for nebulae, missed the remaining objects? Many of the Abells are highly evolved planetaries with bloated spherical shells, anemic surface brightnesses, and dim central stars. The collection poses a formidable observing challenge, regardless of aperture or experience, and tracking down over half the list will require careful planning, excellent sky conditions, and dogged persistence.

The stars that center planetary nebulae spent part of their lives as red giants. As these stars transitioned from the Asymptotic Giant Branch (AGB) to a white dwarf, their ultraviolet radiation ionized the surrounding gaseous shells. As the electrons in the shells recombined, they emitted visible light, primarily in the greenish wavelength of doubly ionized oxygen (500.7 nm). The planetary nebula stage is fleeting, lasting only a few tens of thousands of years, for the shell gradually expands to several light-years and disperses into the interstellar medium.

Fortunately there's a powerful observing tool for planetary nebulae — the O III line filter, which selectively transmits the wavelength of doubly ionized oxygen while suppressing background light pollution and skyglow. Because of the contrast boost, O III and UHC-style narrowband filters are essential tools in chasing ghostly planetaries.

I've selected 13 summer favorites that will test your observing skills using a 10-inch or larger scope (though all have been spotted through an 8-inch aperture under pristine skies). As a general guideline, start with fairly low magnification (~70× to 100×) and an O III filter to identify the target. Unfiltered observations at higher power may reveal elusive details including the central star. I used my 18-inch reflector for these descriptions, as well as detailed computer-generated finder charts to pinpoint the locations.

Abell 39 is a beautifully symmetric gaseous bubble located 4.7° southwest of Zeta (ζ) Herculis, the southwestern star of the distinctive Keystone asterism. Shining at 13th-magnitude, its light is spread over a 3′ diameter and the surface brightness is quite low. It was faintly visible unfiltered at 115× as a round glow over 2.5′ in diameter with a 14th-magnitude star just off the western side. The disc was crisply defined with an O III filter, and the rim contained a couple of slightly brighter narrow arcs, most noticeably along the eastern edge. The 15.7-magnitude central star occasionally winked at 283× in moments of steady seeing.

Distances and physical diameters of planetaries have long been notoriously difficult to pin down, but a new technique developed by astronomers David Frew and Quentin Parker (University of Hong Kong) using H-alpha surface brightness and angular size yields an impressive diameter of 5.5 light-years and a distance of 5,500 light-years for Abell 39 with an uncertainty of only 18%.

Abell 43 lies in northern Ophiuchus, roughly midway between 2nd-magnitude Alpha (α) Ophiuchi (Rasalhague) and 3.7-magnitude 72 Ophiuchi. In the eyepiece field of view, the planetary lines up with a 9th-magnitude star 4′ northwest and two 10.5- and 11th-magnitude stars at a similar distance southeast.

Viewing at 175× with a narrowband filter, I found a moderately large circular glow, perhaps 70″ in diameter, with a fairly smooth surface brightness. I easily spotted the 14.7-magnitude central star without a filter; two dimmer stars appeared at the southern and eastern limb. I saw no sign of the planetary's intricate network of woven filaments.

Abell 43's unusual nucleus is a pulsating hydrogen-deficient white dwarf. An investigation published in *Astronomy & Astrophysics* in 2007 identified pulsations at six different vibration frequencies with periods from 40 to 100 minutes. This instability is driven by the ionization of carbon and oxygen in the star's envelope in a process called the *Kappa mechanism* (κ-mechanism).

Abell 50 was first discovered by William Herschel while sweeping for nebulae on July 8, 1788, and later cataloged as

▲ **PULSATING WHITE DWARF** Small changes in density within the ionization zone of the star at the center of Abell 43 produce associated changes in opacity. When density increases, the ionization zone becomes more opaque and absorbs more energy from the stellar interior. The ionization layer subsequently heats and expands, then drops back to its previous density. These expansion and collapse cycles set up an oscillation pattern, causing the white dwarf's outer layers to pulsate.

▲ **CYAN CIRCLE** With a low-power eyepiece, Abell 50 will appear stellar, but you might be able to detect a slight blue-green color. Use an O III filter and higher magnification to reveal the nebula's circular structure.

ABELL 43: ED WALENDOWSKI / ADAM BLOCK / NOAO / AURA / NSF; ABELL 50: STEFAN BINNEWIES / JOSEF PÖPSEL

▲ **BLUE BOX** For this 25′ × 25′ field of view, Don Goldman applied O III, H-alpha, and S II filters to bring out the structure of Abell 65. RGB data were also gathered for star colors for a total exposure time of 13 hours.

NGC 6742. You'll find this compact 13.4-magnitude planetary in southern Draco, about 1.6° north-northwest of 5th-magnitude 16 Lyrae.

With a filter-equipped low-power eyepiece, Abell 50 showed as a bright 30″ disc, a mere 3′ northeast of an 8.8-magnitude star. Upping the power to 325× exposed subtle details — the planetary was a bit distended east-west and seemed weakly annular due to an augmented fringe. A 15th-magnitude star lies just off the north side and occasionally a 16th-magnitude star emerged along the west edge.

Abell 55 is set in a wonderfully rich section of the Milky Way, 2.7° north-northeast of 3.4-magnitude Lambda (λ) Aquilae. In the same region you'll also find the brighter planetaries NGC 6741, NGC 6772, and NGC 6778. Abell reported a discouragingly faint photographic magnitude of 15.4, but don't be deterred by that. Visually, Abell 55 appears about two magnitudes brighter, and that's typical for his planetaries.

Although I vaguely detected Abell 55 without a filter, I noticed a significant contrast gain with both O III and narrowband filters. At 160× I could hold it continuously as a fairly uniform oval, extending 45″ × 35″ from northeast to southwest and fading a bit at the periphery. Unfiltered, the field was chock-full of dim stars with several tightly hugging the edge.

Abell 65 is an unusually elongated planetary in eastern Sagittarius, just following a string of four 10th-magnitude stars. Based on its diffuse elliptical appearance, Abell 65 was mistaken for a remote galaxy and appears in several galaxy catalogs, so don't be confused if you find it identified as PGC 63654 in some amateur sky-plotting software.

Using 115×, I found a moderately bright boxy oval, extending 1.8′ × 0.8′ wide. A 13th-magnitude star is pinned to the southeast end, and at high power the 15th-magnitude central star popped into view.

A study published in the *Monthly Notices of the Royal Astronomical Society* in 2013 characterized Abell 65 as a unique double-shelled planetary with a binary central star. The shells have a bipolar, peanut-shaped structure resulting from two ejections of fast stellar wind perpendicular to the orbital plane of the binary star.

Abell 70 is one of my favorite summer objects because of a remarkable juxtaposition — a background radio galaxy shines through the halo! At an approximate distance of 250 million light-years, PGC 187663 is over 10,000 times as distant as the planetary. Since the nucleus of the galaxy is visible directly through the nebula's rim, Abell 70 has been dubbed the "Diamond Ring" planetary. You'll find this planetary in eastern

Aquila, 4.6° northwest of 3.8-magnitude Epsilon (ε) Aquarii.

At 175× Abell 70 appeared as a crisp-edged disc roughly 35″ across. When I upped the power to 283×, a slightly brighter strip around the periphery formed a weak ring. The nucleus of the 15.5-magnitude galaxy showed as a small bump along the north-northeast edge, but with averted vision it extended to a 20″ × 6″ sliver tilting west-northwest.

I've only viewed the planetary's dim nucleus through Jimi Lowrey's 48-inch reflector. A study conducted in 2012 using the Gemini South telescope identified the central star as an ultra-rare barium-rich binary, consisting of a 17.8-magnitude G8-class star and a UV-emitting 20.4-magnitude white dwarf. While still on the AGB, the (now) white dwarf polluted its main sequence neighbor with a dense stellar wind including heavy elements like barium.

Abell 72 is a somewhat ragged bubble 2° southeast of 4.4-magnitude Delta (δ) Delphini and just 2′ east of a distracting 8th-magnitude star. My O III filter partially masked the star and showcased a well-defined 1.7′ disc with a slightly darker interior. A 12th-magnitude star is attached to the southwest side, and another is just beyond the east end. At high power the 15.5-magnitude central star flickered in and out of view with the seeing.

PGC 65491, a wraithlike 16th-magnitude galaxy, is a scant 2′ south-southeast of Abell 72. I was unable to catch it in my 18-inch but saw it as a feeble smudge, just brighter than the background sky, through my 24-inch.

Abell 75 is a snap to locate less than 1° east-northeast of 2.5-magnitude Alpha Cephei (Alderamin), the brightest star in its constellation, and 15′ east-southeast of a 7.4-magnitude star. Abell reported the photographic magnitude at a dismal 17.0, but the visual magnitude is closer to 14.5.

First discovered by William Herschel on October 15, 1794, Abell 75 is also cataloged as NGC 7076. Abell missed the news about that earlier discovery, however. In fact, even the 1992 Strasbourg-ESO *Catalogue of Galactic Planetary Nebulae* and the 2000 version of Luboš Kohoutek's *Catalogue of Galactic Planetary Nebulae* still identify the planetary as Abell 75 rather than NGC 7076.

▲ **DIAMOND RING** The bright sparkle at the north-northwest edge of Abell 70's nebulous ring comes from PGC 187663, a background radio galaxy some 250 million light-years from Earth. Abell 70, an estimated 13,500–17,500 light-years distant, lies comparatively close to us.

ABELL 70: MIKE DURKIN AND LILY JOE / ADAM BLOCK / NOAO / AURA / NSF; ABELL 72: JAY BALLAUER / ADAM BLOCK / NOAO / AURA / NSF; ABELL 78: ADAM BLOCK / NOAO / AURA / NSF

▲ **FAINT COMPANION** Finding Abell 72 southeast of Delta Delphini is probably challenge enough, but if you want to level up your galaxy-hunting skills, try for the dim galaxy PGC 65491 just 2 arcminutes south-southeast of the nebula's shell.

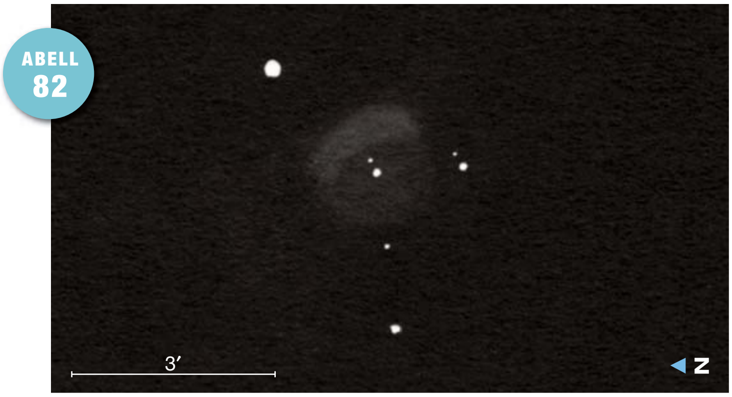
▲ **RENAISSANCE** Abell 78 is considered a "Born-Again" planetary. In rare cases, after the star at the center of a planetary nebula burns through its helium and hydrogen and collapses, helium fusion reignites in the star's outer layers. This fresh nuclear activity produces a second, stronger wind that blows stellar material through the existing shell of the nebula.

The planetary appeared as a slightly elongated, moderately faint disc 40″ to 45″ across. The shape was irregular at 225× with a partial ring formed by a brighter eastern side. The field is rich in faint stars, with two 14th- to 15th-magnitude stars lodged on the north and east edge and a couple of 14th-magnitude stars 1′ and 2′ north.

Abell 78 lies in the southeast corner of Cygnus, 3.5° northwest of the close binary Mu (μ) Cygni and conveniently centered between two 7.4- and 8.2-magnitude stars 8′ northwest and 8′ southeast. A 1.5′ diameter shell was easily seen at 115× surrounding a 13.3-magnitude central star. The disc appeared slightly uneven but was otherwise featureless.

Abell 78 is a member of the rare class of "Born-Again" planetaries. A rebirth of sorts occurred for the nebula after hydrogen and helium burning had ceased in its core and its visual outer envelope was ejected. When the nebula's progenitor star descended onto the white dwarf track, a shell of helium reached

▲ **WHITHER THE WINGS** This unfiltered view of Abell 79 was captured through a 27-inch f/4.2 Newtonian reflector at 419×. Although aperture helps, the author recommends using an O III filter to observe the uneven surface brightness. Deep-sky images suggest that this planetary has wing-like extensions, but they're very difficult to find visually.



▲ **IMPOSTER** The 13th-magnitude star shining near the center of Abell 82 is not responsible for the dumbbell-like shape of this planetary. Rather, it's caused by the 15th-magnitude star 18 arcseconds to the northwest. This sketch shows the view through the eyepiece of a 16-inch f/4.5 Newtonian reflector at 150× with an O III filter.

critical mass and ignited fusion into carbon and oxygen. This "final helium flash" ejected hydrogen-deficient clumps inside the old planetary. The star's temperature decreased, and it returned to the AGB. Abell 78's born-again event is thought to have occurred between 600 and 1,100 years ago.

On deep images, **Abell 79** is an unusual elliptical ring with extensions that morph into thin outer arcs or wings. The orbit and interaction with the binary central star played a crucial role in sculpting its bipolar morphology. This celestial butterfly hovers in a Lacerta star field, 2.7° southeast of 4.2-magnitude Epsilon (ε) Cephei.

Through an O III filter at 115×, Abell 79 is an irregular oval roughly 50″ × 40″ and it dips slightly in brightness towards the center. The rim was a bit uneven and slightly more concentrated on the southeast side, but there was no evidence of the wings. A couple of 14th- and 15th-magnitude stars cling to the south side, and a similar star is pinned against the east edge.

Abell 81, also known as IC 1454, was originally discovered by accomplished British amateur William Denning in 1891 while he was comet hunting in the northern reaches of Cepheus, 3.9° northwest of 3.2-magnitude Gamma (γ) Cephei. Using his 10-inch reflector, Denning reported finding "rather a difficult object, except on a good night, though I picked it up with a power of only 40. It is noteworthy as being situated in the midst of a region containing very few nebulae."

A glaring 7th-magnitude star is parked 4′ east, but the O III filter suppressed the star and revealed a faint 30″ disc. Using a narrowband filter at 225×, the planetary appeared fairly bright with a crisply defined periphery. A relatively thick rim enclosing a small, weaker center formed a delicate smoke ring. Two 14th-magnitude stars are just off the northeast edge, and a 13.4-magnitude star rests 1′ southeast.

Abell 82 lies 3.7° southwest of 2.4-magnitude Beta (β) Cassiopeiae (Caph), the western star in the constellation's distinctive W asterism, and 1.5° west-northwest of the gorgeous open cluster NGC 7789 ("Caroline's Rose"). The planetary was faintly visible unfiltered as an irregular, diffuse patch, roughly 1.5′ across. When I attached the O III filter, the outline sharpened up and the contrast increased considerably. Images display an apple-core body with lobes extending both northwest and southeast (a mini-version of M27), though visually only the northwest end seemed enhanced.

A 13th-magnitude star is superimposed just southeast of center and masquerades as the central star. A more careful look disclosed the 15th-magnitude central star only 18″ to its northwest. I later checked the professional literature and found the ionizing source is somewhat of a mystery. The 15th-magnitude star turns out to be a *K*0-type orange subgiant, and the true central star is likely an invisible companion.

Abell 84 is tucked into the southwest corner of Cassiopeia less than ½° southwest of a 6.5-magnitude star and centered within a 12′ pentagon formed by five 10th-magnitude stars. An 11th-magnitude star abuts the east edge — look for a dim glow spreading to its west.

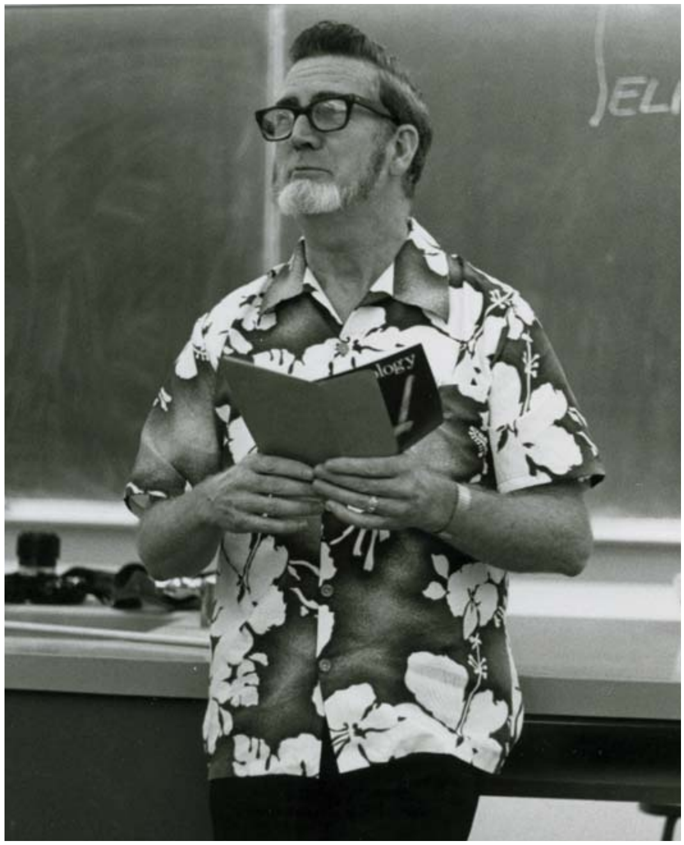
I found the best view using a combination of 115× and an O III filter, which yielded a 4-mm exit pupil. The moderately

▲ **DIMMER YET** Abell 84 is a ghostly apparition in the eyepiece. Look for the 11th-magnitude star on the east edge of the shell. The faint nebulosity extends west and southwest of the star.

SKETCHES: UWE GLAHN (2); ABELL 84: SHARON KEMPTON & KAREN BRISTER / ADAM BLOCK / NOAO / AURA / NSF bright disc was irregularly round and slightly brighter along the eastern rim, particularly near the embedded star.

It's fair to say that tracking down Abell planetaries is not the easiest task in the universe. It is, however, one of the more rewarding. Good planning makes success more likely. Know where to search in the sky, be ready to switch up your eyepieces, and have an O III or UHC filter handy on the observing table. Find some dark skies and take your time, and you'll find the views well worth the effort.

■ Last year, Contributing Editor and deep-sky fanatic **STEVE GOTTLIEB** completed a 40-year project to observe the entire NGC (7,500 objects), but he's still working on the Abell list.



SKY & TELESCOPE ARCHIVES

▶ **OUTSTANDING IN THE FIELD** George O. Abell (1927–1983) earned his Ph.D. from the California Institute of Technology, where he studied the distribution of galaxy clusters based on POSS plates. He was passionate about science education and served as president of the Astronomical Society of the Pacific and chairman of the American Astronomical Society Education Committee. He also served as chair for the Astronomy Department at UCLA, where he was considered an inspired and brilliant lecturer by students and faculty alike.

FURTHER READING

In 1977, Spencer Weartt conducted an oral history of George Abell for the American Institute of Physics. Read more at **https://is.gd/abellhistory**. For the full Abell catalog, see **https://is.gd/AbellPNeCat**.

Summer Abell Planetaries

Object	Alt ID	Mag(v)	Central Star Mag (v or photographic)	Size	RA	Dec.	Distance (light-years)
Abell 39	PN G47.0+42.4	12.9	15.7	162″ × 162″	$16^h\ 27.6^m$	+27° 55′	5,500
Abell 43	PN G36.0+17.6	14.7	14.8	80″ × 74″	$17^h\ 53.5^m$	+10° 37′	7,700
Abell 50	PN G78.5+18.7	13.4	20.0 pg	32″ × 32″	$18^h\ 59.3^m$	+48° 28′	13,000
Abell 55	PN G33.0-05.3	13.2	20.5 pg	57″ × 52″	$19^h\ 10.5^m$	–02° 21′	10,000
Abell 65	PN G17.3-21.9	13.8	15.4	134″ × 72″	$19^h\ 46.6^m$	–23° 08′	4,700
Abell 70	PN G38.1-25.4	14.7	17.8	45″ × 38″	$20^h\ 31.6^m$	–07° 05′	20,000
Abell 72	PN G59.7-18.7	12.7	16.1	134″ × 118″	$20^h\ 50.0^m$	+13° 34′	6,500
Abell 75	PN G101.8+08.7	14.5	17.2 pg	67″ × 47″	$21^h\ 26.4^m$	+62° 54′	6,800
Abell 78	PN G81.2-14.9	13.4	13.3	113″ × 88″	$21^h\ 35.5^m$	+31° 42′	6,600
Abell 79	PN G102.9-02.3	15.3	18.7 pg	59″ × 49″	$22^h\ 26.3^m$	+54° 50′	11,000
Abell 81	PN G117.5+18.9	14.4	18.8 pg	34″ × 31″	$22^h\ 42.4^m$	+80° 27′	16,300
Abell 82	PN G114.0-04.6	12.7	14.9	34″ × 31″	$23^h\ 45.8^m$	+57° 04′	5,800
Abell 84	PN G112.9-10.2	13.0	13.0	146″ × 114″	$23^h\ 47.7^m$	+51° 24′	6,400

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

OBSERVING
July 2017

1 EVENING: The waxing gibbous Moon forms a broad triangle with Jupiter and Spica in the southwest.

3 EARTH is at aphelion, farthest from the Sun for 2017 (152,092,504 kilometers).

3–7 DAWN: Brilliant Venus shines about 7° south (lower right) of the Pleiades low in the east.

6 ALL NIGHT: Golden Saturn shines about 3° below the waxing gibbous Moon.

11 DAWN: Venus, low in the east, lines up with the Pleiades above it and orange Aldebaran below it.

13, 14 DAWN: Venus is 3° north (upper left) of Aldebaran, the brightest star in Taurus.

20 DAWN: Find the slim crescent Moon about 3° or 4° lower right of Venus.

24 DUSK: The super thin waxing crescent Moon cuts the sky 5° lower right of Mercury, very low in the west soon after sunset. Bring binoculars. Can you see fainter, twinkly Regulus, just to Mercury's upper left?

25 DUSK: Just 1° separates Mercury and Regulus now. Find them very low in the west in evening twilight, about 8° lower right of the slim crescent Moon. Bring binoculars.

27 MORNING: The modest but long-lasting Delta Aquariid meteor shower peaks this morning. This shower is best observed from southerly latitudes; see page 51.

28 DUSK: The thicker waxing crescent Moon hangs 3° above or upper left of Jupiter. Blue-white Spica twinkles about 8° to their left.

As NASA's Juno spacecraft passed over Jupiter's south pole on February 2, 2017, it captured this dramatic image of circular polar storms and churning clouds.

NASA / JPL-CALTECH / SWRI / MSSS / JOHN LANDINO

JULY 2017 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
July 1
00:51 UT

FULL MOON
July 9
04:07 UT

LAST QUARTER
July 16
19:26 UT

NEW MOON
July 23
09:46 UT

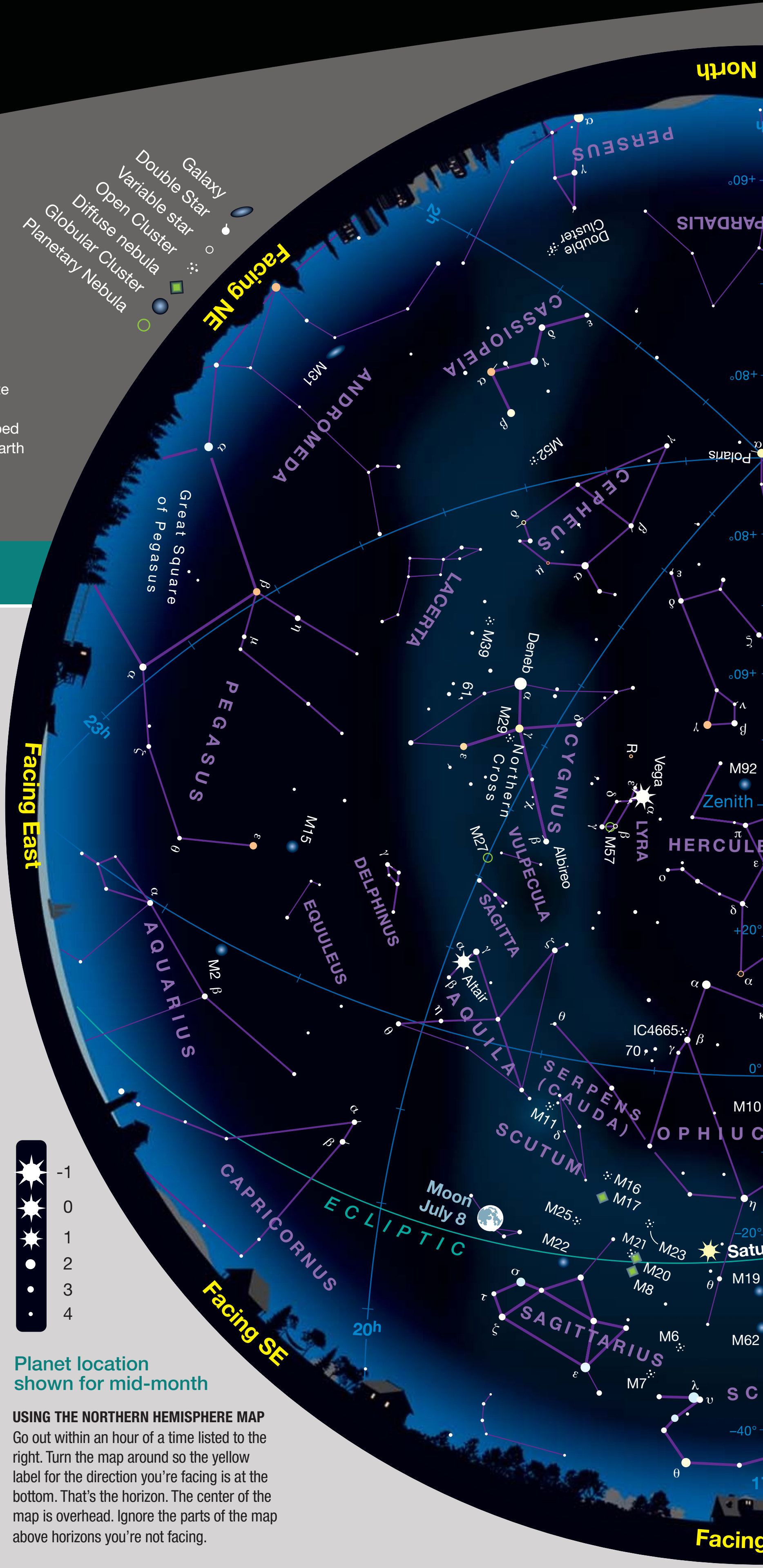
FIRST QUARTER
July 30
15:23 UT

DISTANCES

Apogee	July 6, 04h UT
405,934 km	Diameter 29′ 26″
Perigee	July 21, 17h UT
361,238 km	Diameter 33′ 05″

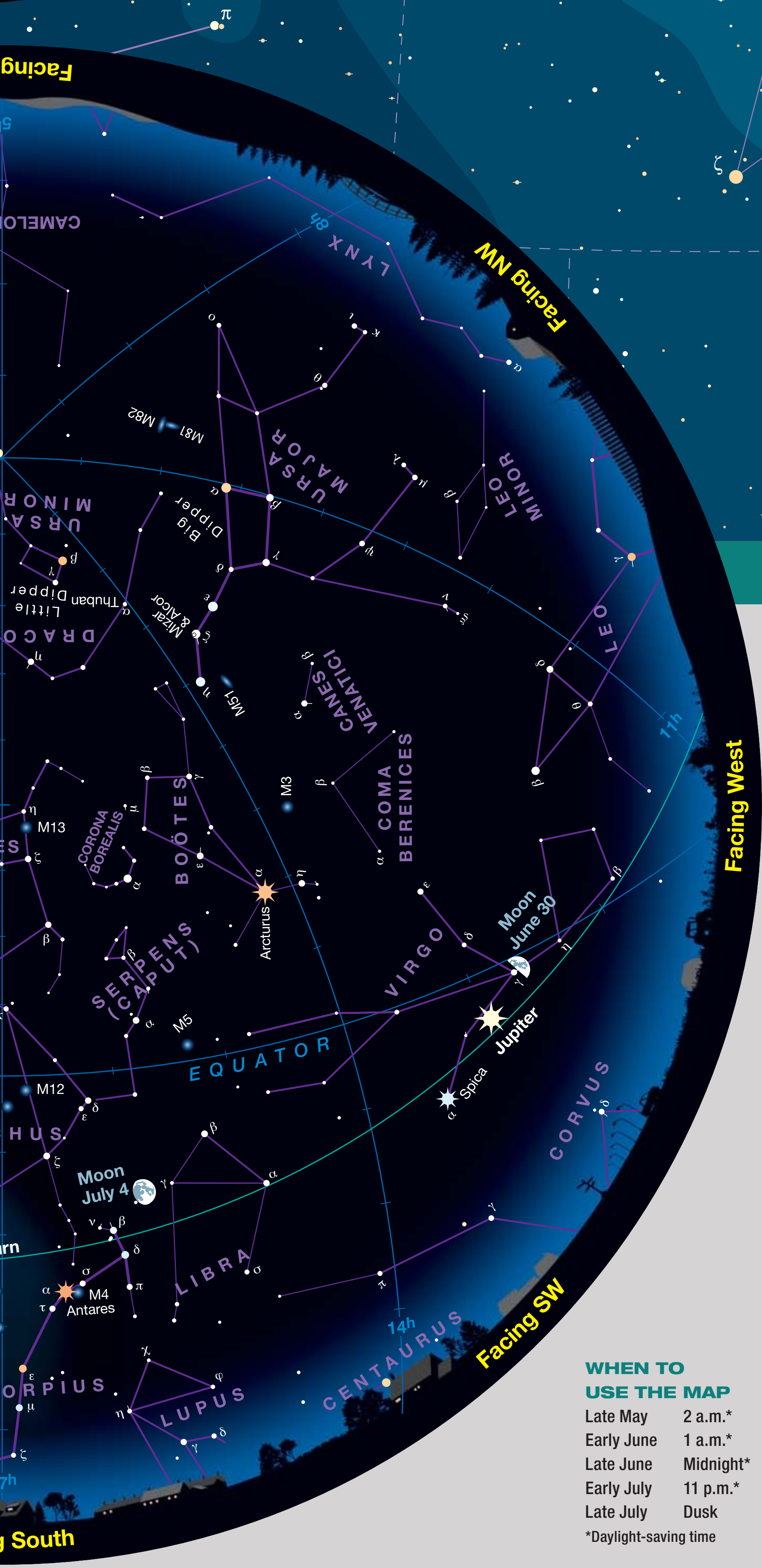
FAVORABLE LIBRATIONS

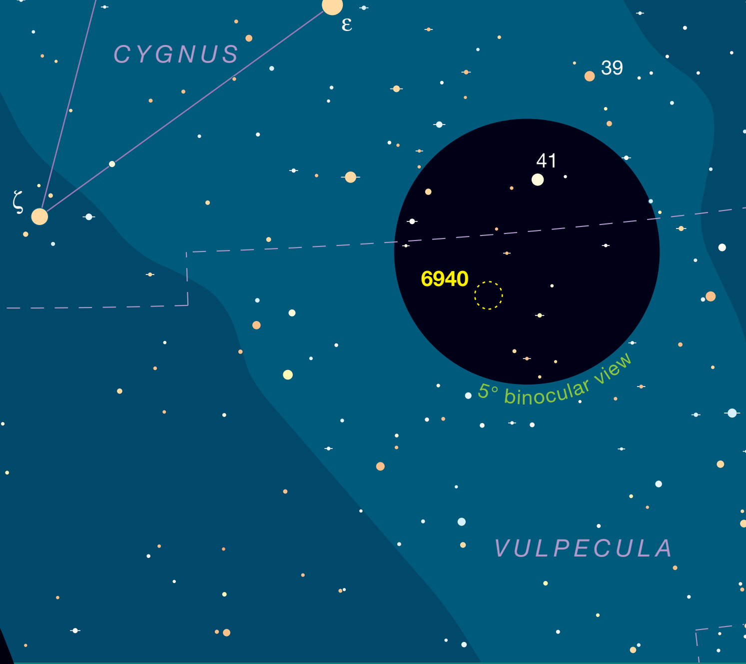
Lyot Crater	July 3
Russell Crater	July 15
Pythagoras Crater	July 20
Neper Crater	July 25



Planet location shown for mid-month

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





Binocular Highlight by Mathew Wedel

Against the Wall of Night

On a clear, dark night, the summer Milky Way is made up of bright streams of stars and dark rivers of dust interwoven with almost hypnotic complexity. Gazing into the depths gives me the same tingle of excitement I get driving across the desert Southwest: The bones of the land are showing through.

It's a double-edged sword, though. Revelation and concealment go hand in hand in the night sky. Every object along our line of sight obscures countless others along the same line that we will see poorly, or not at all.

The open cluster **NGC 6940** rides the ragged edge of this dichotomy — and the ragged edge of the summer Milky Way itself. The cluster is an easy find. Start next to the southern "wing" of Cygnus, the Swan, and draw a line from 39 Cygni to 41 Cygni. Then go on about the same distance, just a little over 2° and over the border into Vulpecula, the Little Fox, and NGC 6940 will swim into view. The cluster sprawls across almost ⅓°, elongated from northeast to southwest, with shoals of stars at every level of brightness, until the dimmest hover at the edge of resolution and merge into the background of the galaxy.

Deep-sky images show that NGC 6940 lies in a fairly dark part of the Milky Way, against a wall of gigantic dust clouds. These dark clouds are continuous with the Great Rift that runs through Cygnus to Sagittarius, the Archer, and beyond. Still, there are enough background stars that it can be difficult to tell where the cluster ends and the Milky Way begins. This is where binoculars show their worth, revealing both the objects and the larger cosmic context in which they — and we — are embedded.

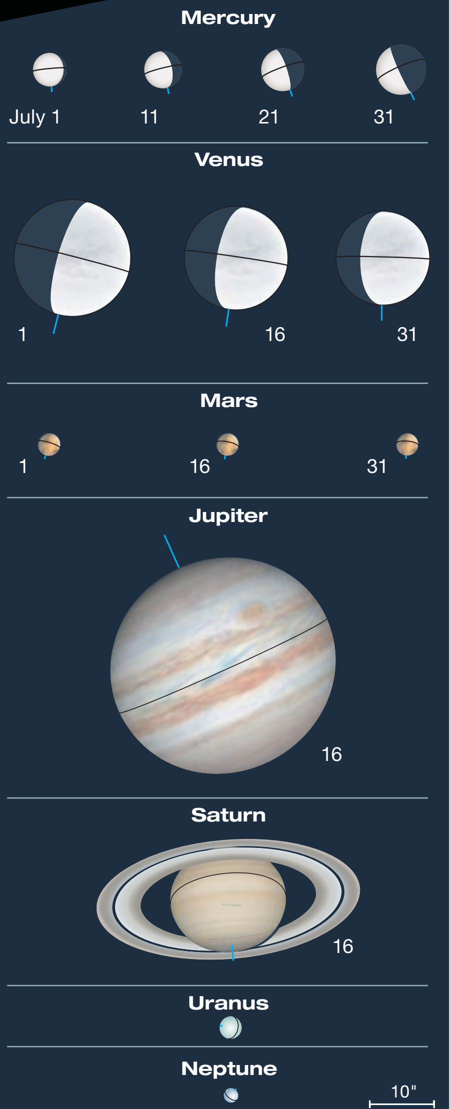
■ **MATT WEDEL** likes to kick back with his binoculars on a driveway in Claremont, California.

WHEN TO USE THE MAP

Late May	2 a.m.*
Early June	1 a.m.*
Late June	Midnight*
Early July	11 p.m.*
Late July	Dusk

*Daylight-saving time

PLANET VISIBILITY: Mercury: Visible all July low in evening twilight, WNW; best late in the month • **Venus:** All month, before and during dawn, ENE • **Mars:** Invisible all July • **Jupiter:** All month, evening, WSW • **Saturn:** All month, evening and late night, south to SW.

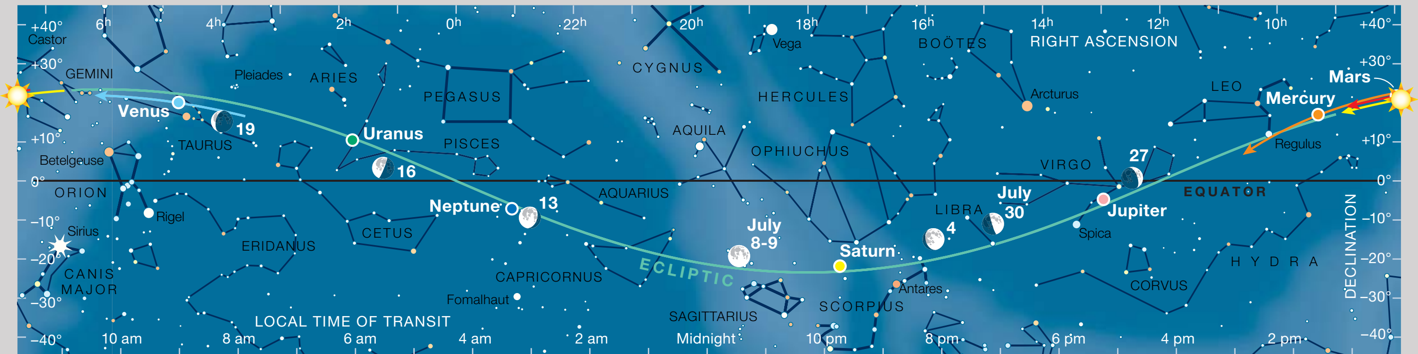


PLANET DISKS have south up, to match the view in many telescopes. Blue ticks indicate the pole currently tilted toward Earth.

July Sun & Planets

	Date	Right Ascension	Declination	Elongation	Magnitude	Diameter	Illumination	Distance
Sun	1	6^h 39.7^m	+23° 07′	—	–26.8	31′ 28″	—	1.017
	31	8^h 40.7^m	+18° 20′	—	–26.8	31′ 31″	—	1.015
Mercury	1	7^h 28.2^m	+23° 47′	11° Ev	–1.1	5.3″	91%	1.279
	11	8^h 45.6^m	+19° 38′	20° Ev	–0.4	5.8″	75%	1.155
	21	9^h 44.1^m	+13° 59′	25° Ev	0.0	6.7″	60%	1.008
	31	10^h 24.9^m	+8° 23′	27° Ev	+0.3	7.8″	45%	0.859
Venus	1	3^h 34.9^m	+16° 31′	44° Mo	–4.2	18.2″	63%	0.919
	11	4^h 19.8^m	+18° 58′	42° Mo	–4.1	16.8″	67%	0.995
	21	5^h 07.0^m	+20° 47′	41° Mo	–4.1	15.6″	71%	1.069
	31	5^h 55.9^m	+21° 49′	39° Mo	–4.0	14.6″	74%	1.140
Mars	1	7^h 14.7^m	+23° 21′	8° Ev	+1.7	3.6″	100%	2.620
	16	7^h 56.4^m	+21° 50′	4° Ev	+1.7	3.5″	100%	2.645
	31	8^h 36.8^m	+19° 43′	2° Mo	+1.7	3.5″	100%	2.657
Jupiter	1	12^h 52.3^m	–4° 11′	95° Ev	–2.1	37.4″	99%	5.277
	31	13^h 03.1^m	–5° 26′	69° Ev	–1.9	34.4″	99%	5.733
Saturn	1	17^h 30.4^m	–21° 56′	164° Ev	+0.1	18.3″	100%	9.078
	31	17^h 23.1^m	–21° 55′	134° Ev	+0.2	17.8″	100%	9.332
Uranus	16	1^h 45.4^m	+10° 17′	85° Mo	+5.8	3.5″	100%	19.978
Neptune	16	23^h 01.7^m	–7° 13′	130° Mo	+7.8	2.3″	100%	29.289

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



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

Enter the Summer Citadel

The sights and scents of the season encourage a visit to an old friend.

The greatest science popularizer of the past 50 years — and probably of all time — was American astronomer Carl Sagan. Among his many quotable statements, the most famous has always been, "We're made of star stuff."

But more than a century before Sagan said those words, American poet Walt Whitman said something similar. "I believe a leaf of grass," Whitman wrote, "is no less than the journey-work of the stars." Of course, Whitman couldn't have known, as Sagan did and meant to convey, that the creation of life on Earth was literally a work of the stars. Carbon, oxygen, and other essential elements in our composition, and substances that went into the formation of our Sun (a third-generation star) and its planetary system, came from the supernovae of earlier generations of stars.

Whitman lived in a time before anyone knew anything about nucleosynthesis. But as I stand on a fragrant, freshly mown lawn while a July dusk ever so slowly deepens, and Vega and Arcturus roll into view followed by dozens and then hundreds more stars, I can't help but think of Whitman's beautiful and seemingly prescient line. I'm freshly stirred to seek out the stellar wonders of a summer night.

Summer's citadel of stars. There's much to be said for tracking down sights you've never seen before, but on a calm summer night you should also return to the traditional objects on everyone's watch list. For instance, take the time to consider a masterwork made by the stars, fashioned by its component stars with gravity and nuclear fusion. It's the best placed and most popular of all globular clusters for observers at mid-northern latitudes and may even be the most popular deep-sky object of any kind except for winter's M42, the Great Orion Nebula. But unlike M42, this summer cluster passes nearly overhead as seen from the world's most populous latitudes (exactly overhead from 36½° N). I'm speaking, of course, about M13, the Great Globular Cluster in Hercules.

Sagan at least once used the phrase "the citadel of the stars" in his *Cosmos* series, and if he didn't sometimes apply the phrase to globular clusters, somebody should. It's an apt description of these congregations of up to hundreds of thousands of stars seemingly guarding the rest of our galaxy.

You can see quite a few of M13's stars in a sizable telescope. But your first approach to M13 should be with the naked eye. You can see it as a soft little hazy patch of light on the west side of the Keystone asterism in Hercules — under skies with a limiting magnitude of about 6.0 or better. Binoculars reveal it in more light-polluted areas, showing a larger puff of light flanked by 7th-magnitude stars on either side.

Stellar stronghold revealed. Through an 8-inch, 10-inch, or larger telescope M13 truly looks like a mighty fortress of stars. It has more obvious arms or tentacles of stars — John Herschel's "curvilinear branches" — extending outward from it than perhaps any major globular. Just let the wonder flow through you for a while as you behold this beauteous, many-armed beast — then you can search for its subtleties. These include dark lanes: A famous dark Y or propeller is centered southeast of the cluster's core, but a particular combination of aperture and magnification helps make it more obvious (see page 55).

Also worthy of note in an 8-inch or larger telescope is the 11th-magnitude spiral galaxy NGC 6207, approximately 40 arcminutes northeast of M13. M13 is only about 23,000 light-years from Earth, but NGC 6207 lies about 46 million light-years distant.

Happy 303rd, M13! M13 was discovered by the great Edmond Halley in 1714, the 58th year of his 85-year-long life. That's 303 years ago.

■ Contributing Editor FRED SCHAAF has been writing about the skies above us for more than 40 years.

Four Out of Five

Whether you're a night owl or an early riser, you can observe a bright planet this month.

Though Mars remains too close to the Sun for observation in July, four other relatively bright planets make their appearances this month. Mercury shows up low in the west during evening twilight. Jupiter, too, comes into view at dusk, low in the west-southwest, and doesn't set until around midnight. Saturn shines at its highest in the south not long after dusk, setting a few hours before the Sun comes up. Brilliant Venus appears about three hours before July's early sunrises, and it dominates the eastern view during the early stages of dawn.

DUSK

Mercury offers a fairly poor apparition for observers at mid-northern latitudes. Although it reaches a greatest elongation of 27° east of the Sun on July 30th, it's highest for observers around latitude 40° north on July 19th. Even then, it's only about 8° above the west-northwest horizon just 30 minutes after sunset.

Mercury fades only slightly this month, dropping from magnitude –1.0 on July 1st to +0.4 by the 31st. Still, binoculars will help, especially through summer haze.

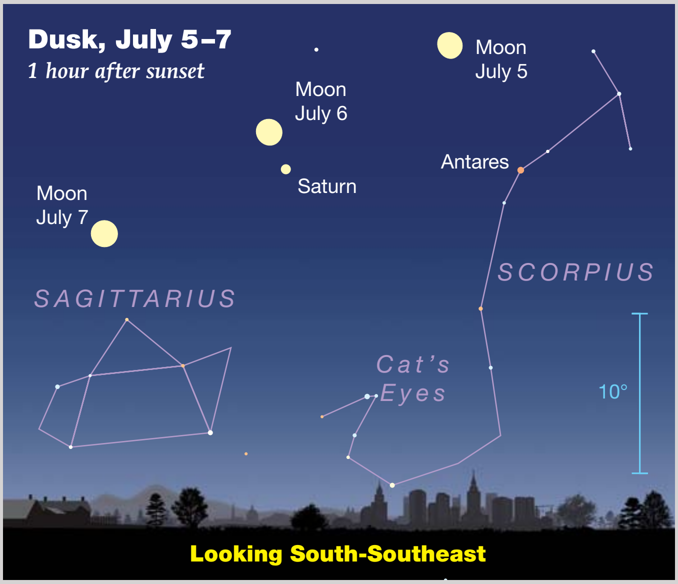
On the evening of July 25th, with a crescent Moon about 8° to its upper left, 1st-magnitude Regulus twinkles just 1° upper right of Mercury. This may be the last convenient opportunity to see the star until August 21st, when it appears about 1° from something else — the totally eclipsed Sun!

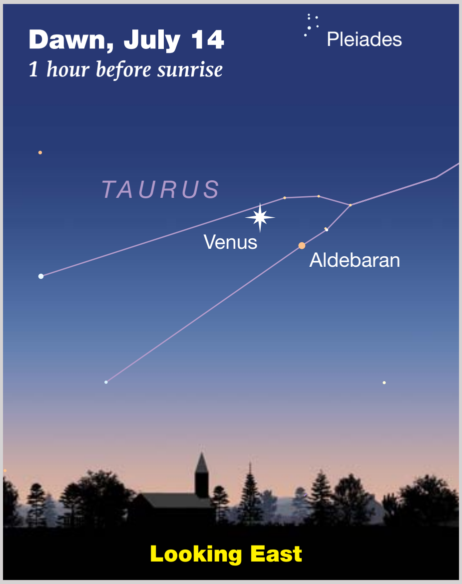
EVENING

Jupiter dominates the low southwest at dusk. It sets around 1 a.m. (daylight-saving time) as July begins but about 2 hours earlier as the month ends. The giant planet dims subtly from magnitude –2.0 to –1.9 during July and shrinks from 37″ to 34″ wide at the equator.

Worse for telescopic observations is that by late in the month, Jupiter is little more than 20° high in the west-southwest an hour after sunset. Even so, Jupiter reaches eastern quadrature (90° east of the Sun) on July 6th, so its shadow falls far to the east side all month, facilitating views of Jovian satellites emerging from their eclipses (see p. 51). Naked-eye observers can enjoy Jupiter slowly closing the gap between itself and Spica from 11° to 8° through July.

Saturn is at its highest around midnight on July 1st but before 10 p.m. by the month's final days. Shining in southeastern Ophiuchus above the body of Scorpius, Saturn is almost as far south as it can be in the zodiac, so even at its highest it's 25° to 30° above the south horizon for viewers around latitude 40° north. Still, that's high enough on summer nights of good seeing to try glimpsing extra detail on the planet's globe and in its rings — which are now open by 26.7°, very nearly their greatest possible tilt.





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

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

NIGHT

Neptune rises in the late evening in Aquarius and is highest in the south in morning twilight. The dim planet is moving slowly westward and lies about 2° east of Lambda (λ) Aquarii in July.

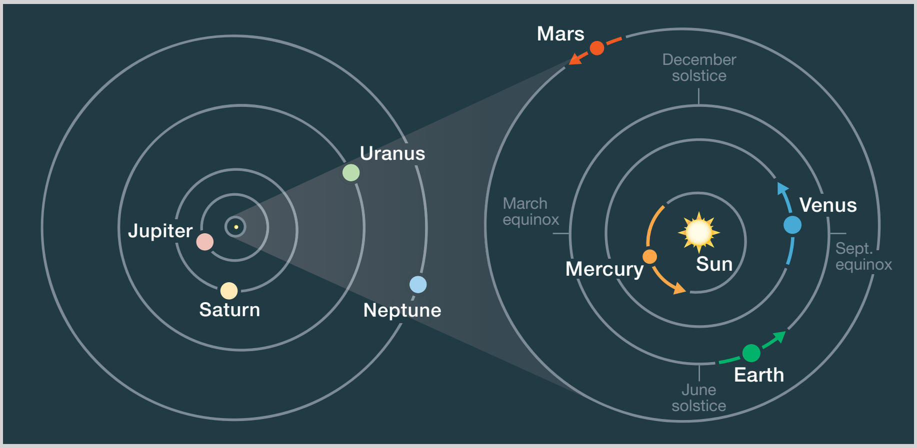
Uranus, in Pisces, rises in the middle of the night and is still in the east as dawn begins. See **http://is.gd/urnep/** for finder charts for Uranus and Neptune.

DAWN

Venus rises about 2½ hours before the Sun as July opens and 3 hours before the Sun as July closes. Its altitude an hour before sunrise is already almost 20°.

This month, the brilliant planet fades perceptibly from magnitude –4.2 to –4.0 as its gibbous phase increases from 63% to 74% sunlit and its disk shrinks from 18″ to 15″.

On July 5th, Venus beams about 7° lower left of the Pleiades. During the next week it skirts the Hyades, passing just 3° north of Aldebaran on July 13th and 14th. Venus approaches M35 in Gemini as July ends.



ORBITS OF THE PLANETS

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

MARS

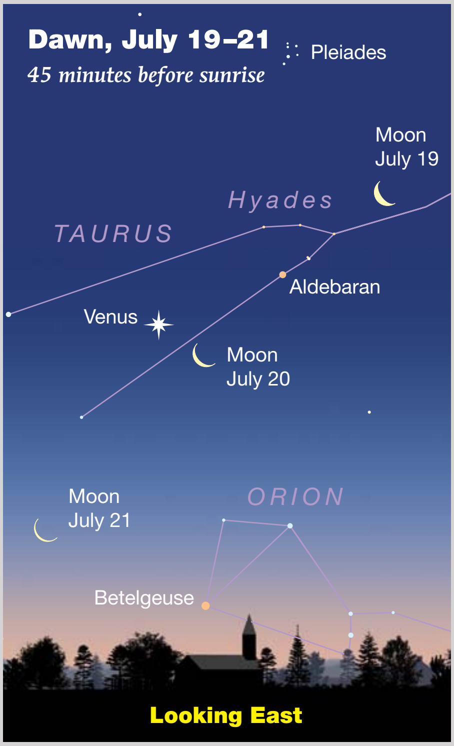
Mars is at conjunction with the Sun on July 27th — but exactly one year (to the day) later Mars will be at perihelic opposition, shining bigger and brighter than it has at any time since 2003.

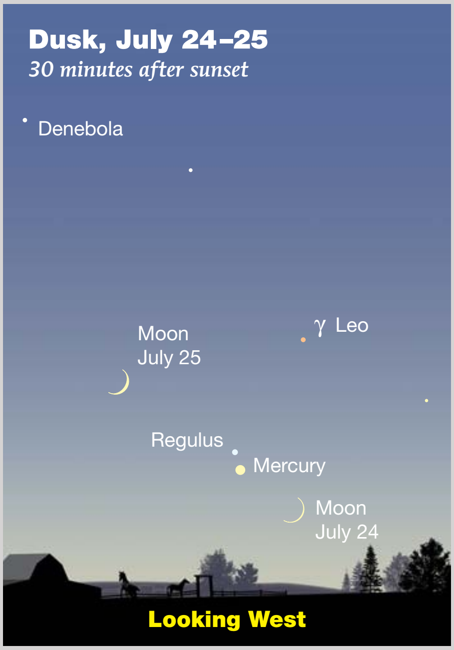
EARTH AND MOON

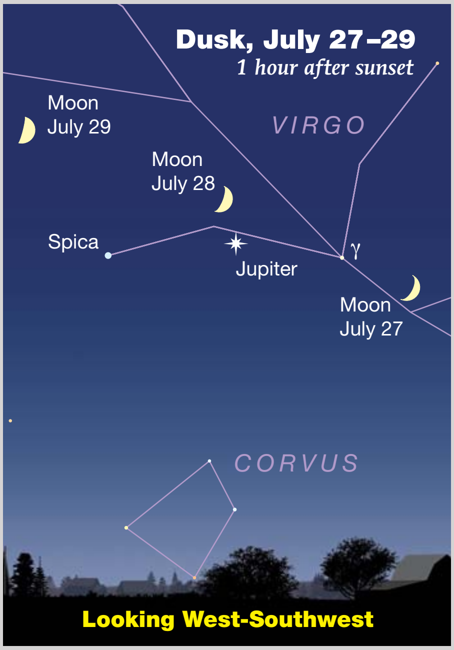
Earth arrives at aphelion, its farthest point from the Sun in space, at 4 p.m. EDT on July 3rd. Earth's distance from the Sun at aphelion is only 3.3% farther than at perihelion in January.

The waxing gibbous **Moon** forms a triangle with Jupiter and Spica on the evening of July 1st. The nearly full Moon beams just above Saturn on July 6th. The waning lunar crescent nears Aldebaran and the Hyades at dawn on July 19th, and it's about 3° lower right of Venus the next morning. The waxing crescent Moon hangs 4° to 5° lower right of the Mercury–Regulus pairing about 30 minutes after sunset on July 24th; good luck. It's much easier, about 8° upper left of the pair, the next evening. A thicker lunar crescent curves 3° above Jupiter on July 28th.

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

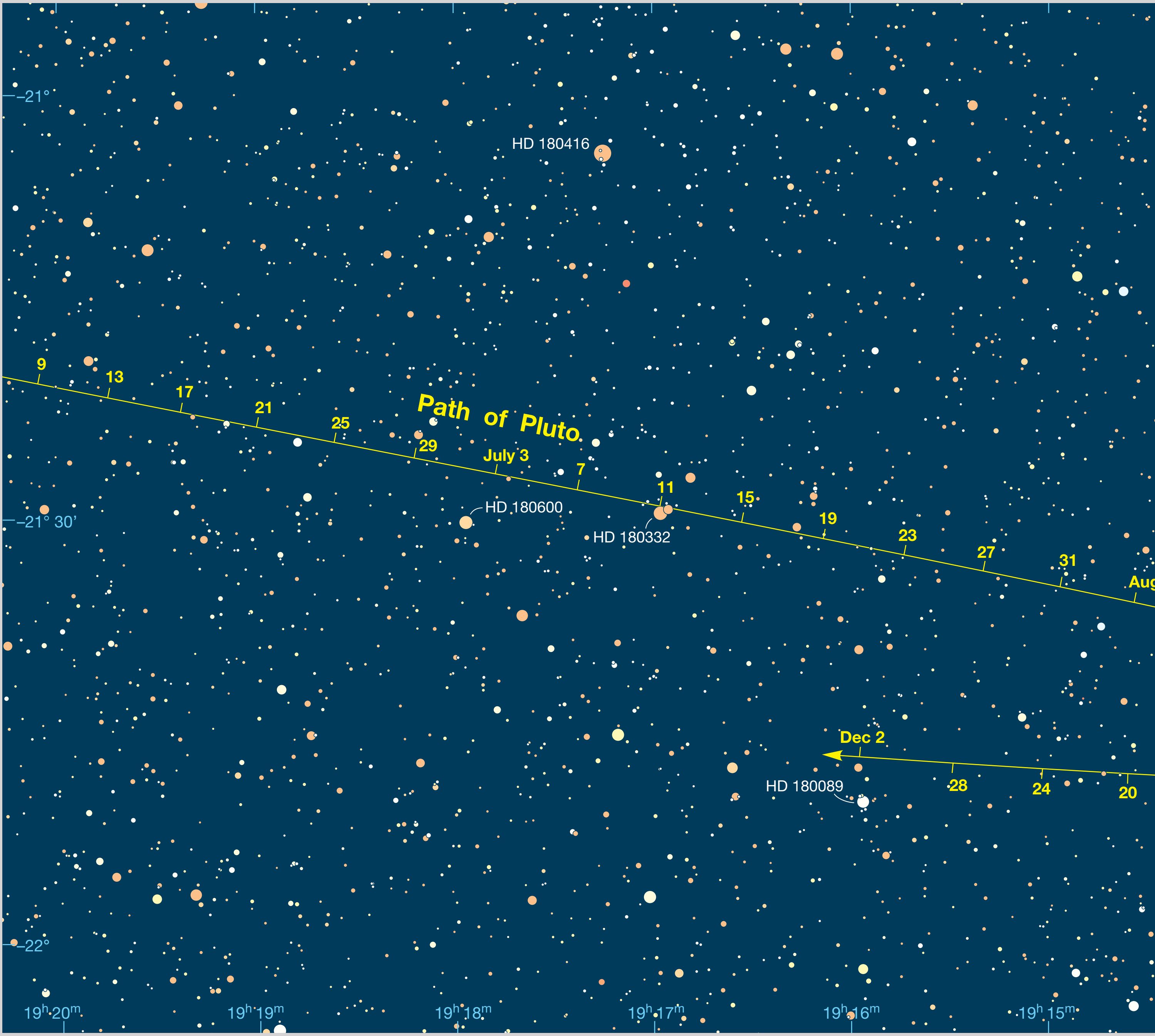




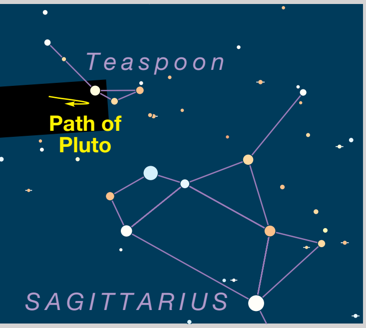


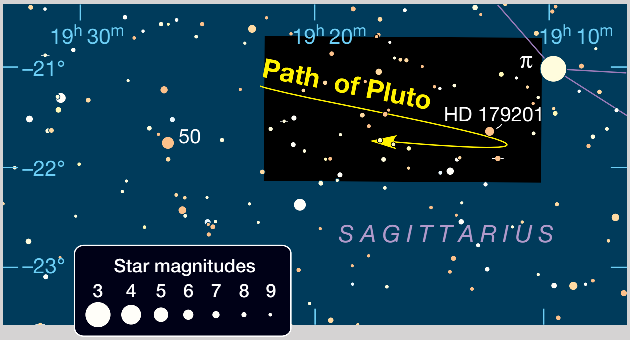
Pluto in 2017

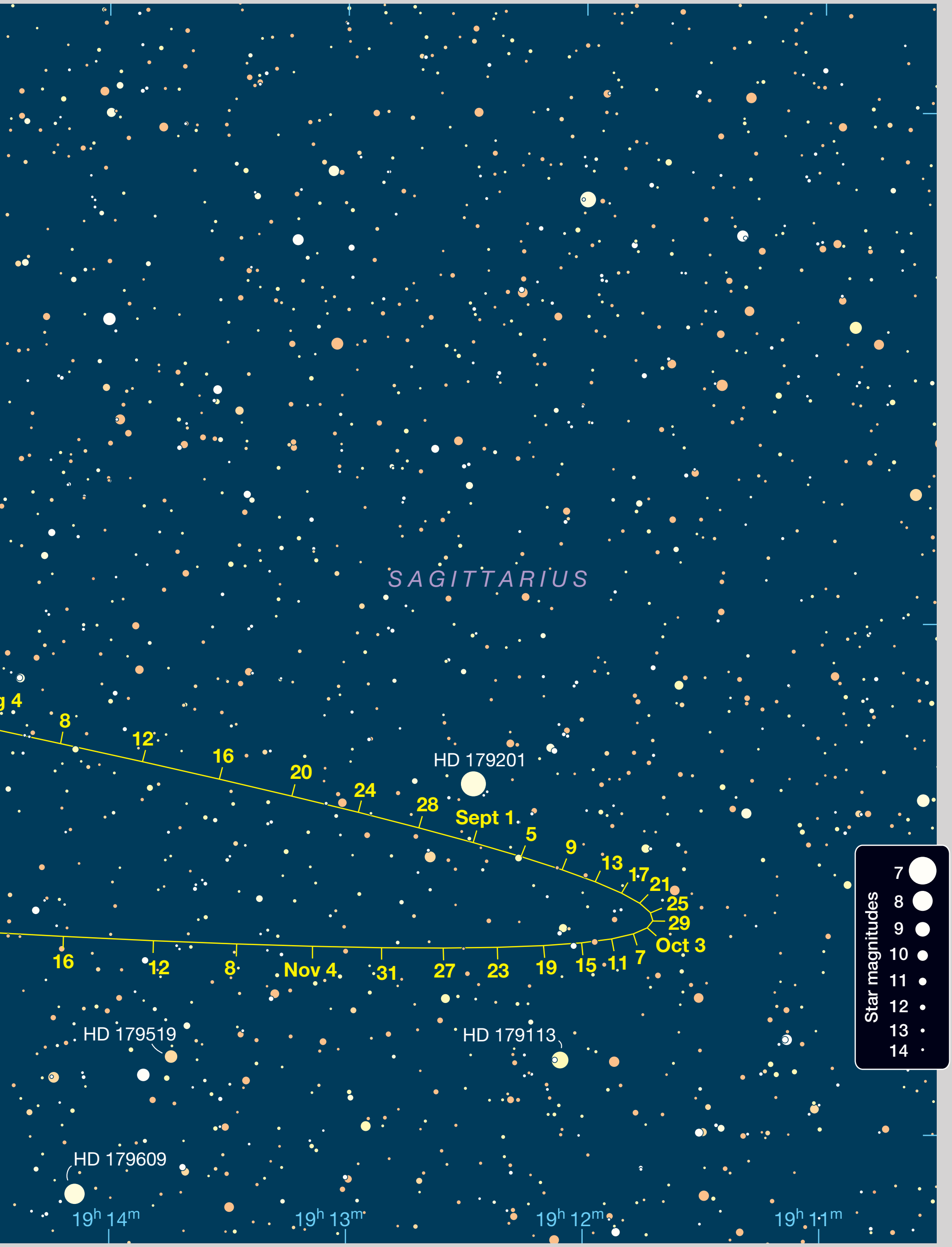
Don't look now, but a proposed sizing scheme would make it a planet again.



BANNER: NASA / SOUTHWEST RESEARCH INST.







Well, actually you *can* look now — if you have a 14-inch or larger telescope and a sky dark enough to detect a 14.4-magnitude speck low in the south. Good luck. Pluto is fading into the distance year by year, and it's at declination –21°. We're edging into a century-plus era when, for practically all visual observers, Pluto will be nothing but a memory at most. But it will always remain a fairly easy target for long-exposure telescopic imagers.

The chart here is your other essential visual equipment. Pluto is in northern Sagittarius just below the Teaspoon asterism, as shown on the small charts above. The black box on each one shows the field of the next one up. The large chart is only 1.2° tall, and its brightest stars are 7th and 8th magnitude. Use these to start narrowing in on the precise point where Pluto will be hiding at the time and date when you look. The date ticks on Pluto's path are for 0^h Universal Time; put a pencil prick at exactly the right point on the path. As you get close with the scope, switch to your highest power to improve the visibility of the very faintest stars.

The tiniest in these swarms are no fainter than Pluto itself, so if you think you see something that ought to be it, make a careful sketch of its position in the star field right around it. Come back in a day or two to see if your suspected object is moving.

The Name Game

The stunningly successful New Horizons flyby of Pluto two years ago, a triumph from start to finish, resurrected this dwarf planet as an important object in planetologists' pantheon of worlds. It's currently more geologically active than Mercury or Mars, and it's only the third place in the solar system where we see plain evidence of an active *hydrological cycle.* On Earth, water is the volatile that evaporates, then rains or snows out of the atmosphere, flows in rivers or glaciers to pool in lowlands, and then evaporates again. On Titan, it's mixtures of methane and ethane. On Pluto, New Horizons found nitrogen forming great frozen plains, a hazy, layered atmosphere, and long glaciers flowing down between mountains. And it spotted a 20-mile slab of frozen nitrogen that was apparently once a liquid lake. Other volatiles are probably involved as well.

So should Pluto be called a planet again? Kirby Runyon (Johns Hopkins University) is pushing to have the International Astronomical Union decide on a new and perhaps better definition, one having to do more with an object's physical nature than whether it has cleared away other objects near its orbit. But be careful what you wish for. Runyon's proposed new definition, based on size and roundness, would add "moon planets" like our Moon and other big satellites to the roster, as well as dozens of trans-Neptunian objects of Pluto's size and smaller. He estimates that his proposed redefinition would add at least 110 new planets.

A list that long would need quite a mnemonic to remember it by. Our guess? This is going nowhere.

Action at Jupiter

Jupiter in July is getting lower in the evening sky and farther away in its orbit around the Sun, so get your scope on it early in the evening (even in twilight) and early in the month. Jupiter shrinks from 37″ to 34″ across its equator in July.

The wavy-line diagram on the facing page identifies which of Jupiter's four big Galilean satellites is which at any UT date and time in July.

The table on the facing page lists all the interactions of Jupiter with its satellites and their shadows for July. Scan for events when Jupiter will be visible in early evening for your time zone. Eastern Daylight Time is UT minus 4 hours; PDT is UT minus 7 hours.

Jupiter's Great Red Spot should cross the planet's central meridian at the following UT dates and times:

June 1, 7:25, 17:21; **2,** 3:16, 13:12, 23:08; **3,** 9:04, 18:59; **4,** 4:55, 14:51; **5,** 0:46, 10:42, 20:38; **6,** 6:34, 16:29; **7,** 2:25, 12:21, 22:16; **8,** 8:12, 18:08; **9,** 4:04, 13:59, 23:55; **10,** 9:51, 19:46; **11,** 5:42, 15:38; **12,** 1:34, 11:29, 21:25; **13,** 7:21, 17:17; **14,** 3:12, 13:08, 23:04; **15,** 9:00, 18:55; **16,** 4:51, 14:47; **17,** 0:43, 10:38, 20:34; **18,** 6:30, 16:25; **19,** 2:21, 12:17, 22:13; **20,** 8:08, 18:04; **21,** 4:00, 13:56, 23:51; **22,** 9:47, 19:43; **23,** 5:39, 15:35; **24,** 1:30, 11:26, 21:22; **25,** 7:18, 17:13; **26,** 3:09, 13:05, 23:01; **27,** 8:56, 18:52; **28,** 4:48, 14:44; **29,** 0:39, 10:35, 20:31; **30,** 6:27, 16:23.

July 1, 2:20, 12:16, 22:12; **2,** 8:07, 18:03; **3,** 3:59, 13:55, 23:50; **4,** 9:46, 19:42; **5,** 5:38, 15:34; **6,** 1:29, 11:25, 21:21; **7,** 7:17, 17:12; **8,** 3:08, 13:04, 23:00; **9,** 8:56, 18:51; **10,** 4:47, 14:43; **11,** 0:39, 10:35, 20:30; **12,** 6:26, 16:22; **13,** 2:18, 12:13, 22:09; **14,** 8:05, 18:01; **15,** 3:57, 13:52, 23:48; **16,** 9:44, 19:40; **17,** 5:36, 15:31; **18,** 1:27, 11:23, 21:19; **19,** 7:15, 17:10; **20,** 3:06, 13:02, 22:58; **21,** 8:54, 18:50; **22,** 4:45, 14:41; **23,** 0:37, 10:33, 20:29; **24,** 6:24, 16:20; **25,** 2:16, 12:12, 22:08; **26,** 8:03, 17:59; **27,** 3:55, 13:51, 23:47; **28,** 9:42, 19:38; **29,** 5:34, 15:30; **30,** 1:26, 11:22, 21:17; **31,** 7:13, 17:09.

These times assume that the spot will be centered at System II longitude 266° in June, 267° in July. If the Red Spot has drifted away from these predictions, as it sometimes does, it will transit 1⅔ minutes earlier for each degree less, or 1⅔ minutes later for each degree more.

Moon Occults a Bright Double Star

SMALL-TELESCOPE USERS across most of the U.S. and Canada are in for a treat. On the evening of Friday, June 30th, the dark limb of the first-quarter Moon will occult Porrima, Gamma (γ) Virginis, a binary star whose total magnitude is 2.9. Its components are almost equally bright, about magnitude 3.6 each; a barely detectable difference of 0.1 magnitude distinguishes them. Most viewers will see a *step occultation* — the star will suddenly drop in brightness when one component gets covered, then will disappear when the other goes.

The two stars are currently separated by 2.6 arcseconds, making the pair resolvable in almost any telescope during not-awful seeing. This year they're lined up exactly north-south. So as witnessed from some places, the Moon's limb will hit them simultaneously; no step occultation there. On the other hand, where the occultation happens near one of the Moon's poles, the delay between the two events could be quite extended. The occultation's southern limit, where grazing events will occur, passes south of Florida and across south and west Texas at night, New Mexico in twilight, and northern Arizona, Nevada, and southern Oregon in daylight. Check **iota.timerson.net** for a map.

Some times of the star's disappearance: **Seattle,** 6:50 p.m. PDT (daytime); **Denver,** 8:23 p.m. MDT (sunset); **Austin,** 10:05 p.m. CDT; **Kansas City,** 9:34 p.m. CDT (twilight); **Chicago,** 9:36 p.m. CDT (twilight); **Toronto,** 10:40 p.m. EDT; **Miami,** 11:28 p.m. EDT; **Atlanta,** 10:59 p.m. EDT; **Washington, DC,** 10:53 p.m. EDT; **New York,** 10:51 p.m. EDT; **Boston,** 10:50 p.m. EDT.

The paired stars will reappear from behind the Moon's bright limb up to an hour or more later, where they will be hard to see in the glare of the brilliantly sunlit moonscape.

Precise time predictions, and the altitudes of the Sun and the Moon at the time, are listed for hundreds of cities and towns at **lunar-occultations.com/iota/bstar/0701zc1821.htm**. (That page displays three long tables with less-than-obvious divides: for the disappearance, the reappearance, and the locations of cities. Times are UT.)

July Meteors

The second half of July sees meteor activity start to pick up after a relatively quiet six months. Several weak, long-lasting showers with radiants in the southern sky should each produce several meteors visible per hour late in the night: mainly the southern Delta Aquariids but also the Piscis Austrinids and Alpha Capricornids. You might also notice the occasional early Perseid.

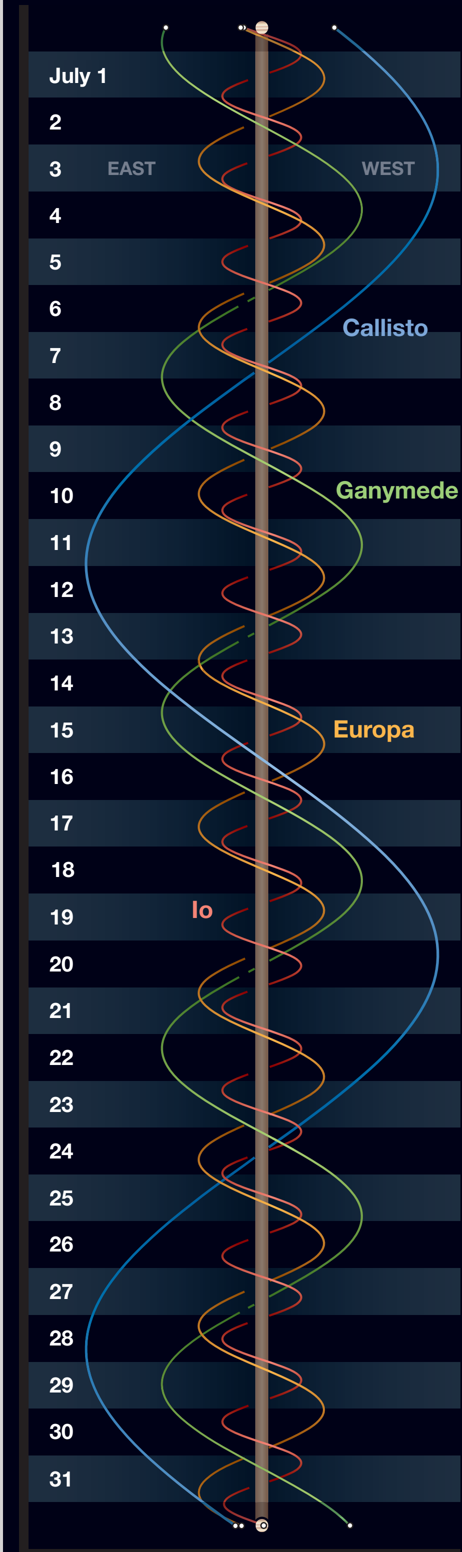
The Alpha Capricornids, which originate from Comet 169P/NEAT, stand out as unusually slow-moving and sometimes bright. You might see five or ten of these per hour in the last week of July under ideal conditions.

Phenomena of Jupiter's Moons, July 2017

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

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

Jupiter's Moons



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

Eyepieces for Planetary Observing

Jupiter and Saturn are easy to observe now — but what eyepiece type will give the best views?

This generation of amateur astronomers can choose from a bewildering variety of eyepiece types made to suit all purposes and pocketbooks. Complex designs that provide apparent fields of view of 80° or even 100° can deliver a dramatic "spacewalk" viewing experience. Many of these optical marvels command prices surpassing a decent 8-inch Newtonian reflector complete with an equatorial mount.

Just as some telescope designs provide discernibly superior visual views of solar system targets, so do certain eyepiece types. The planets all subtend very small apparent angular sizes, so devoted planetary observers don't place a premium on wide apparent fields of view (or even 2-inch-format eyepieces) that require a multitude of lens elements, air-glass surfaces, or complex edge correction.

The Virtues of Simplicity

Instead, contrast and definition are the qualities of paramount importance to the fastidious planetary observer. Discerning all of the planetary details that a telescope's optics and the state of the atmosphere allow demands eyepieces that have high light transmission and freedom from ghost images, internal reflections, and scattered light.

Ghost images are caused by double reflections from air-glass surfaces that come to focus at or near the eye's focal plane. The more of these interfaces within an eyepiece, the greater the chance that ghost images will arise. Modern anti-reflection coatings dramatically reduce such spurious reflections, but eliminating scattered light requires optical elements with well-polished surfaces that are free of sleeks and scratches, blackened lens edges, a finely threaded and effectively blackened interior of the eyepiece barrel, and a sharp, well-defined field stop.

A steady hand and steady sky — along with an 18-inch reflector and a binocular viewer with high-quality 4.5-mm eyepieces — all came together for this sketched rendering of Jupiter on March 27, 2017.

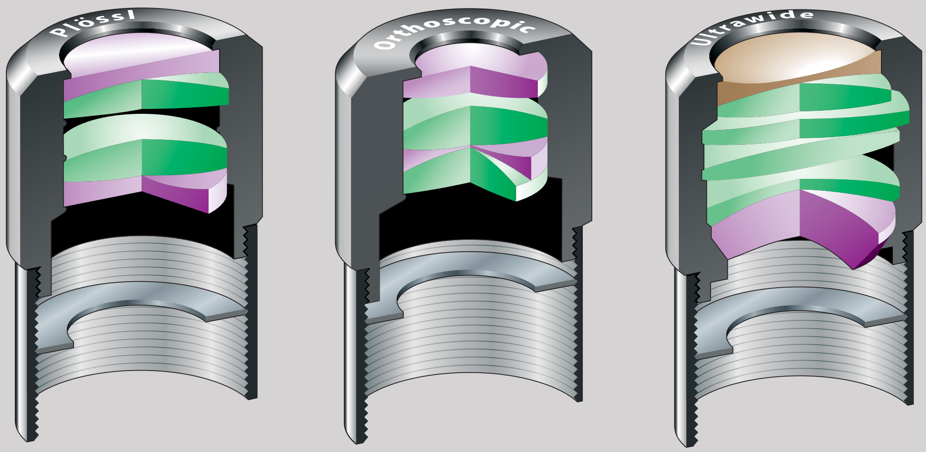
PETER VERCAUTEREN / ASTRONOMYDRAWINGS.COM

Conventional wisdom has long held that the best planetary eyepieces are those with the smallest number of lens elements and air-glass surfaces that can still provide a well-defined image in the center of the field of view. Three optical configurations that satisfy this "minimum glass" paradigm have emerged.

Monocentric: Introduced by Hugo Adolf Steinheil in 1883, the monocentric design consists of a cemented triplet lens with spherical surfaces that share a common center and radius of curvature. With only two air-glass surfaces, monocentrics provide images of unsurpassed brightness and contrast. But they have a very narrow apparent field of view, only 25° to 30°, that many observers have compared to looking through a drinking straw. In 1911 Charles Hastings patented a refinement of the design that Carl Zeiss produced until the 1950s. The firm TMB briefly revived this design a decade ago, but today monocentrics are only available on the secondhand market.

Orthoscopic: Designed by the brilliant German mathematician and physicist Ernst Abbe, the orthoscopic (from the Greek roots for "straight seeing") was the first eyepiece to offer virtually complete correction of optical aberrations and distortion. Introduced in 1880, it consists of a cemented triplet field lens paired with a single-element biconvex or plano-convex eye lens. Widely available even today, orthoscopic eyepieces offer excellent sharpness, color correction, and contrast combined with a 40° to 45° apparent field of view.

Plössl: This brainchild of Viennese optician Georg Simon Plössl originally consisted of a pair of identical cemented doublets. It was also known as the symmetrical eyepiece. Twentieth-century refinements by Rudolf König and Chester Brandon of the original 1860 design place the interior surfaces almost in contact to minimize ghost reflections and employ an eye lens of shorter focal length than the field lens. Providing a 45° to 50° apparent field of view, the best Plössls rival the performance of orthoscopics. But the quality of today's commercial offerings varies widely.



▲ Eyepiece designs with fewer lenses tend to deliver the most light to your eye, but those with complex optical combinations often provide more expansive views and better eye relief.

Importance of Eye Relief

During a typical planetary observing session, you'll maintain a prolonged vigil at the eyepiece, waiting patiently for those fleeting moments when the atmosphere steadies momentarily to provide what Percival Lowell called "revelation peeps." Comfort is of paramount importance if you want to maintain visual acuity for long periods.

To fully exploit the resolving power of any telescope when viewing a low-contrast target, you'll need to use a magnification of at least 25× per inch of aperture (or 1× per millimeter) — and, when the seeing permits, you can double that value profitably (*S&T:* March 2015, p. 54). A classic, long-tube achromatic refractor with a focal ratio of f/15 achieves this range of magnification with eyepiece focal lengths of 15 to 7.5 mm. The popular f/10 Schmidt-Cassegrain requires focal lengths of 10 to 5 mm, while the increasingly common "fast" f/5 Newtonian reflector needs 5 to 2.5 mm.

The problem is that such short focal lengths tend to offer poor *eye relief,* the distance from the outer surface of the eyepiece's eye lens within which you can view the full viewing angle. Although monocentric, orthoscopic, and Plössl eyepieces all provide decent eye relief, about 70% to 80% of their focal length, the short focal lengths required for planetary observing involve squinting through tiny eye lenses located a small fraction of an inch from your eye. Not only does this present an insurmountable obstacle to eyeglass wearers, but the surface of the eye lens is also prone to smearing with eyelash oils.

The time-honored solution to this ergonomic difficulty is to combine an eyepiece of moderately long focal length (and thus comfortable eye relief and an eye lens of reasonable diameter) with a Barlow lens or other image amplifier that doubles or triples the magnification. Most observers find that any loss of image quality resulting from the Barlow's two additional air-glass surfaces is almost imperceptible — and more than offset by the combination's ease of use and comfort.

In fact, many of the best eyepiece designs offered today integrate a Barlow lens to provide a remarkably generous eye relief of 20 mm even in eyepiece focal lengths as short as 3 mm, combined with well-corrected apparent fields of 50° to 60°. At one point, TMB offered six-element eyepieces of this form that the designer, the late Thomas M. Back, claimed were the equal of the firm's "gold standard" monocentrics in sharpness, contrast, and lack of scattered light while overcoming their poor eye relief and narrow field of view. If you use a Dobsonian reflector or some other undriven telescope, the wider field is a welcome bonus because the target doesn't drift out of the field as quickly.

> Contrast and definition are the qualities of paramount importance to the fastidious planetary observer.

Frankly, much of the conventional wisdom about what constitutes virtue in the design of a planetary eyepiece has ceased to be true. Maximizing light transmission while minimizing internal reflections and contrast-robbing scattered light remain essential goals, of course. But achieving them no longer limits optical designers to a small number of lens elements and uncomfortably tight eye relief.

Modern high-index glasses and efficient, broadband, multilayer antireflection coatings allow many eyepieces with as many as 10 air-glass surfaces to rival the performance of traditional eyepiece designs in critical side-by-side comparisons on the most challenging planetary details.

The "minimum glass" paradigm for planetary eyepieces still has its vocal adherents, just as there are ardent audiophiles who disparage digital components in favor of old analog technology. But there's been a marked shift toward complex, high-quality eyepieces — many of which, happily, don't command substantially higher prices than those of older, simpler designs.

■ Contributing Editor **TOM DOBBINS** has forsaken his old orthoscopic eyepieces in favor of modern, short-focus offerings by Pentax and Baader.

GREGG DINDERMAN / S&T

Summer Highlights

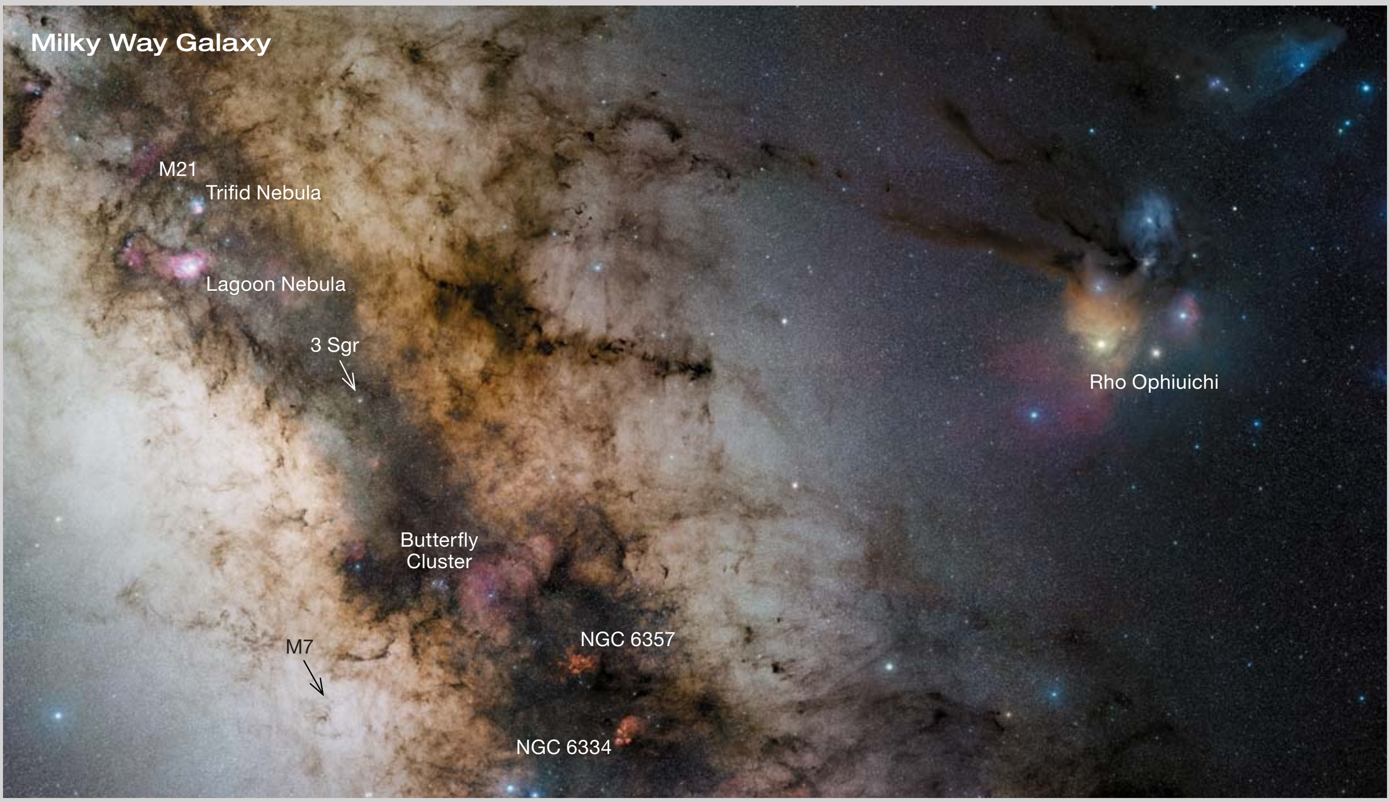
Warm nights and dark skies are ideal for enjoying these classic beauties.

Atop our windy hill, emerald fields turn obsidian as night sweeps her cloak across the world. A scope is waiting, the stars appear, and I'm where I belong. Summer nights are an ideal time for those of us who feel at home among the stars to lose ourselves in some of the most beautiful wonders of the deep sky.

Planetary nebulae are shining baubles on the dome of the sky that come in an amazing wealth of guises. One of the most famous is the **Ring Nebula** (M57) in Lyra, which Antoine Darquier independently discovered with a small refractor while observing the Comet of 1779. He claimed it resembles a planet that's fading away. Although Darquier may have been the first to compare this type of nebula to a planet, it was William Herschel who coined the term "planetary nebula" several years later.

My 130-mm refractor at 23× clearly shows M57 as a very small nebula bracketed by the stars Beta (β) and Gamma (γ) Lyrae. Its ring-like structure reveals itself at just 37×. At 117× the annulus becomes distinctly oval, with ends that are dimmer than its sides. The ring's interior isn't as dark as the sky, creating an overall effect that John Herschel likened to "gauze stretched over a hoop." M57 bears magnification well and appears quite stunning at 234×. Variations in brightness along the rim are accented at this higher power, and the ring's interior appears rounder than its outer periphery, as shown in my sketch on the next page.

▼ Bright nebulae and brilliant star clusters sparkle along the dark dust lanes of the Milky Way Galaxy. Taken from Cerro Paranal, Chile, the image below, which shows the summer Milky Way between Sagittarius and Scorpius, was assembled from 52 different sky fields composed from about 1,200 individual images taken through B, V, and R filters with a 10-cm refractor. The final mosaic represents a total of 200 hours exposure time.



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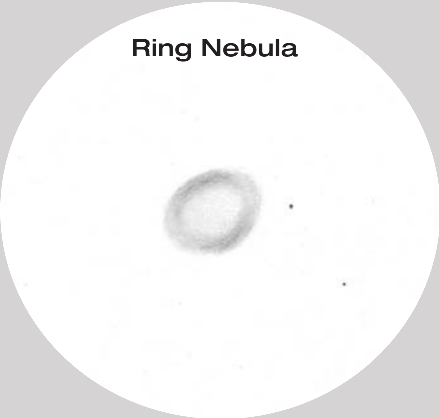


▲ The author's sketch of M57, the Ring Nebula, as seen through her 130-mm refractor at 234×, shows the nebula's gauzy, circular interior.

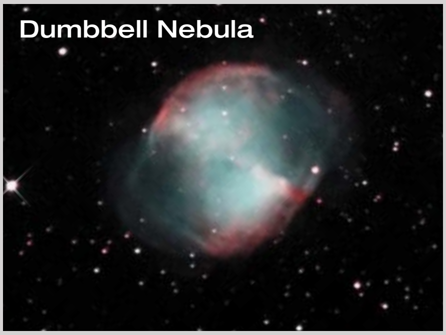
Those who hunt more difficult game can stalk M57's 15th-magnitude central star. Although folks have snared it through scopes as small as 8 inches in aperture, I've never nabbed it with anything smaller than my 14.5-inch. The key to a successful sighting lies in having exceptionally good seeing (atmospheric steadiness) and very high magnification.

Although M57 looks like a simple ring, its structure is actually much more complicated. You could think of it as a bright doughnut wrapped around the middle of a faint football, all embedded in a complex, tenuous halo. The ring structure dominates largely because we're gazing down the pole of the planetary nebula. If we could see the Ring Nebula from the plane of its equator, it might look much like our next object, the **Dumbbell Nebula** (M27) in Vulpecula, the Little Fox.

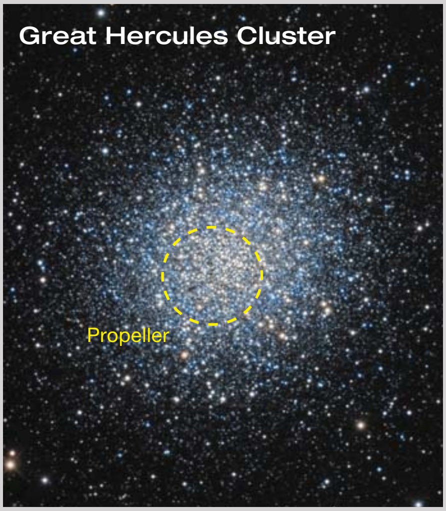
Swept up by Charles Messier in 1764, M27 was the first planetary nebula ever discovered. It rests 24′ south-southeast of 14 Vulpeculae and can be recognized in my 9×50 finder. When seen through my 130-mm scope at 23×, the Dumbbell Nebula looks substantially larger than the Ring Nebula. Its bright region is shaped like an apple with the sides munched away. Protruding from the sides of this apple core is a dimmer region that turns the nebula into a football. At 48× the apple core's rims shine brightest, and its pinched-in sides are more obvious. There's also a fairly bright bar diagonally connecting the caps from east-northeast to west-southwest. The football extensions stand out best at 63×, but it's a rather plump football. Upping the power to 164× the apple core displays brighter wedges hugging the narrower angles where the bar meets each cap. At 234×, the southwestern wedge seems brighter than its counterpart in the northeast.

The Dumbbell's central star is easier to spot than the Ring's, but it's still no walk in the park. The smallest scope I've seen it in was my husband's erstwhile 140-mm refractor, employing a magnification of 300×.

Let's move on to the **Great Hercules Cluster** (M13), a group of more than 200,000 stars about 23,000 light-years away from us. Most globular clusters are not confined to the disk of our galaxy but instead follow inclined orbits and spend much of their time in the



▲ The Dumbbell Nebula looks like a well-gnawed apple core in the eyepiece. Upping the magnification may reveal extensions more evocative of an American football.



▲ M13, the Great Hercules Cluster, resolves from mist to a spangle of brilliant pinpoints with enough magnification. This globular takes magnification well. Increase the aperture to 10 inches or more and raise the magnification to 100× to 200×, and you should be able to see the trio of dark lanes known as "the Propeller." Look southeast of the cluster's core.

Sue's Summer Favorites

Object	Type	Mag(v)	Size/Sep	RA	Dec.
Ring Nebula (M57)	Planetary nebula	8.8	1.6′ × 1.1′	$18^h\ 53.6^m$	+33° 02′
Dumbbell Nebula (M27)	Planetary nebula	7.4	8.0′ × 5.5′	$19^h\ 59.6^m$	+22° 43′
Great Hercules Cluster (M13)	Globular cluster	5.8	20′	$16^h\ 41.7^m$	+36° 28′
Lagoon Nebula (M8)	Emission nebula	3.0	45′ × 30′	$18^h\ 04.1^m$	–24° 18′
Omega Nebula (M17)	Emission nebula	5.5	20′ × 15′	$18^h\ 20.8^m$	–16° 10′
Butterfly Cluster (M6)	Open cluster	4.2	33′	$17^h\ 40.3^m$	–32° 16′

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

▲ The author sketched the Lagoon Nebula as viewed through her 130-mm refractor at 48×.

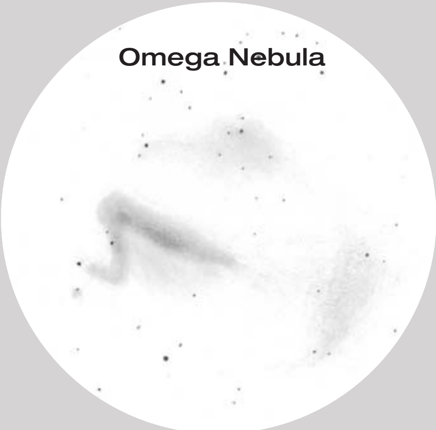
galaxy's halo. M13 is currently 15,000 light-years above the galactic plane.

M13 is visible as a small misty patch to the unaided eye in a dark sky or through binoculars in a suburban sky. The cluster is beautiful even at 37× in the 130-mm scope. It seems to sit on a line between two bright field stars: a 6.8-magnitude, yellow-orange star to the east and a white star just a half magnitude dimmer to the south-southwest. The hazy ball of light is flecked with barely resolved stars and otherwise appears quite grainy. Its very faint halo spans about 15′. The cluster becomes suddenly brighter within a diameter of about 8′ and is a bright, speckled haze within 4′. At 102× a large halo of pinpoint stars surrounds a dense core adorned with glittering flecks tangled in the fleecy glow of unresolved suns. Eye-catching star chains spring mostly from the southwestern half of the bright region and droop toward the white star. The bright region is wonderfully resolved at 164×. It flaunts a greater range of star magnitudes than most globulars and evokes a mound of glittering sugar.

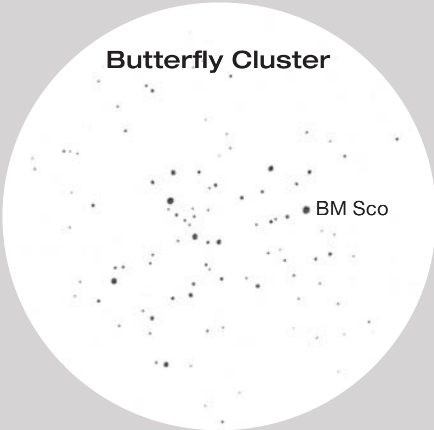
Dusky lines arranged like a three-bladed propeller overlay the southeastern part of M13. They're visible through my 10-inch reflector at 219× and smack-in-the-face obvious through the 15-inch at 192×. Two of the blades cradle the cluster's bright interior, and the third strikes out away from the cluster, where it may be invisible if your view doesn't expose enough stars to backdrop it. The propeller was first brought to light in a sketch by Bindon Stoney, who was in charge of Lord Rosse's Birr Castle observatory in the mid-1800s.

Next we'll visit the gorgeous **Lagoon Nebula** (M8), named for the darkling channel within, like a shadowy bay lapping on a silver shore. In a fairly dark sky, this emission nebula is readily visible to the unaided eye as a misty patch hovering above the spout of the Teapot asterism formed by the brightest stars of Sagittarius. My sketch shows the view through my 130-mm refractor at 48×. No filter was used when placing the stars, but a narrowband filter was added to help define the nebula. The ebony lagoon divides the nebulosity enveloping the open cluster NGC 6530 from the section harboring the brilliant but tiny double-knot of nebulosity called the Hourglass. The two sections are crowned by fainter bands of mist to their north. The brightest star within the nebula is blue-white 9 Sagittarii, and just off M8's western side, 7 Sagittarii shines pale yellow.

Another captivating nebula in Sagittarius that begs for a sketch is the **Omega Nebula** (M17), though I've always preferred its alternate nickname,



▲ Sometimes called the Swan Nebula due to its evocative shape, the Omega Nebula improves when viewed through an O III or narrowband filter. The sketch shows the view through a 130-mm refractor at 63×.



▲ You may be able to spot the Butterfly Cluster with your naked eye if you're under dark enough skies, but this cluster really sparkles with binoculars or a small scope. The sketch shows the individual lights as viewed through a 130-mm refractor at just 48×.

the Swan Nebula. One look at its most prominent feature brings to mind a celestial swan floating on the dark waters of the night. Beyond the figure of the swan, large swaths of diaphanous haze wrap around the swan's body. An O III or a narrowband filter makes the nebula stand out better, and each was used to refine the nebulosity on my sketch. Surrounded by its full retinue of stars, the swan is also enchanting without a filter.

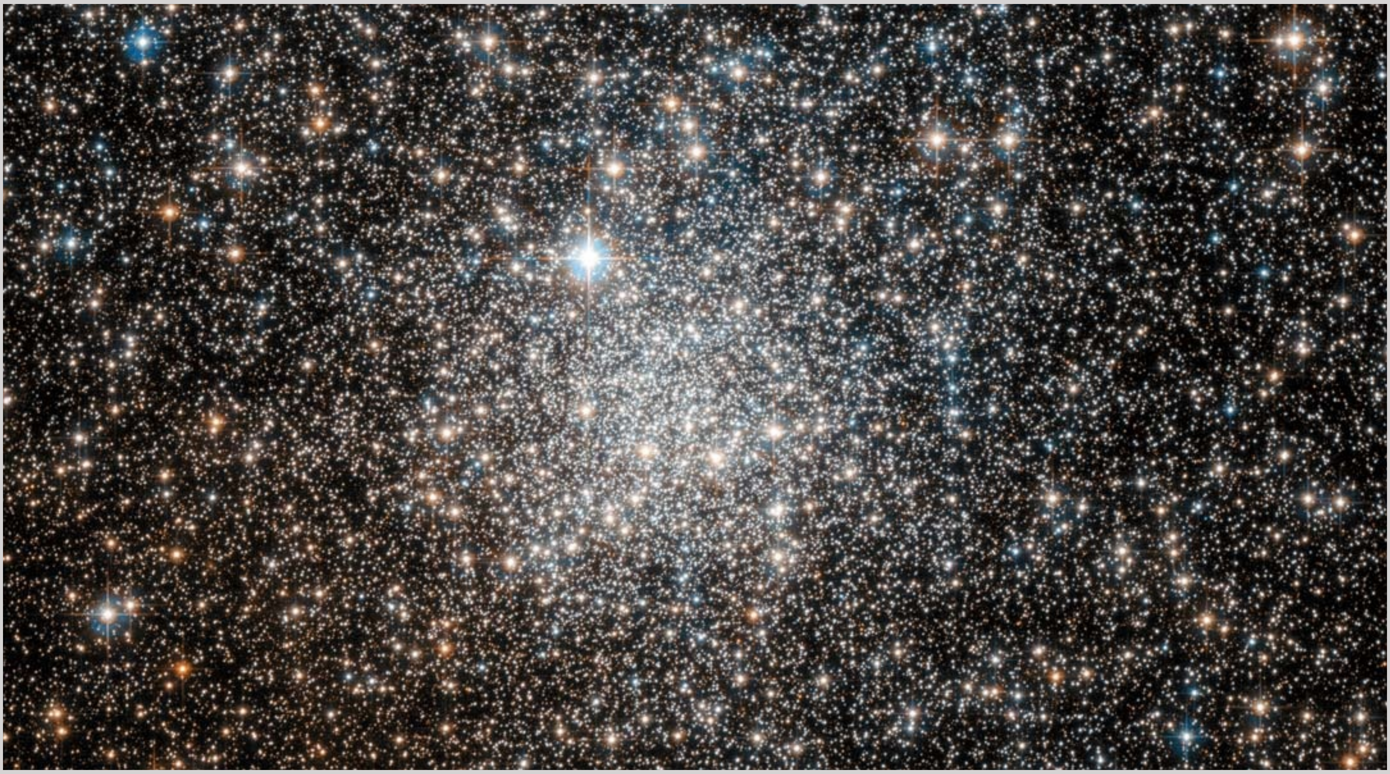
We'll wind up this month's tour with a drawing of the **Butterfly Cluster** (M6) in Scorpius. It was a faint daub of light to the unaided eye when I sketched this lovely pile of jewels with my 130-mm refractor at 48×. Its brightest star is the irregular variable BM Sco, which looks yellow-orange through the telescope. Its magnitude range is about 5.3 to 6.5. While a sketch can't compare to a nice personal view or photo, it gives a good idea of the relative brightness of the stars. The Butterfly Cluster is so named because many of its stars seem to outline four wings, with perhaps even a head and antennae to the northwest. Can you picture our star-spangled lepidopteran?!

■ Contributing Editor **SUE FRENCH** welcomes your comments at **scfrench@nycap.rr.com**.

SUE FRENCH (3)

Seeing Through the Dust

Turning to technology can improve your resolution of globular clusters.



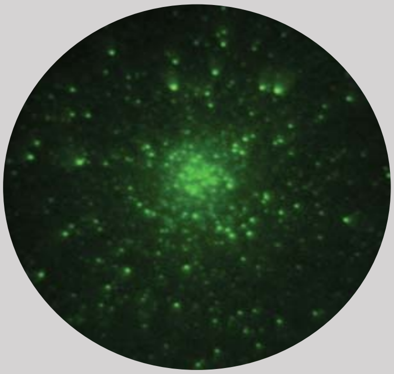
▲ **DISTANT BRILLIANCE** We'll never see the glorious globular cluster NGC 6401 as well as the Hubble Space Telescope can, but with an assist from night-vision technology, we can improve our ground-based observations. NGC 6401 lies 35,000 light-years from Earth in the direction of Ophiuchus and typically looks like a round patch of haze in the telescope eyepiece.

ESA / NASA / HUBBLE SPACE TELESCOPE

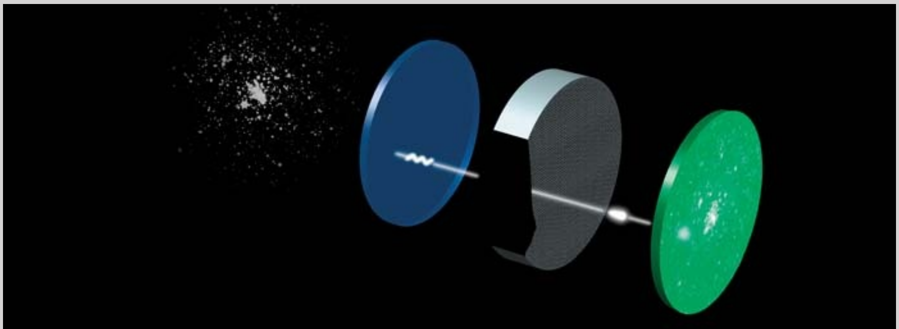
I admit it: I'm a globular cluster junkie. Before I got into amateur astronomy I'd never heard of these beautiful spherical arrays containing tens to hundreds of thousands of ancient suns (see *S&T:* June 2012, p. 62). Now, nothing quite matches the real-time visual experience of a fully resolved globular. But therein lies the rub. Of the approximately 150 globular clusters in our Milky Way galaxy, relatively few resolve into myriad stars in standard backyard telescopes. The problem is not just one of distance, although the distances to most of these clusters are enormous. The bigger problem is interstellar dust.

William Herschel thought "the holes in the heavens" represented an absence of stars. American astronomer E. E. Barnard, even with his decades of photographing these "vacuities," was slow to embrace the concept that interstellar matter exists and can block more distant sources of visible light. Today we know that regions of interstellar dust dramatically dim the light of distant stars, and the vast distances to globular clusters, especially those embedded in the galactic disk, allow the dust to do its mischief. As a result, unsuspecting amateur astronomers excitedly focus their scopes on stellar prey only to be greeted by faint cotton balls of light with no stars resolved. Happily, modern technology has provided a solution to this dilemma.

Night vision electronics in the guise of a telescope eyepiece cuts through the dust as if it were not there. I acquired



▲ **GLOWING GLOBULAR** Dennis di Cicco connected a DSLR camera to his setup to capture this image-intensified view of the globular cluster NGC 6760 through the eyepiece. The eyepiece shows stars some two magnitudes fainter than what he could see through a conventional eyepiece.



GREEN SCREEN The amplifying element in the author's image-intensified eyepiece is the microchannel plate, which is perforated with millions of tunnels with coated walls. When light strikes the intensifier's photocathode, the emitted electrons enter the perforations, ricochet off the tunnel walls, and create more electrons. The electrons pass through the tunnels, hit a phosphor screen, and create an enhanced image.

my Collins I³ image-intensified eyepiece not long after it was reviewed in this publication (*S&T:* February 1999, p. 63). After many years of looking at the brighter globulars with truly remarkable results, I decided to pursue an observing program of fainter globular clusters that are largely ignored by most amateurs. Here, I describe a sampling of my observations using the I³ eyepiece firmly seated in the focuser of my 10-inch Ritchey-Chrétien Cassegrain reflector. I chose to make my observations "blind." That is, I entered every cluster into my Go-To mount and described the view through the eyepiece. The true field-of-view of my setup is 25′, and my site conditions are relatively good. I observe from a site above 7,000 feet in elevation with a naked-eye limiting magnitude of 6.0. Good to excellent transparency is key to resolving these targets.

NGC 6626 (Messier 28), relatively big and bright, is obscured by a little more than one magnitude of dust. That's enough dimming to cause some amateurs to bypass this gem as they head over to magnificent M22. I find the cluster fully resolved with a diameter of 8′. The nucleus consists of a 1′ crowding of five large, closely packed stars surrounded by a heavily populated core of stars extending out to a 5′ diameter. As with most globulars, the outliers of the cluster are more thinly distributed, but here the pattern is a bit more irregular than most. The three levels of star density make this a worthy target that I've enjoyed on many nights.

Not far away is the gorgeous cluster **NGC 6624**. I call it a "starburst" globular in that it has a very intense 1′ nucleus with the rest of the stars radiating out in all directions to a total extent of 5′. If you've ever had a well-resolved view of M80 you'll probably recognize this description. NGC 6624 stands out well from the surrounding star field that adds to the attractiveness of the scene.

Our next target is big and beautiful **NGC 6553**. The total extent is 8′ with innumerable pinpoint stars defining the highly circular cluster. A multitude of bright individuals define a 4′ core that suggests to my mind the outline of a five-pointed star. Without electronic amplification resolution, the resolution of this

Dust-obscured Globular Clusters

Object	Class	Mag(v)	Size	RA	Dec	Dimming	Distance (l-y)
NGC 6626	IV	6.8	11′	18h 24.5m	–24° 52′	1.2	17,900
NGC 6624	VI	7.9	5.9′	18h 23.7m	–30° 22′	0.84	25,800
NGC 6553	XI	8.1	8.1′	18h 09.3m	–25° 55′	1.9	19,600
NGC 6304	VI	8.2	8.0′	17h 14.5m	–29° 28′	1.6	19,200
NGC 6539	X	9.3	7.9′	18h 04.8m	–07° 35′	3	25,400
NGC 6287	VII	9.4	5.1′	17h 05.2m	–22° 42′	1.8	30,300
NGC 6401	VIII	9.5	5.6′	17h 38.6m	–23° 55′	2.2	34,600
NGC 6426	IX	11	4.2′	17h 44.9m	+03° 10′	1.1	67,100
NGC 6256	—	11.3	6.6′	16h 59.5m	–37° 07′	3.1	27,400
NGC 6749	—	12.4	6.3′	19h 05.3m	+01° 54′	4.5	25,800

Class information is from Strong & Sinnott, *Sky Atlas 2000.0 Companion*. 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.

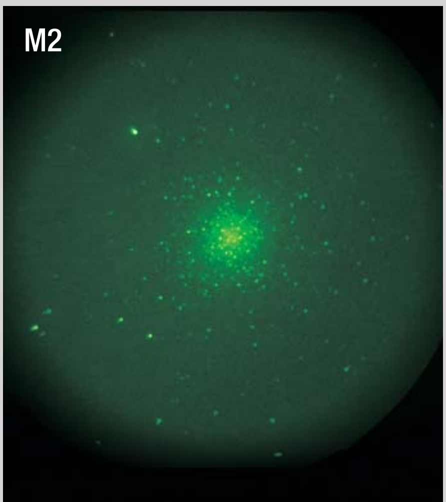
GREGG DINDERMAN / *S&T* ARCHIVES

cluster would be hopeless as it's dimmed by nearly two magnitudes of dust.

Globular cluster **NGC 6304** may take the cake for the most interesting shape it conjures up in my mind. The central portion of its 8′ extent features an oval collection of stars containing a straight line of five brighter stars crossing it about ⅓ of the way down. To me this resembles an acorn in the sky with the line of stars defining the top of the acorn from its main body.

The next cluster has no central concentration at all. **NGC 6539** has a 7′ extent that can only elicit the classic description of diamond dust on black velvet. Three magnitudes of interstellar dust enshroud this cluster, making it an unresolvable target for all but the largest amateur telescopes. Interestingly, NGC 6539 lies at almost the same distance and is of the same absolute magnitude as M92, a common target for the backyard enthusiast. The fact that it's virtually unknown to many highlights the difficulty that dust introduces to visual observations.

NGC 6287 is a well-resolved 5′ cluster. The arrangement of brighter stars on the globular's periphery led me to calling this the "Eiffel Tower" cluster. The top star of the tower is to the southwest, and the heart of the cluster occupies



DEEPER LOOK Image-intensified eyepieces are ideal for viewing star clusters. Although your view will be tinted, color photography falsely boosts the screen's green hue in this image.

TOP: POSS-I / NATIONAL GEOGRAPHIC SOCIETY / PALOMAR OBSERVATORY / CALTECH; BOTTOM: DENNIS DI CICCO

the "observation deck." In contrast to this circular cluster, **NGC 6401** forms a distinct arrowhead shape composed of similar magnitude stars in a 2′ array. Over two magnitudes of obscuration and a distance approaching 35,000 light-years make these stars faint but still observable with my equipment.

As far as distance is concerned, **NGC 6426** is the hands-down winner in my tabulation. It's a faint, fully resolved loose collection of stars covering a section of sky approximately 4′ or 5′ across. I observed these clusters from numeric lists with no preconceived notions of what I would see. I was quite surprised to find out later that this cluster was 67,000 light-years away with a magnitude of dust-dimming to boot.

I was even more amazed to see **NGC 6256** as a faint but well-resolved cluster of 7′ diameter. It's very loose, and my notes at the eyepiece are "class X-XI?" (the Shapley–Sawyer classification class, categorizing this globular as loose and homogenous at the center). This cluster is so obscure that it's neither described in any of my reference books nor listed with any of the professional classifications that I use to compare my own observations.

Our final target, **NGC 6749**, would be an average cluster for amateurs if not for the whopping 4½ magnitudes of dimming by interstellar dust. I'm able to see a patch of light approximately 4′ in diameter with about half a dozen stars making a faint appearance. These stars are barely brighter than 17th magnitude!

In an article published in 1900, George W. Ritchey wrote, "The visual limit . . . of the 40-inch [great refractor at Yerkes] is at about 16.5 to 17 magnitude." He was talking about globular clusters. This comparison provides a measure of aperture increase that I'm achieving with the electronic eyepiece coupled to my 10-inch reflector.

I've been able to make these observations for two simple reasons. A globular star cluster is the ideal target for night vision technology like that originally produced by Collins. The brightest stars of a globular are swollen red giants with

▲ **WELL RESOLVED** The author estimates the resolution of globulars viewed through assistive technology matches that using the red channel of the Digitized Sky Survey with a 15′ × 15′ field of view.

peak luminosities in the near-infrared at a wavelength that exactly corresponds to the maximum sensitivity of the eyepiece. This longer wavelength, invisible to the human eye, has a second benefit especially germane to assisted observing of globulars. As wavelength increases, interstellar dust is less able to hinder its travel. This means the electronic eyepiece is seeing more starlight exactly at the sweet spot of its sensitivity. The result is a field of pinpoint stars of varying magnitude with the brightest stars of somewhat larger diameter.

My particular eyepiece is dated and no longer commercially available, but Night Vision Devices sells a wide range of monoculars with specifications that meet or exceed the Collins design. These devices are useful for a wide range of deep-sky objects, not just globular clusters. You may be able to find image-intensified eyepieces on the second-hand market as well. I'm convinced this technology is under-utilized by amateurs and deserves serious consideration, especially at light-polluted observing sites.

I'm amazed by the number of clusters that I've been able to resolve and the cluster diameters that I've recorded. The most satisfying feature of all is the fact that every cluster is different and visually enthralling. I'll never grow tired of viewing them.

■ **ED MIHELICH** has resolved 80 globular clusters from mid-northern latitudes.

The Astro-Physics 1100GTO

This powerful German equatorial mount offers many features for astrophotographers.

Astro-Physics 1100GTO

U.S. Price: $7,970.00 (base model)
astro-physics.com

▲The Astro-Physics 1100GTO mount on an Astro-Physics pier with an AP 130EDFGT telescope on top. The mount weighs 54 pounds and can carry a 100-pound payload.

What We Like:

Tracking across the Meridian

Payload capacity

Command Center software

What We Didn't Like:

Controller display difficult to read in daylight

Confusing settings in *ASCOM* driver and *APCC* software

HOW WOULD YOU like to have your cake and eat it, too? How about an observatory-class mount that can carry a 100-pound payload and still be portable enough to pop in your car and go to a remote observing site?

You can't say that about many mounts, but you can with the 1100GTO, the Astro-Physics replacement for its venerable 900GTO, which served as one of the company's most-popular mid-range mounts for 20 years. The 1100GTO has some tall shoes to fill; let's find out how it stacks up.

Designed by Robert Watters and Roland Christen at Astro-Physics, the precision CNC-machined 1100GTO has managed the neat trick of keeping the weight of the mount the same as the 900GTO while increasing the payload by 50%. This was accomplished by increasing the diameter of the RA and declination shafts to 3.15 inches and the bearings to 3.94 inches. The declination worm-wheel diameter has also increased from 6 to 7.2 inches.

For astrophotography purposes the 1100GTO will easily bear its rated capacity, and possibly more unless you are using a long telescope in a howling wind. The mount, which is steady as a rock, can also be operated from

ALL PHOTOS COURTESY THE AUTHOR

a latitude range of 0° to 78° without requiring additional adapters.

The equatorial head weighs in at 54 pounds, including the counterweight shaft. Even at my advanced age and with back problems, I can lift the entire head of the 1100GTO in one piece to move it from the car to its portable pier. If you can't handle that much weight, the mount has a very clever dovetail with a tool-free design that allows you to separate the head into two pieces, with the RA portion weighing 26 pounds, and the declination section and top plate weighing just about 18 pounds.

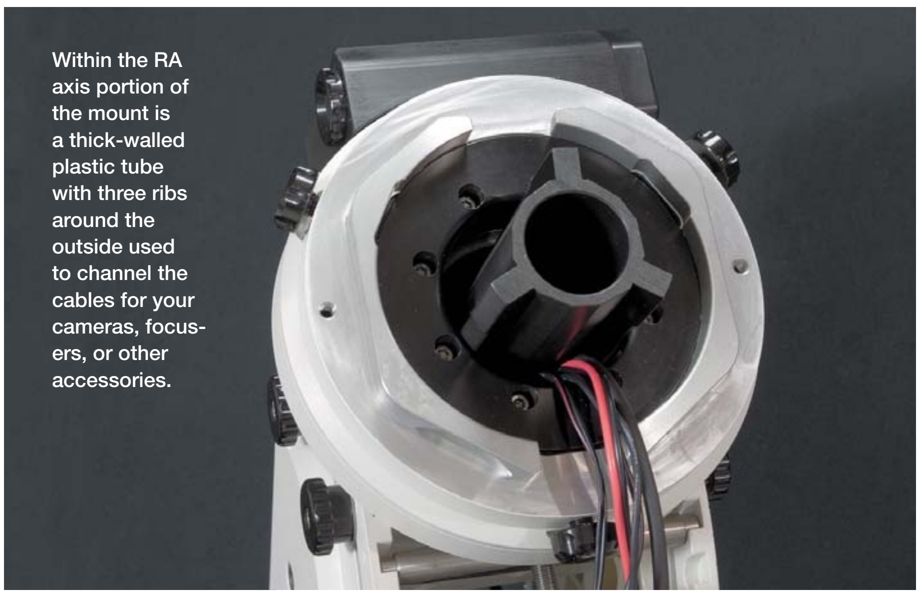
The mount is offered in three versions: the 1100GTO (borrowed for this review), 1100GTO-AE ($14,196) with absolute encoders, and the 1100GTO-AEL ($14,961) with extended-temperature absolute encoders. These allow the mount to unequivocally know its exact pointing position — something that is very useful in a remote observatory. The encoders also nearly eliminate periodic error, reducing it to just 0.2 arcsecond, according to the manufacturer.

The GTO keypad hand controller for the mount is sold separately for $1,060 for those who intend to only use the mount with an external computer or have a hand controller from another Astro-Physics mount. Additional accessories, including the polar alignment scope, counterweights, and dovetail saddle, are purchased à la carte. The Right-Angle Polar Alignment Scope is invaluable for portable observers and a work of art that will save your neck and get you aligned to within a couple of arcminutes of the pole in roughly 30 seconds. This accuracy is more than adequate for long-exposure astrophotography. The counterweight shaft has been redesigned with a new lead-in thread that greatly reduces the chance of cross threading.

Originally introduced in April, 2013, the latest version of the 1100GTO now sports the new GTOCP4 controller as well as auto-adjusting gearboxes. Its spring-loaded worm gears maintain full engagement with an automatic worm mesh that shouldn't require adjustments. A lever disengages the worm

As supplied by Astro-Physics, the 1100GTO includes a counterweight shaft and GTOCP4 control box, as well as 12-volt power cables and a CD containing the user manual, *PEMPro,* and *PulseGuide* software. The pier shown is sold separately.

The equatorial head can be separated into two pieces with the RA axis and polar base (left) weighing 26 pounds, and the declination axis (right) weighing 18 pounds.



Within the RA axis portion of the mount is a thick-walled plastic tube with three ribs around the outside used to channel the cables for your cameras, focusers, or other accessories.

▲ The new Astro-Physics GTOCP4 control box (which is backwards-compatible with older mounts) offers two full-service RS-232 serial ports, a USB 2.0 port, Ethernet, and WiFi connectivity.

from its worm wheel so the scope can spin freely, making balancing a scope quick and easy, something that will be appreciated by users without a permanent installation.

Tracking Accuracy

The 1100GTO comes with a guaranteed peak-to-peak periodic error of 7 arcseconds or better. In measurements I made with *PEMPro,* the periodic error was 2.9 arcseconds with the Periodic Error Memory (PEM) correction curve turned off.

Astro-Physics also supplies its mounts with a factory-generated correction curve installed, which should improve PE even more, though I had trouble getting it to work. On both a Mach1GTO that I own, as well as this test mount, the factory-installed PEM made the PE worse. I was, however, using beta versions of both *Astro-Physics Control Center* (*APCC*) and *PEMPro*, but neither I, nor the support staff at Astro-Physics, were able to figure out exactly what went wrong. I ended up recording a new correction curve with *PEMPro* (which is included with the mount), and the periodic error dropped to 1.8 arcseconds. In actual use with autoguiding during long-exposure imaging, I found the guiding accuracy to be better than 0.5 arcseconds in poor seeing. This should improve in better conditions.

Other Features

Astro-Physics mounts can track the sky well past the meridian, and with *APCC*'s new meridian limits you can trust that your equipment won't be damaged if you are inattentive or happen to fall asleep, or if you are using it in a robotic observatory. You can also target a field that is near but has not yet crossed the meridian, so you can start shooting early and continue without requiring a meridian flip — a wonderful feature for astrophotographers.

Another very nice feature of the 1100GTO is its through-the-mount cabling. All of the motor and power cables are internal, and you can run your auxiliary power and camera-control cables through the hollow RA and Dec axes and have them come out under the telescope-mounting plate. This eliminates the possibility of cables getting snagged while slewing or tracking, but can be problematic if you need to break the mount down into two pieces for transport.

▲ An optional GTO Keypad is available for users who prefer to avoid additional computers while operating the mount.

▶ The 1100GTO with the author's telescope and additional imaging equipment is seen ready for a night of action. Note that the autoguider and camera cables run through the mount axes, exiting near the polar finder.

▲ The 1100GTO tracks effortlessly as seen in this photo of reflection nebula IC 2169 and its surroundings in Monoceros. North is to the right. The image was captured using the setup seen on page 62.

◀ The counterweight shaft includes a section of lead-in threads designed to lessen the chance of cross-threading when attaching to the mount.

GTOCP4 Control Box

Another new feature with the 1100GTO as well as the company's other mounts is the GTOCP4 control box ($1,195). This control box includes pretty much every kind of computer interface you could ever want, except maybe direct mind control. You can still connect to the mount using its serial port, as well as Ethernet, USB, and even WiFi. You can perform firmware updates with a direct download.

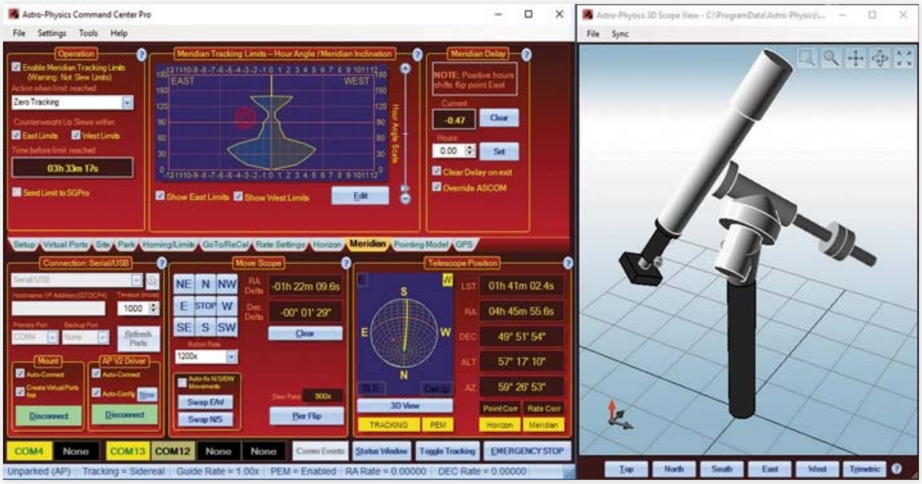
Note that previously if you planned to control the mount through WiFi with a planetarium app on a mobile device, the mount needed to be initialized with either the keypad or a separate computer using the Astro-Physics *ASCOM* driver. Both *SkySafari* and *Luminos* apps now incorporate the Astro-Physics mount initialization into their apps.

The GTOCP4 offers safety slew logic and park features for "counterweight-up" positions. Because you can image past the meridian, and pre-flip the mount, the counterweight shaft can be positioned higher than the scope itself. Previously, this start position could be dangerous for your equipment, as your camera or scope could run into the pier or tripod leg. The new safety slew will move the mount in right ascension first, until the scope is in a normal counterweight-down position, and then continue to slew in both axes until the scope reaches the desired pointing position.

Astro-Physics Command Center

For users who prefer to control the 1100GTO with a computer, the *Astro-Physics Command Center* (*APCC*) software suite is available in standard ($249) and pro versions ($499). Developed by Ray Gralak, *APCC* enables advanced mount-control features such as home and slew limits for non-encoder mounts, user-definable meridian and horizon tracking limits, with custom variable meridian limits for different declinations.

The program also provides the ability to slew to counterweight-up positions, custom tracking rates, savable slew coordinates, and a safety countdown timer that will protect the mount from running into the pier if its computer connection is lost. A virtual 3D



▲ *Astro-Physics Command Center Pro* software showing the Meridian Tracking Limits tab open and with the 3D Scope View window also open and displaying the position of the telescope in relation to the pier. Custom meridian limits can be set for different declinations (represented by the hour-glass figure in the graph) to avoid accidental impacts when tracking your target.

telescope shows simulated views of the scope and mount from various angles to help you visualize its location, which can be useful for remote observatories or if you are sitting in your car on a cold night and running your scope with a remote desktop program.

The pro version of *APCC* offers the ability to build a detailed dual-pointing model (one for each side of the meridian) that works transparently even with the mount in a counterweight-up position, so the model will keep working no matter if you start before, or shoot past, the meridian.

You can record the pointing and tracking model using *Astro-Physics Point Mapper*, a separate application included with *APCC*. Note that a camera-control program such as *MaximDL* or *Sequence Generator Pro* is required, as well as plate-solving software — all of which are available from third-party vendors.

Included with both versions of *APCC* is *Horizons*, a program that lets you download ephemeris elements for solar system objects as well as satellites and then automatically track them.

The only issue I had with both *APCC* and the *ASCOM* driver is that some of the settings are duplicated in multiple locations, and it can be confusing as to which one takes precedent.

In Closing

The 1100GTO offers superlative craftsmanship, design, and execution, but when you buy an Astro-Physics product you're also getting industry-leading support. I can't help but rave about how helpful George and Howard were at Astro-Physics when I had a question or problem with any of the hardware or software. In addition to the traditional online support forums, you can even call and talk to them in person. In this age of automated telephone directories, Astro-Physics support and service are simply remarkable.

When I used the 1100GTO mount, I had to say that I felt, like Oscar Wilde, "always satisfied with the very best."

■ Contributing Editor **JERRY LODRIGUSS** shoots the sky from rural locations in New Jersey and Pennsylvania.

▶ The edge-on spiral galaxy NGC 891 is seen with nearby galaxy cluster Abell 347 in Andromeda, shot with a 5-inch refractor on the Astro-Physics 1100GTO mount.

▼ Astro-Physics' optional Right-Angle Polar Alignment Scope is a must-have accessory for users who set up and take down their equipment each night.

MIRRORLESS CAMERA FILTERS ▶

Astronomik now produces clip-in filters for Canon EOS M-series mirrorless cameras. Prices start at €139 (about $175) for a CLS Clip-Filter. Designed to fit between most Canon lenses and its M1 and M3 camera series detectors, the filters' placement ensures minimal distortions to stars throughout your images. These filters offer the same specialized passbands as the firm's DSLR clip-in filters, including clear (CLS) with UV/IR blocking, narrowband wavelengths such as Hα, O III, S II, and many other passbands particularly useful when shooting with modified mirrorless Canon cameras.

Astronomik
astronomik.com

MODULAR CAMERA ▶

iNova announces a new series of modular CCD cameras to enable virtually any type of astronomical imaging. The Smart Imaging System (starting at $629 for the SIS224C) is a compact camera body that features an internal CPU with an 8-core ARM processor and 2 gigabytes of RAM. Its Linux Ubuntu operating system permits planetary or deep-sky imaging without an additional computer at the telescope. The camera is available with a variety of low-noise Sony IMX CMOS sensors, and it can be upgraded with a host of additional options including removable SSD disks, Micro SDHC cards, and even a mini-wireless keyboard. The SIS camera also incorporates a built-in web server with wireless access and many other connections, such as Ethernet, Micro USB, and a two-port USB 2.0 hub. See website for additional details.

iNova Technologies
inovaccdusa.com

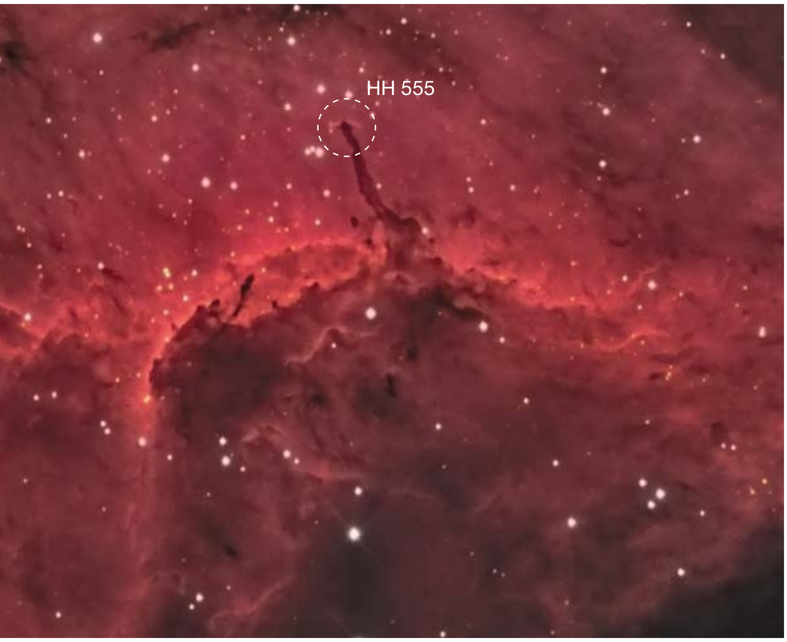
EQUATORIAL TRACKER ▶

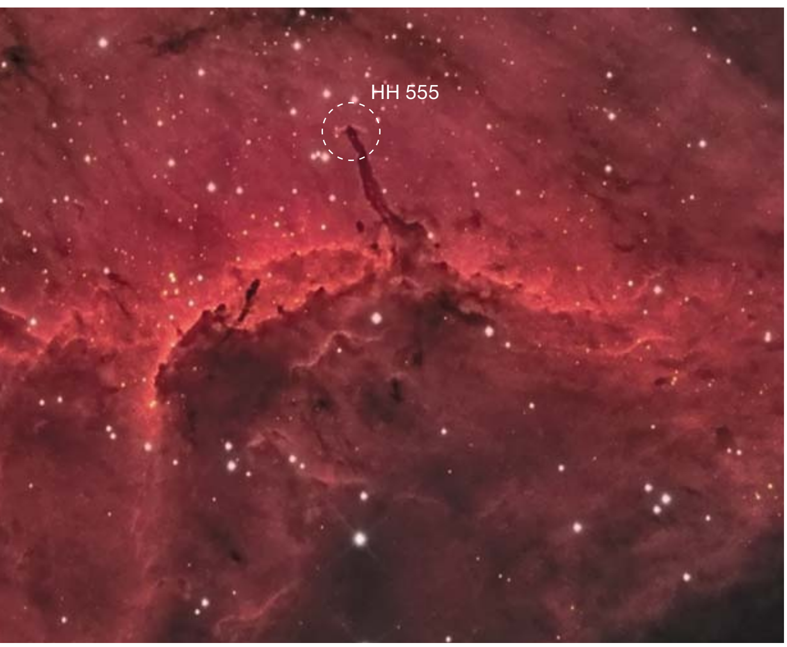
iOptron unveils the SkyGuider Pro Camera Mount Package ($498), a complete, ultra-portable mount for wide-field astrophotography. The SkyGuider is a compact single-axis drive for cameras. The unit can sturdily bear a load of up to 11 pounds (5 kg) and has 4 tracking rates for nightscape or deep-sky astrophotography. The SkyGuider Pro package is powered by an internal rechargeable battery and also has a removable counterweight shaft and 3.3-pound counterweight that can be replaced with an additional ball head for dual-camera operation. A declination mounting bracket, polar scope with a variable-brightness illuminator, and stainless-steel field tripod come with each purchase. Additional options are a hand-paddle controller and ball head with a quick-release dovetail system.

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

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

Restoring Detail *with* Deconvolution





Recover information in your deep-sky images with this powerful technique.

Most of us don't have the luxury of imaging with an orbiting space telescope, where there's no atmosphere to degrade our images. For us Earth-based imagers, the reality is that turbulent air inevitably blurs detail in our deep-sky shots. Even in the steadiest seeing conditions, the "true" image — as it would be with no degradation — is *convolved*, or mixed, with the blurring effect of the atmosphere and distortions caused by imperfect optics. Fortunately, many image-processing software packages include powerful deconvolution and sharpening tools that can recover much of the detail buried in your frames.

Sharpening vs. Deconvolution

Sharpening and deconvolution tools work in very different ways. Sharpening primarily increases contrast along well-defined edges in images, whereas deconvolution performs an iterative pixel-by-pixel restoration using a mathematical model of the blurring function, leading to an overall sharper image.

Deconvolution is rooted mainly in work done by Norbert Wiener of MIT. He published these findings in the 1949 book *Extrapolation, Interpolation and Smoothing Stationary Time Series with Engineering Applications*. Since then, deconvolution has been used in weather forecasting, seismology, spectroscopy, microscopy, forensic photography, and many other scientific and engineering applications, including, of course, astronomy. In one famous example, deconvolution was used to improve early Hubble Space Telescope images impaired due to the orbiting observatory's flawed primary mirror (*S&T:* Oct. 1990, p. 352). In the nearly 70 years since its development, deconvolution has become an essential image-processing step for most professional and many amateur astrophotographers.

◀ **NOTABLE DIFFERENCE** Deconvolution can restore faint stars and small-scale detail hidden by the blurring effects of our atmosphere. This pair of images show a close-up of Herbig-Haro Object 555 (circled) in the Pelican Nebula. The bottom image uses Regularized Richardson-Lucy deconvolution in *PixInsight* to tighten up many stars, as well as features within the nebula itself.

ALL IMAGES COURTESY OF THE AUTHOR

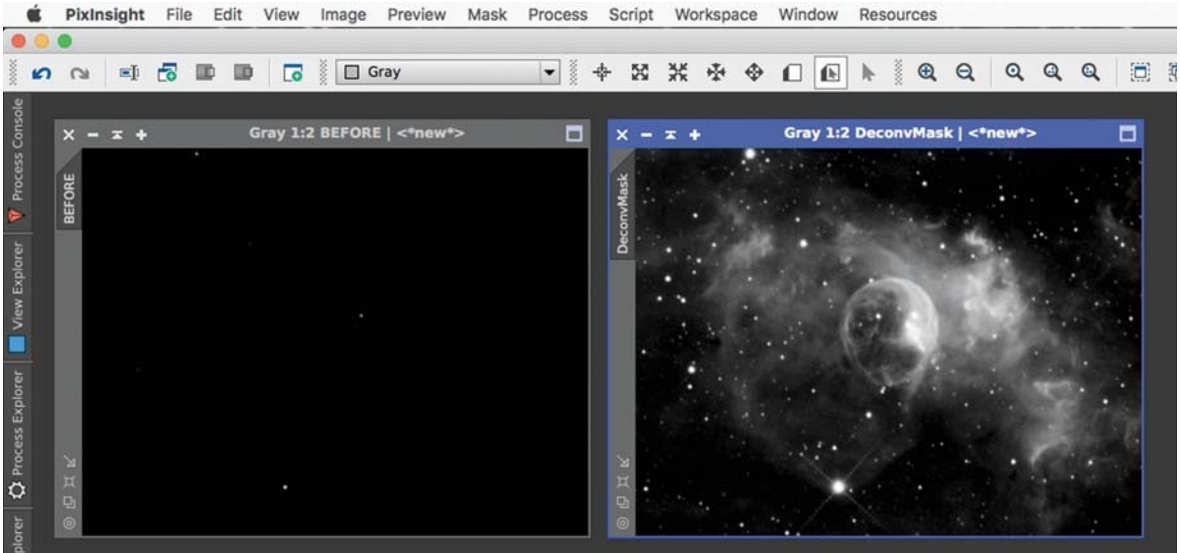


IMAGE AS MASK A stretched copy of the target image is used as a Deconvolution Mask in *PixInsight* to limit detail enhancement to the brightest areas.

When to Apply Deconvolution

While most astrophotographers have success improving their images using standard sharpening tools like the popular Unsharp Mask tool in *Adobe Photoshop,* they often report that deconvolution either didn't work or made their images appear worse. I've learned that, to be applied successfully, deconvolution must be performed at the right place in the workflow.

The technique is best applied to linear images, before the image is non-linearly stretched to reveal both the brightest areas and faintest regions simultaneously. Non-linear processing alters the relationships between pixel values in the original data, and deconvolution won't work properly after that point. (Standard sharpening tools may work well on these stretched files, however.)

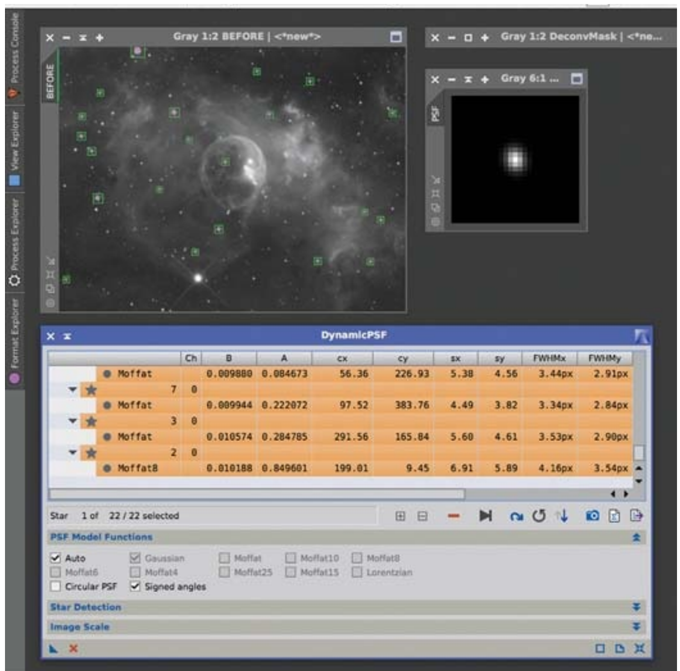
Deconvolution works best on luminance images, which tend to have the highest signal-to-noise ratio. A luminance image can be created by shooting through a luminance filter, or synthesized from the combined red, green, blue, or narrowband photos, and can even be extracted from a color image. While most astronomical image-processing software includes some form of deconvolution tool, my preference is to use *PixInsight* (**pixinsight.com**). For more information on where deconvolution fits in a *PixInsight* workflow, see *S&T:* Aug. 2016, p. 66.

Preparation

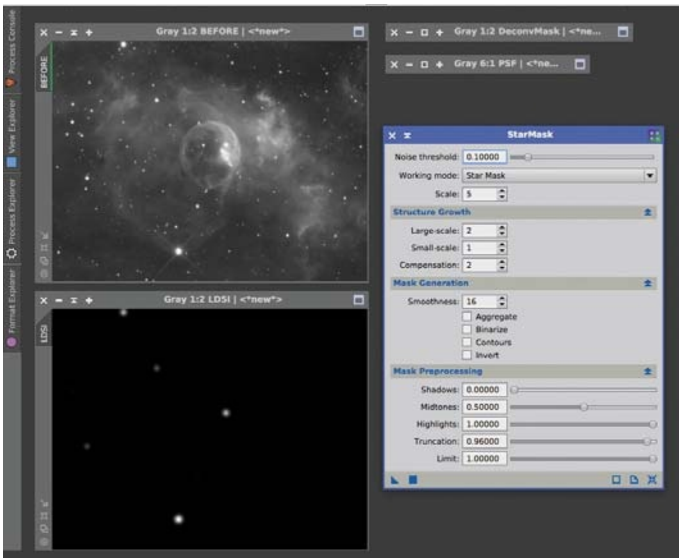
To perform deconvolution in *PixInsight*, three support images need to be generated from the image that you want to process.

The first support image is a deconvolution mask. Because the background in your image contains little detail, deconvolution in these areas will only enhance noise. So you should generate a mask that protects these areas from the deconvolution process. You can make it in varying ways, including creating a copy of the image and stretching it using HistogramTransformation. Or you can apply the RangeSelection tool, found in the pulldown menu at PROCESS > MaskGeneration > RangeSelection.

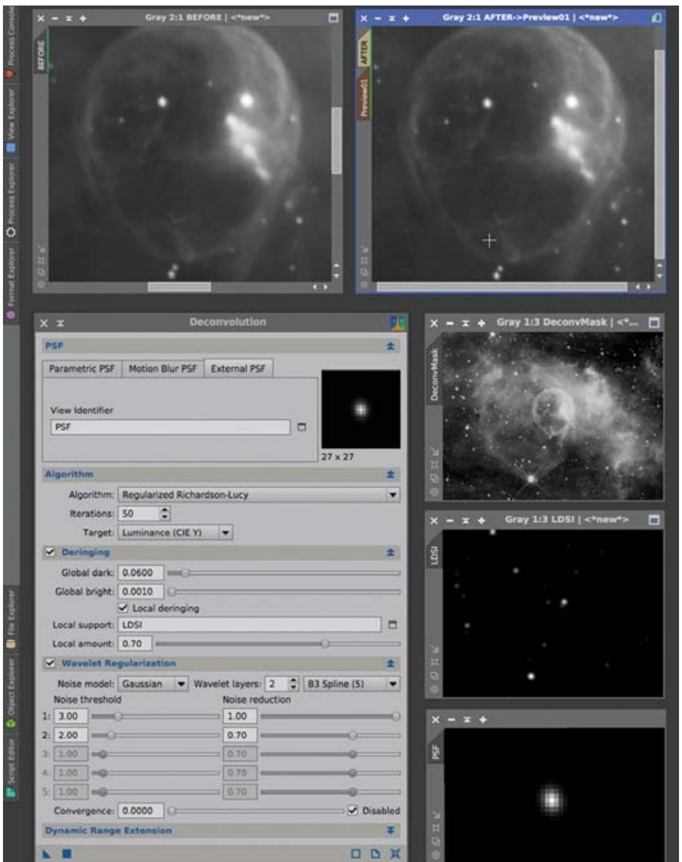
In this process window, increase the lower limit and the smoothness settings, then click the "apply" square at the bottom left to produce the mask. You might need to experiment with these settings and apply them a few times until you construct a mask that blocks everything but the stars and the brightest area you want to deconvolve.



MEASURING BLUR The DynamicPSF tool estimates the point spread function (PSF) from a selection of stars in the image, which the deconvolution tool then uses to accurately restore detail. Choose at least 20 unsaturated stars to get the best results. Clicking on the camera icon generates the PSF image.



NO DARK DONUTS A "local deringing support image" (LDSI) at bottom left is created using the StarMask tool, and prevents dark circles from appearing around the brighter stars — a common processing artifact that often results from deconvolution.



APPLYING DECONVOLUTION Compared to the "before" image of the Bubble Nebula, NGC 7835, at top left, the "after" image to its right shows increased detail, and faint stars are made more apparent. Getting this result required applying the three support images at right with *PixInsight*'s Deconvolution tool.

Next, you need to generate a point spread function (PSF) image. This file contains the information needed to deconvolve your image properly. The PSF estimates how each point source in the image has been spread out due to blurring. This image is prepared by selecting PROCESS > Image > DynamicPSF and then manually clicking about 20 or more stars in your target image. Try to choose fainter stars in your linear image; the best choices will show a value of between 0.25 and 0.9 in column A. Once you've clicked on enough stars, select them all in DynamicPSF with Control+A and click the camera icon to generate the PSF image.

The last support file needed to perform deconvolution is a local deringing support image (LDSI). The brightest stars in the target image need extra protection to avoid introducing artifacts that appear as dark rings in the deconvolved result. The LDSI is a grayscale image that is completely black except for the brightest stars, and can be made by applying StarMask (PROCESS > MaskGeneration > StarMask) to the target image using its default settings. The Deconvolution tool uses this file to provide special deringing protection for the brightest stars. To include more stars in the LDSI, reduce the value in the Midtones slider.

Adjusting the Settings

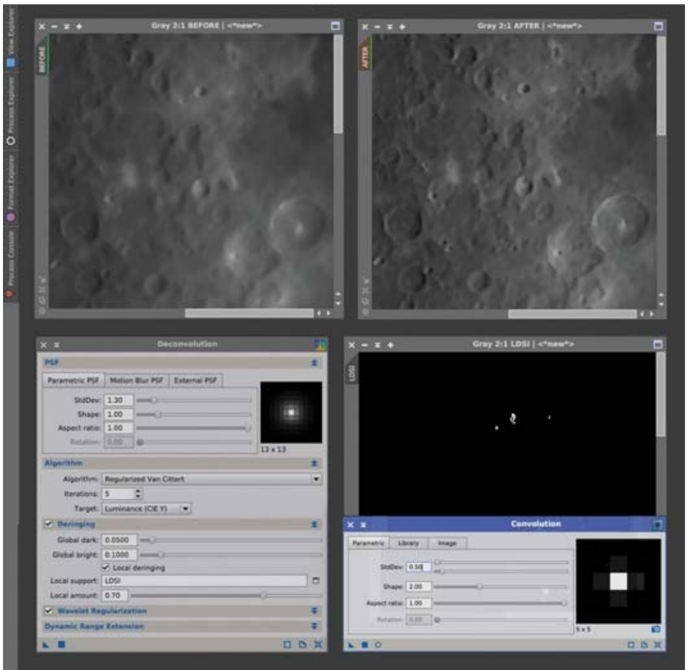
Now that you have created the support files, apply the deconvolution mask image to the target image by selecting MASK > Select Mask and choosing your deconvolution mask image. Next, open the Deconvolution tool from the pulldown menu (PROCESS > Deconvolution > Deconvolution), select the External PSF tab in the deconvolution tool window, and choose the PSF image in View Identifier.

Check the box next to Deringing, as well as the Local Deringing option, and choose your LDSI image in the Local Support section.

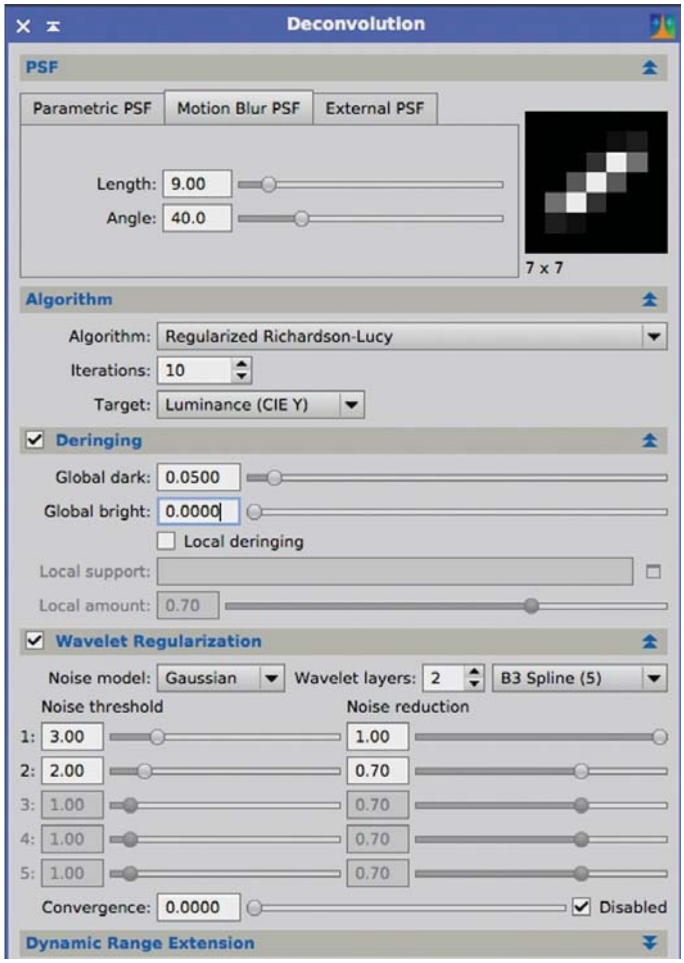
For most deep-sky images, the Richardson-Lucy deconvolution algorithm works best. The Van Cittert algorithm sometimes works well on lunar and solar images, as we'll see shortly.

For both these algorithms, *PixInsight* includes a "regularized" version that suppresses noise during deconvolution. I usually tweak the settings on a small portion of the image made using the Preview menu option (Alt-N). The Preview should contain both high and low signal areas. This speeds up the task of optimizing settings for detail restoration, background protection and suppression of ringing artifacts around stars. I focus on finding the best settings for Global Dark Deringing and the number of iterations. For Global Dark Deringing, find the lowest value that prevents ringing artifacts around the stars. You can use a small amount of Global Bright Deringing to suppress bright artifacts, but a gentle touch is recommended since deconvolution is extremely sensitive to tiny changes.

Once you're satisfied with the Preview result, apply the tool to the image by clicking the Apply square at the bottom left corner of the tool window. At this early stage in the workflow, the improvements produced by deconvolution might appear subtle. But make no mistake: They will definitely



LUNAR RESULTS For bright solar system targets such as lunar close-ups, the Regularized Van Cittert algorithm produces significant improvement. A range mask (made using the RangeSelection tool) was used as the LDSI to prevent artifacts from appearing on crater rims and other bright features.



▶ **TRAILING FIX** Using the Motion Blur PSF mode in the Deconvolution tool can correct slightly elongated stars.

improve the amount of detail in the final result. You can also bring to bear sharpening tools later in the processing workflow to further enhance details recovered with deconvolution.

Other Uses

Images of solar system objects, including the Sun, Moon, and planets, can greatly benefit from deconvolution. For these bright targets, the Regularized Van Cittert algorithm works well in Parametric PSF mode, but it takes some experimentation to dial in the best settings. As with deep-sky imagery, make a deconvolution mask of your target image as described above. If you're processing a lunar picture, you can generate the LDSI file from the deconvolution mask using the RangeSelection tool to select just the brightest features.

Once again, create a Preview on which to experiment and try to find the best setting for the StdDev slider first, ignoring artifacts that might occur. Next, adjust the Global dark and Global light sliders in the Deringing section to taste. As for deep-sky objects, choose the lowest settings that achieve the desired result. If the outcome still looks a little too sharp after Van Cittert deconvolution, applying a slight blur can give the image a more natural appearance. The Convolution tool works well for this purpose.

PixInsight's Deconvolution tool can also fix slightly elongated stars, as long as the direction and amount of elongation (eccentricity) of all stars are similar; it won't fix field rotation issues. Of course, it's much better to correct the root causes of the eccentricity — usually an issue related to the optics, tracking, or polar alignment. With realistic expectations in hand, make a star mask from a stretched copy of the image and apply it to protect nonstellar features and background.

Open the Deconvolution tool and select the Motion Blur PSF tab. Here is where you'll adjust the length and angle to match the amount of elongation in your target image. One or two iterations of deconvolution is usually sufficient, though you'll need to experiment with the Global dark slider in the Deringing section to home in on the best setting that prevents dark artifacts appearing around the stars.

Although the examples in this article demonstrate deconvolution using *PixInsight*, you'll find many tutorials online on how to perform deconvolution with other image-processing software. Deconvolution has the ability to reveal the hidden small-scale detail in deep-sky and solar system images, and it can even help fix out-of-round stars. Don't be afraid to experiment — the improved clarity and detail in your photos will be well worth the effort.

■ **RON BRECHER** hunts faint deep-sky targets from his backyard observatory in Guelph, Ontario.

Solar Finders

How to point out the obvious.

LAST MONTH I wrote about making your own solar filter. Now you're all set to look at the Sun, right? So how do you aim your scope at it?

Come on, how hard can it be? It's right there, big and bright and half a degree acro. . . ss. Oh. Yeah. It only covers half a degree of sky. And it's too bright to look at with your Telrad or optical finder. (Seriously, don't do that.) The Sun is too bright to even sight down the your telescope's tube at safely. With the filter on your scope, you won't see any glow through the eyepiece until you're right on it. Until you've tried it, you'd be amazed at how difficult it is to aim a telescope at the Sun without some kind of finder.

Here's how to make one.

There are two basic ways, and both use the Sun as part of the system. You can either cast a shadow onto a target or cast a beam of light on a target.

The simplest finder I've seen consists of two tabs of masking tape. Stick one on the front edge of your scope with an inch-long tab standing out. Put another tab a foot or two back, in line with the one on the front. Poke a hole in the middle of the front tab, and move the scope around until the ray of light shining through the front tab hits the back tab. Center it up, and you're on target.

Cut the front tab into an arrow shape with its point half as high as the rear tab and you get the same effect with a shadow instead of a bright spot.

Masking tape isn't very elegant, and it's hard to get the two tabs precisely aligned. You're better off building a finder that you can mount solidly on your scope so it'll remain aligned from use to use. Designing it to fit on your regular finder's mount is a good strategy, since you won't be using that finder by day anyway.

▲ David Lazaroff made this Sun finder from a detergent jug spout.

▲ This folding finder casts a bright spot on a frosted screen. The front element shades the screen, and sunlight shines through the hole.

A 4- or 5-inch length of 1-inch-diameter PVC pipe makes a good finder body. Cap the front end and drill a small (1⁄16-to-1⁄8-inch) hole in the middle of the cap, then stretch a section of white plastic bag across the back. When aimed at the Sun, a bright spot of light shines on the white plastic. After you've found the Sun in the scope for the first time with the finder attached, put a black dot in the center of the bright spot with a felt marker and you'll have no trouble finding the Sun again.

One nice variant is to open the body of the finder so you can look at the bright spot on the screen from above. That eliminates bending down to see it. I made the finder at left from two pieces of flat PVC plastic and a piece of clear Plexiglas, which I frosted with fine sandpaper to make a screen. The upright

TOP: DAVID LAZAROFF; BOTTOM: JERRY OLTION sections are hinged so they fold down out of the way when not in use.

David Lazaroff has made a clever design using the plastic spout from a detergent jug. The front end has a nifty cross-hair design molded in, so all David had to do was remove the opaque back and glue a translucent plastic cap from a spray bottle on it. He then sanded the screw thread section of the spout to fit the curve of his telescope, threaded a piece of nylon cord through holes in the spout, and added a cord lock to hold the whole works in place. When aimed at the Sun, it projects a beautiful cross hair on the end cap.

You can undoubtedly come up with several designs of your own. Just about anything that casts a shadow or a bright spot on a screen will do, as long as you're not magnifying the Sun's intensity through a lens.

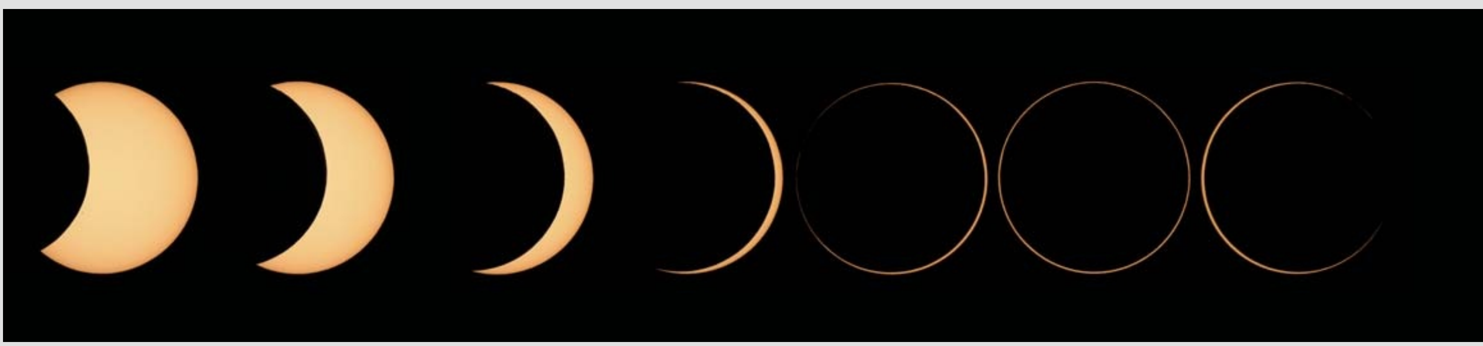
Happy hunting — and finding!

■ Contributing Editor **JERRY OLTION** enjoys looking at the Sun whenever it deigns to come out, which is about twice a year as seen from his home in the Pacific Northwest.

The detergent jug spout includes a convenient target frame.

DAVID LAZAROFF

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



▷ COLORFUL COATHANGER

José J. Chambó

A popular binocular target, the Coathanger asterism includes the 10 brightest members of Collinder 399. Persian astronomer Al Sufi first noted this random group of stars in AD 964.

DETAILS: *GSO 8-inch reflector and Canon EOS 100D DSLR camera at ISO 1600. Total exposure: 64 minutes.*

◁ TULIP IN THE SWAN

Kfir Simon

The Tulip Nebula, Sh2-101, glows prettily across 70 light-years of interstellar space in southwestern Cygnus.

DETAILS: *Celestron C14 Schmidt-Cassegrain telescope and Moravian Instruments G3-16200 CCD camera with Hα, S II, O III, and RGB filters. Total exposure: 12½ hours.*

▷ POLAR DAY

Chang-Jen Wu & Shih-Yi Lin

In Gjesvær, a small fishing village at the northernmost tip of Norway, the midsummer Sun never sets, as typified by this composite taken over 24 hours.

DETAILS: *Canon EOS-1Ds Mark III DSLR camera at ISO 100 and 8-mm fisheye lens. Exposures: 1/160 second.*

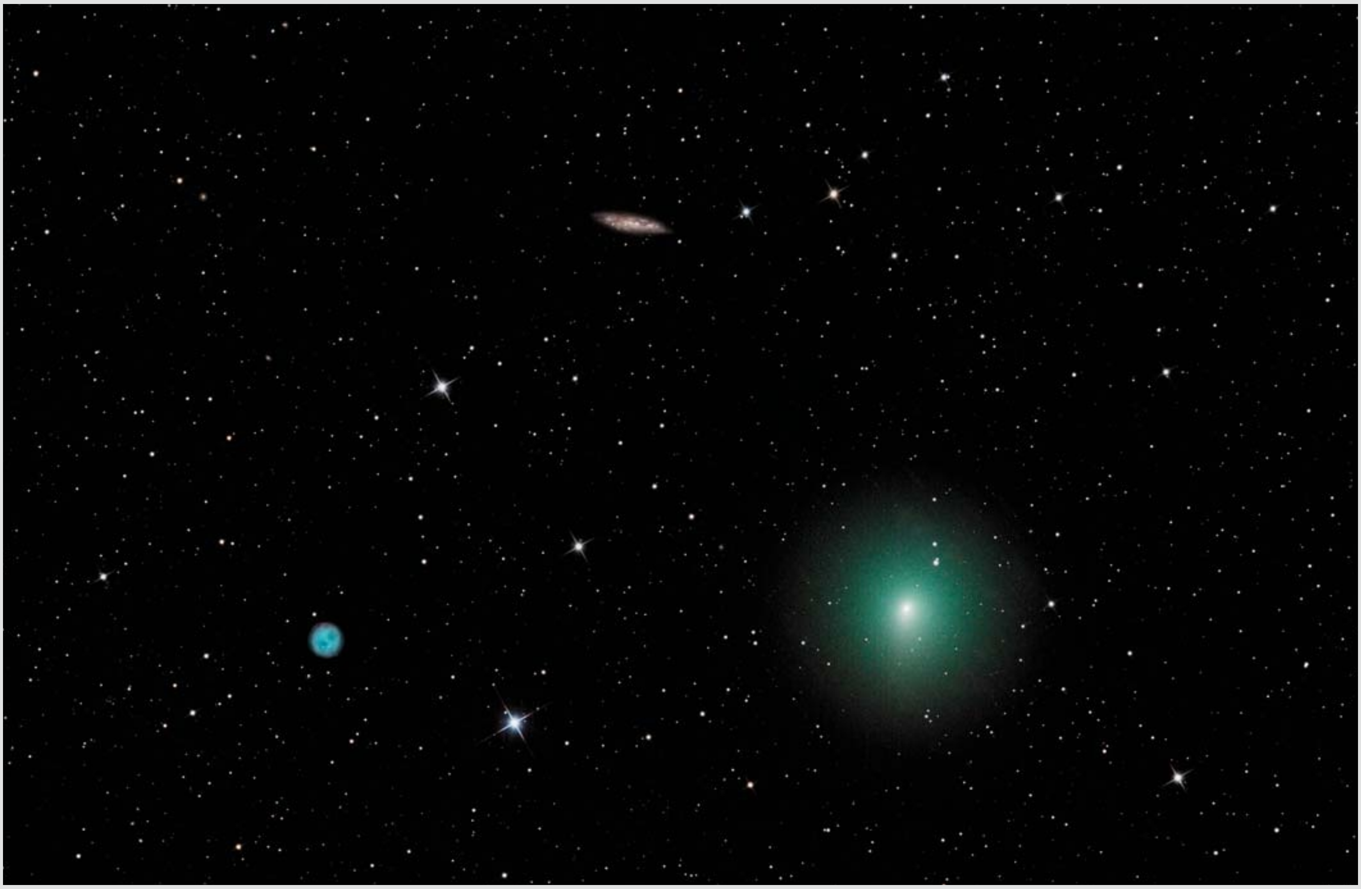
Visit **skyandtelescope.com/gallery** for more of our readers' astrophotos.

FEBRUARY'S ANNULAR ECLIPSE

César Briceño & Kathy Vivas

Clear skies prevailed over Puerto Chacabuco in southern Chile during February 26th's annual solar eclipse. This sequence was recorded over 1¾ hours.

DETAILS: *Celestron NexStar 4SE Maksutov-Cassegrain telescope with Thousand Oaks solar filter and Canon EOS Rebel T3i DSLR camera at ISO 200. Exposures: 1/125 second.*



△ **JUST PASSING BY**

Gregg Ruppel

Comet 41P/Tuttle-Giacobini-Kresak glided past the Owl Nebula (M97) and the barred spiral galaxy M108 on March 21, 2017. The comet's green glow is from diatomic carbon in its coma.

DETAILS: *ASA 10N astrograph and SBIG STL-11000M CCD camera with Astrodon GenII LRGB filters. Total exposure: 80 minutes.*

▷ **SKULL & CROSSBONES**

Richard S. Wright Jr.

Recorded from this year's Winter Star Party in Florida, NGC 2467 (better known as the Skull and Crossbones Nebula) is a vast star-forming complex of gas and dust in northern Puppis.

DETAILS: *Sky-Watcher Esprit 150-mm ED triplet APO refractor, FLI ProLine PL16803 CCD camera, Hα and RGB filters. Total exposure: 4½ hours.*

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DARK SKY LAND FOR SALE: Adjoins Arizona Sky Village in Portal, Arizona. 5 acres $15,000; 8 acres $8,000; soldiercreekranch1990@gmail.com 530-279-2757

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SKY&TELESCOPE

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Event Calendar

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

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

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June 17–24
GRAND CANYON STAR PARTY
Grand Canyon, AZ
nps.gov/grca/planyourvisit/grand-canyon-star-party.htm

June 21–25
ROCKY MOUNTAIN STAR STARE
Gardner, CO
rmss.org

June 21–25
GOLDEN STATE STAR PARTY
Bieber, CA
goldenstatestarparty.org

June 22–25
CHERRY SPRINGS STAR PARTY
Coudersport, PA
astrohbg.org/CSSP

June 22–25
WISCONSIN OBSERVERS WEEKEND
Hartman Creek State Park, WI
www.new-star.org/index.php?itemid=82

July 18–22
TABLE MOUNTAIN STAR PARTY
Oroville, WA
tmspa.com

July 20–23
STELLAFANE CONVENTION
Springfield, VT
stellafane.org/convention

July 20–23
STARFEST
Ayton, ON
nyaa.ca/starfest.html

July 21–30
SUMMER STAR PARTY
Plainfield, MA
rocklandastronomy.com/ssp.html

July 21–25
ALMOST HEAVEN STAR PARTY
Spruce Knob, WV
ahsp.org

July 23–29
MAINE ASTRONOMY RETREAT
Washington, ME
astronomyretreat.com

July 31 – August 5
NEBRASKA STAR PARTY
Valentine, NE
nebraskastarparty.org

August 17–20
THEBACHA & WOOD BUFFALO DARK SKY FESTIVAL
Fort Smith, NWT
www.tawbas.ca/dark-sky-festival.html

August 17–22
OREGON STAR PARTY
Indian Trail Spring, OR
oregonstarparty.org

The Bright One That Got Away

Fifty years ago this month, the author, then 16, came a hair's breadth from making a huge discovery.

IN THE CONSTELLATION Delphinus the Dolphin, on the evening of July 8, 1967, British observer George Alcock discovered what became the brightest nova in 25 years, peaking at magnitude 3.5. He spotted Nova Delphini 1967 (later designated HR Del) with binoculars after 800 hours of nova-searching during the previous six and a half years. While Alcock is rightly credited with discovering this star, I saw it as a 6th-magnitude interloper two nights earlier from my backyard observatory in Burbank, California — and I wasn't even looking for novae!

I was 16 that summer and had become a prolific variable star observer. During the 1966–67 American Association of Variable Star Observers observing year, I submitted over 5,200 magnitude estimates, fourth in the world in the AAVSO's tally that year. As the summer of 1967 began I added two bright semi-regular variables to my observing list, U and EU Delphini, which were not part of the regular AAVSO program. This seemed a logical thing to do since they were near S Delphini, a long-period variable I'd made 17 observations of in the previous year.

▲ The author in his backyard observatory the year he just missed eternal fame.

> I saw it as a 6th-magnitude interloper two nights earlier — and I wasn't even looking for novae!

I secured my first estimates of these variables, at magnitudes 6.5 and 6.0, respectively, on June 26th.

Around 12:20 PDT on the night of July 6–7, I again pointed the 6×30 finder of my 6-inch Optical Craftsmen reflector to the diamond of Delphinus, above the avocado tree in my parents' backyard. After checking my *Skalnate Pleso* star atlas, I quickly found the pair of 6th-magnitude stars I'd long used in locating S Del. As I found U and EU Del, I noticed something near the top of the 5° field of the finder. It surprised me to see a roughly 6th-magnitude star there; I didn't recall anything that bright forming such a nice equilateral triangle with U and EU Del. It was roughly 2° on a side.

Unfortunately, I remembered just enough of my charts to judge my magnitude estimates without referring back to them, and I just assumed that the questionable object belonged there. I moved on to the next variable on my list. In those days I often made more than 30 variable-star magnitude estimates per hour, a pace that was perhaps a little too fast for me to appreciate anything unusual.

Pre-discovery photographs put Nova Del at magnitude 5.8 that night, and at 6.7 when I conceivably had an earlier chance on June 26th.

I told this story the next summer to my friend Douglas Duncan. Forty-two years later — he was by then a University of Colorado astronomer and director of Fiske Planetarium, and still is — he told me he often shared the story as a lesson to his students. So after all those years I had some consolation: My failure was being used as an example of the need to be careful and meticulous in making observations!

■ **STEPHEN COOK**, a former university professor and high school physics teacher, runs Project Worldview (projectworldview.org) and does CCD variable star photometry from his home in Prescott, Arizona. In 2008, his old Optical Craftsmen telescope helped in the discovery of a new eclipsing binary star (V1047 Persei).

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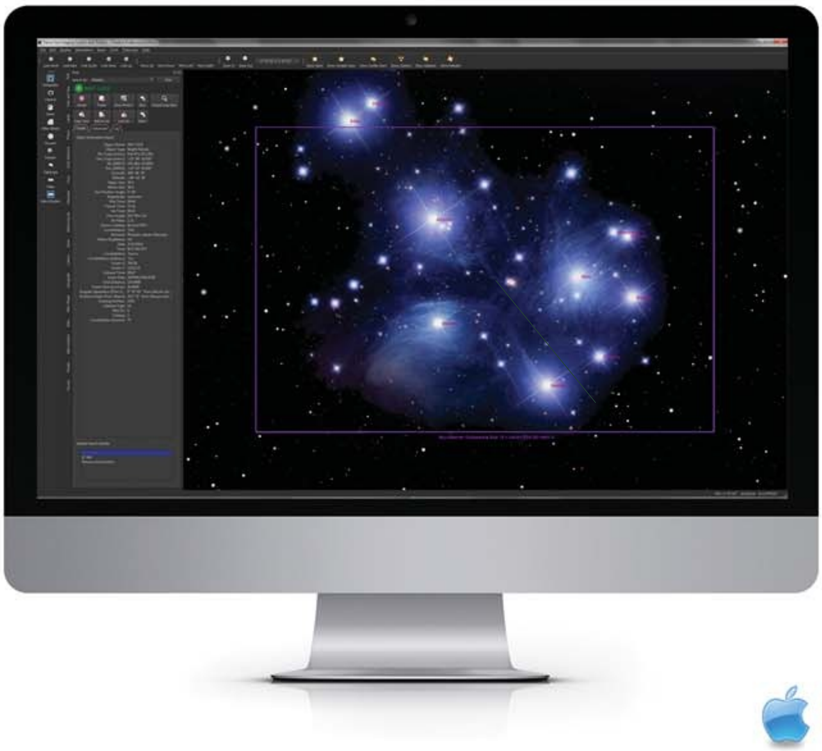

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