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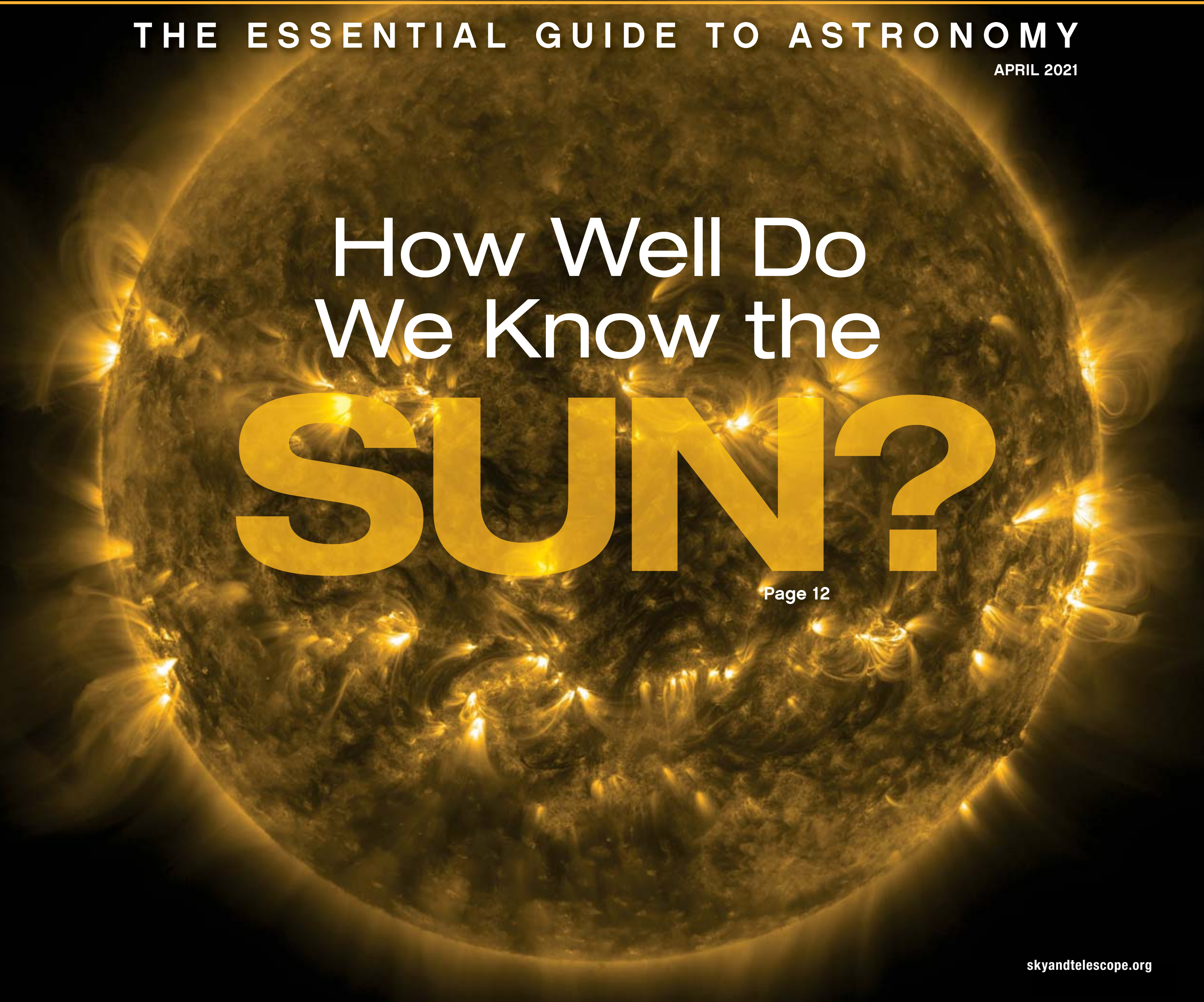
SKY & TELESCOPE

THE ESSENTIAL GUIDE TO ASTRONOMY

APRIL 2021



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WHAT'S UP WEBCAST
FRIDAY, 10-11 AM Pacific
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OLEG BOUEVITCH

ON THE COVER

Extreme UV image of the Sun, taken on October 8, 2014

PHOTO: NASA / SDO

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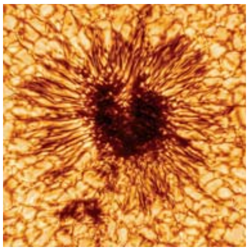
Our Moment in the Sun

THESE ARE EXCITING TIMES for studies of our star — you might even call it a golden age. In the past decade alone, we've advanced our understanding tremendously, with three instruments in particular deserving special attention.

Launched in 2010, the Solar Dynamics Observatory has taken millions of images of the Sun. On the roiling solar surface, it has detected plasma tornadoes spinning at up to 300,000 kilometers per hour (186,000 mph), and giant plasma waves that whip across the surface at close to 5 *million* kph. It has revealed large "dark" patches whose disappearance can help scientists determine when the Sun's magnetic field reversed. It has discovered an entirely new kind of solar explosion — *spontaneous magnetic reconnection* — which might aid in resolving a long-standing mystery: why the Sun's corona is millions of degrees hotter than its surface.



▲ The entire Earth would fit inside this single sunspot imaged by the Inouye Solar Telescope.

NSO / AURA / NSF

Meanwhile, the Parker Solar Probe is making its own revelations (*S&T:* Nov. 2020, p. 20). Launched in 2018 and approaching within 15 million miles of the solar surface, this well-shielded spacecraft is seeking answers to that coronal mystery as well as investigating how the solar wind arises and why it spews from the corona in the way it does. Parker has already spied never-before-seen *switchbacks*, in which the magnetic field embedded in the solar wind suddenly reverses direction for seconds or minutes at a time.

Even more recently, in December 2019, Hawai'i's new Daniel K. Inouye Solar Telescope captured its first image of the Sun. With its 4-meter (13-foot) primary mirror, the Inouye Solar Telescope enables us to see features three times smaller than anything we could see before. In coming years, it will look at how the Sun's magnetic fields are generated and destroyed, and what roles they play in the organization of plasma structure and the abrupt releases of energy seen on our own and other stars. It will also explore the mechanisms responsible for solar variability — important for protecting astronauts in space and power grids on Earth.

Despite all we've learned — and because of it — many puzzles remain. Colin Stuart addresses one of the knottiest in his cover story on page 12: the *solar abundance problem*. It boils down to how many elements heavier than hydrogen and helium the Sun contains. Two groups of scientists, who each swear by their results, come up with different answers. As Stuart explains, that calls into question our understanding not only of our own star but of all stars and even their planets.

Keep your shades handy. Like the Sun itself, future findings promise to be nothing short of dazzling.

Peter

Editor in Chief

SKY&TELESCOPE
The Essential Guide to Astronomy

Founded in 1941 by Charles A. Federer, Jr. and Helen Spence Federer

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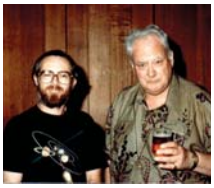
Patrick Moore's Caldwell Catalog

Being a bino nut myself, I enjoy reading Matt Wedel's Binocular Highlight column. I also enjoy the observing articles he writes. So I plowed into "The Caldwell Catalog Turns 25" (*S&T:* Dec. 2020, p. 20) with interest — most enjoyable! I've ignored the catalog since it came out, but after reading his article, I may give it a try!

I had the pleasure of meeting Patrick Moore in 1986 on a two-week tour in Australia to see Halley's Comet. The people on the trip were split between three buses, and each had a different tour leader. I lucked out — Patrick Moore was our guide! I knew of his fame, so I was delighted.



▲ Patrick Moore and Bill Dellinges pose for a picture during a two-week tour in Australia in 1986.

What a walking encyclopedia! The guy could (and did) lecture on any astronomical subject off the top of his head. I was in heaven.

Bill Dellinges
Apache Junction, Arizona

Although Matt Wedel averred that the goal of his article was "not to focus on his [Patrick Moore's] political opinions," he nevertheless chose to mention them and made it clear that he disagreed with Moore's views.

Some other aspects of Patrick Moore's life that may not be well known to fans of his astronomical contributions are that he was a keen follower of cricket, a more than competent performer on the xylophone, and a staunch and vocal opponent of fox hunting.

Jeremy Tatum
Victoria, British Columbia

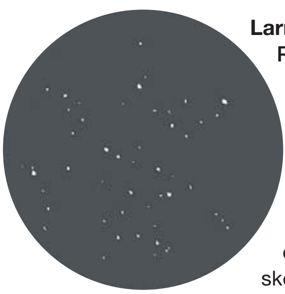
Sketching OB Associations

I enjoyed reading Matt Wedel's "The Fires of Youth" (*S&T:* Jan. 2021, p. 43). Years ago, I visually sketched my way through a number of *OB* associations listed in the article "In Pursuit of *OB* Associations" by Joseph Caruso (*S&T:* Jan. 1986, p. 110).

I have more sketches of *OB* associations and star charts on my website: **stellar-journeys.org/OB-Tour.htm**.

One of the reasons that I really enjoy reading *S&T* is the wonderful observing articles covering a wide range of objects suitable for small and large telescopes. Barely an issue goes by where I'm not cutting out and saving something for a future observing project!

Larry McHenry
Pittsburgh, Pennsylvania



◀ Larry McHenry observed Orion OB-1a on January 29, 1993, through an 80-mm (3-inch) refractor with a 32-mm (1.25-inch) eyepiece and drew this sketch of what he saw.

Cruising Under Totality

Rick Fienberg's "Corona Virus" (*S&T:* Jan. 2021, p. 84) brought back fond memories of two special cruises. Having never seen a total solar eclipse before, my wife and I planned to observe the July 11, 1991, one in Hawai'i. We luckily found ourselves off the shores of Mazatlán, Mexico, on Carnival Cruise Line's *Jubilee* to watch the event. Buzz Aldrin was a guest lecturer! It was a fantastic cruise experience.

Then, during the February 26, 1998, eclipse, we were on Carnival's new, larger *Fascination* near Aruba. Although totality was shorter on this cruise, it had two brilliant "diamond rings"! Each cruise also had a great captain. And both cruises were full of friendly people and pure enthusiasm — the cheering as darkness fell!

John Kuczek
Vero Beach, Florida

The Formation of Planets

The impression that I got from Edwin Bergin's article "Follow the Carbon" (*S&T:* Dec. 2020, p. 34) is that the amount of carbon an Earth-like planet in the habitable zone of a star system winds up with is highly dependent on the circumstances and history of that star system. It could range from almost no carbon to a significantly greater percentage of carbon than Earth has. As we continue to investigate, we should expect the unexpected.

James Scott
Vernon, New Jersey

Einstein Rings

Thank you for Monica Young's News Note "'Dead Ringer' for the Milky Way Found in the Early Universe" (*S&T:* Dec. 2020, p. 10). It takes a remarkable alignment of the foreground and background galaxies to produce such a symmetrical ring.

Your article triggered a thought that I should have had years ago, when Einstein rings were first observed: Where is the foreground galaxy? I can roughly understand the physics of the ring formation, but what happens to the foreground galaxy's light?

It seems that it should be visible somewhere, maybe in the center of the one shown and off-center in less symmetrical rings or arcs.

Phil Petersen
League City, Texas

Monica Young replies: *That's a really good question! In this case, the foreground galaxy is invisible because it doesn't emit much light at the specific wavelength the scientists are looking at. Francesca Rizzo and colleagues used the Atacama Large Millimeter/submillimeter Array (ALMA) to look at emission from ionized carbon in the background galaxy. This spectral line is emitted at 158 microns, but the background galaxy is so far away (redshift 4.2), that the wavelength stretches to 826 microns (0.8 millimeter) by the time it passes through the expanding universe to reach Earth. The foreground galaxy, at redshift 0.2, doesn't emit much light at this wavelength, so it's not visible in the ALMA image.*

However, in other images of lensed galaxies, such as those taken by the Hubble

DELLINGES AND MOORE: BILL DELLINGES

Space Telescope, we can often see the foreground galaxy (or galaxy cluster) in the center of the arc or ring.

Bolstering Diversity in Astronomy

Dara Norman's "Time to Get Serious" (*S&T:* Dec. 2020, p. 84) mentions expanding access to make astronomy more diverse. One of the big issues when it comes to access is the cost of museums. For instance, I live in Baltimore, which has a wonderful science center. However, tickets are expensive. Many families can't afford to go.

In many cities, there are areas that have been abandoned and have houses for sale at extremely low prices. I think it would be a good idea to raise money, buy some of these houses, and turn them into inexpensive museums. For instance, different rooms can be exhibit halls. In Baltimore, we have row houses with flat roofs, so planetariums or telescopes could be placed on top. And the museums can be staffed by students. This would increase access by reducing the cost of attending science museums.

Jason Goldstein
Baltimore, Maryland

S&T Dazzles

The typography on the cover of your November 2020 issue is such that seen from even a short distance, the words that stand out are "SKY & TELESCOPE . . . Dazzles," which is 100% true. I am so pleased with the huge improvements *S&T* has been able to make under its new ownership. I wish *Sky & Telescope* truly dazzling success.

W. Scott Peterson
Middlebury, Connecticut

Subaru

Thank you for your fun monthly astronomy podcast. In your December 2020 podcast (**https://is.gd/Dec2020podcast**), Kelly Beatty mentioned the Pleiades or, in Japanese, Subaru, like the car. I'm not sure how many people are aware of this, but five Japanese companies merged to form this automobile enterprise. The Pleiades were chosen as Subaru's logo to represent the companies that merged together to create Fuji Heavy Industries (the largest star in the logo).

Ernesto de Armas
Piperton, Tennessee

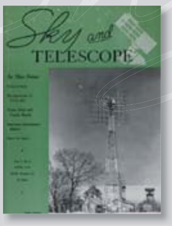
FOR THE RECORD

- The review of *Luna Cognita* (*S&T:* Dec. 2020, p. 57) should have stated that the book's Figure 6.3, and not Figure 6.1, should show celestial east on the left.
- The label to the right of the "Odd number of reflections" image of Mars in "Tips for Planetary Observers" (*S&T:* Nov. 2020, p. 53) should say East.

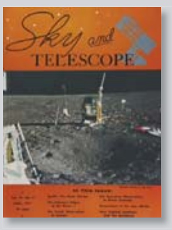
SUBMISSIONS: Write to *Sky & Telescope*, One Alewife Center, Suite 300B, Cambridge, MA 02140, USA or email: letters@skyandtelescope.org. Please limit your comments to 250 words; letters may be edited for brevity and clarity.

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

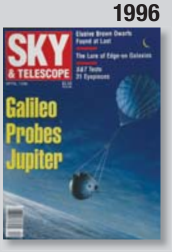
1946



1971



1996



April 1946

Project Diana "Following the announcement on January 25, 1946, that the Signal Corps experiments were successful in making contact with the moon by radar, the imaginations of news reporters and feature story writers went wild with predictions that space ships would soon be a reality. True, our experiment has shown that it is possible . . . to make continuous radio contact with rocket ships far out in space. More important, however, the experiment has provided a new means to make studies of the propagation of radio waves . . .

"Future improvements may lead to radar methods for measuring the moon's distance . . . possibly to the nearest 0.1 mile. Greater antenna gains at higher frequencies may give antenna beams narrow enough to use to study detail in the moon's surface."

Army physicist Harold D. Webb didn't speculate that surface details on Mars and Venus might one day be distinguished by radar. They were, using the late, lamented Arecibo radio dish.

April 1971

Promethium "Spectroscopic studies of stars often reveal unusual and puzzling properties of their atmospheres. One surprising outcome of such a study is the recent discovery by Charles Cowley and myself of the existence of the short-lived unstable element promethium in the atmosphere of the peculiar *A*-type star HR 465. . . .

"It is the first demonstration that this short-lived element can be present naturally in the universe, since all isotopes of it known heretofore were produced synthetically. From the astronomer's viewpoint, it is direct evidence that element synthesis can occur near the surface of a star. Promethium, if generated in a star's deep interior, would have decayed to isotopes of other elements long before rising to the outer layers . . ."

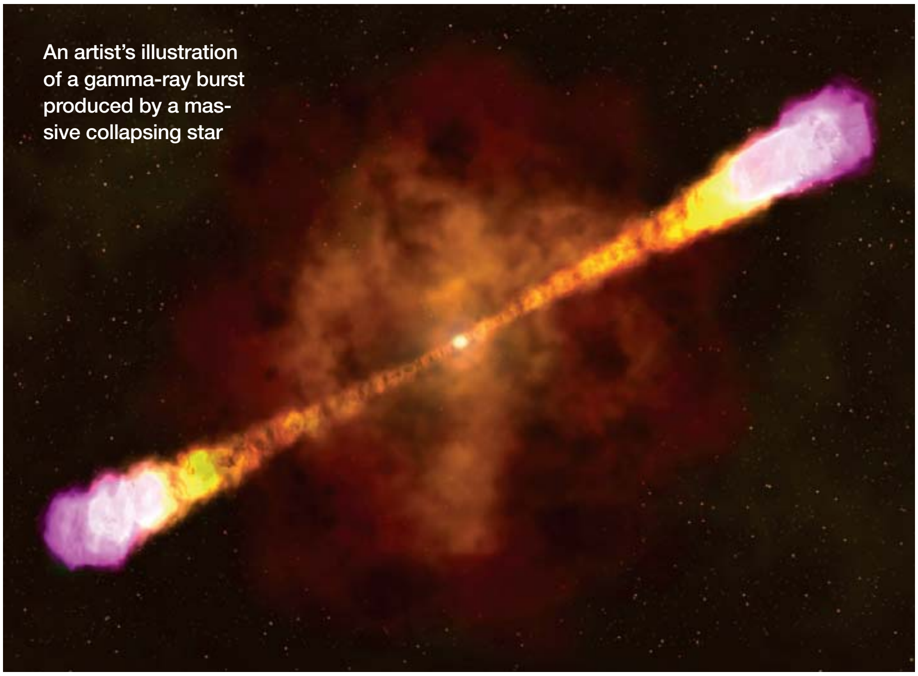
Margo F. Aller (University of Michigan) was describing a lone star in Andromeda, one of several now known to harbor promethium.

April 1996

Brown Dwarfs "The year 1995 will likely be remembered by astronomers for the culmination of a 20-year hunt: the search for the substellar objects known as brown dwarfs. . . . In the Pleiades, observers have uncovered two intriguing brown-dwarf candidates, while a third has been found orbiting a small red star only 19 light-years away. This third target, known as Gliese 229B, is so convincing that many astronomers are finally willing to remove the word 'candidate' . . .

"[A] brown dwarf is an object about the size of Jupiter (but with 10 to 80 times its mass) and is incapable of . . . converting normal hydrogen into helium in sufficient quantities to shine steadily."

Todd J. Henry, now at Georgia State University, offered this laudatory assessment.



An artist's illustration of a gamma-ray burst produced by a massive collapsing star

NASA / GSFC

GAMMA-RAY BURSTS

Most Distant Gamma-ray Burst Found

FROM THE FARTHEST-KNOWN galaxy in the observable universe comes the brightest and most energetic of events: a possible gamma-ray burst.

In 2016, astronomers found GN-z11, a galaxy whose light originated 420 million years after the Big Bang. While conducting about five hours' worth of observations with the Keck I telescope in Hawai'i to confirm the galaxy's distance, Linhua Jiang (Peking University, China) and colleagues captured a brief luminous spike of near-infrared radiation. They think this might be the ultraviolet afterglow following a "long" *gamma-ray burst* (GRB), the blaze of gamma radiation emitted by a massive collapsing star. (The GRB itself went unseen in this case.) The ultraviolet light would have stretched into near-infrared wavelengths as it passed through the expanding universe. The results appeared on December 14, 2020, in two articles in *Nature Astronomy*.

Before this, the youngest-known GRB was one that went off 520 million years after the Big Bang. Younger events are out of range for GRB hunters like NASA's Neil Gehrels Swift Observatory and Fermi Gamma-ray Space Telescope.

The team considered the possibility that something else transited between Earth and the galaxy at exactly the right moment, like a cosmic photobomb. But after considering several likely culprits, including satellites, asteroids, supernovae, and a coincidental GRB in a closer galaxy, they concluded that the flash most likely came from GN-z11 itself. Moreover, the source's spectrum, brightness, and duration are consistent with a GRB.

Surprisingly, even though GN-z11 existed so shortly after the Big Bang, the spectrum includes emission from ionized carbon, an element that would have to be forged inside another star. If the event was a GRB, Jiang says, it would have marked the end of a star already in the second generation.

Péter Mészáros (Penn State), who was not involved in the study, agrees that the spectrum is what he would expect from a GRB. "This is potentially a very important discovery," he says.

Unfortunately, the UV light alone is not enough to definitively rule out other options. But while this find relied on serendipity, even higher-redshift flashes await next-generation instruments.

■ ARWEN RIMMER

GALACTIC

New Multidimensional Map of the Milky Way

ASTRONOMERS HAVE RELEASED the most detailed multidimensional census of our Milky Way galaxy.

The third edition of the star catalog produced by the European Space Agency's Gaia mission contains coordinates for more than 1.8 billion stars between 3rd and 21st magnitude, with a precision of a few tens of micro-arcseconds; most of these also have brightness measurements. In addition, the catalog provides parallaxes and proper motions on the sky for a subset of almost 1.5 billion stars.

This data release includes almost three full years of data, a longer time baseline that gives 30% more precise parallax — and thus distance — measurements. Proper motions across the sky are also twice as precise as the last data release. Gaia is expected to operate until 2025, and the additional years of data will improve the precision of all measurements by at least a factor of two; proper motion precision will increase sevenfold.

In a series of papers to be published in *Astronomy & Astrophysics*, the Gaia Collaboration provides a taste of what can be done with these new data. For instance, proper motion data show that while our galaxy's largest satellite, the Large Magellanic Cloud, is rotating, many of the stars in the nearby Small Magellanic Cloud appear to be flowing toward and into the Magellanic Bridge that connects the two dwarfs.

The Gaia Collaboration also produced a subcatalog of 331,312 stars within 326 light-years of the Sun that's 92% complete (some extremely dim stars may

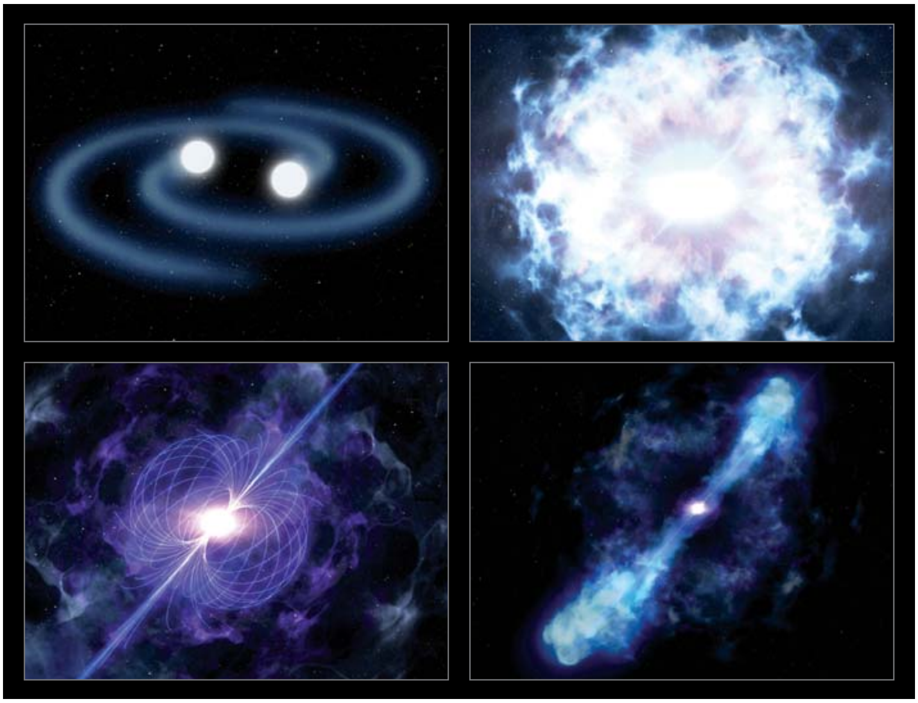
GAMMA-RAY BURSTS

Gamma Rays Herald Birth of a Magnetar

TWO NEUTRON STARS don't always make a black hole, new observations appear to show.

Neutron-star collisions are likely at the heart of "short" gamma-ray bursts (GRBs), flashes of gamma radiation less than two seconds long. Simple math suggests such mergers ought to add up to a black hole, provided material isn't lost in the process.

But the fading afterglow of one such burst, GRB 200522A, suggests that a highly magnetized neutron star, or *magnetar,* has survived one of these violent collisions. The report by Wen-fai Fong (Northwestern University) and her colleagues will appear in an issue of the *Astrophysical Journal*.



▲ Two neutron stars collide in these stills from an artist's animation, forming a stable magnetar.

NASA's Neil Gehrels Swift Observatory first detected this burst after the radiation had traveled 5.47 billion light-years to Earth. Fong's team followed up with observations at multiple wavelengths using the Hubble Space Telescope, the Karl G. Jansky Very Large Array, and other observatories. The later observations traced the afterglow of longer-wavelength emission that follows the initial burst of gamma rays.

When compared to the source's emission at other wavelengths, the near-infrared afterglow was up to 10 times brighter than expected, if the astronomers assumed the emission came from a *kilonova*. This type of explosion results when neutron stars collide to form a black hole and was thought to be the source of short GRBs.

If the remnant was not a black hole but a magnetar, it would explain the excess. What's more, within a few years it would produce observable radio emission, Fong and her colleagues write.

"If detected, this would not only break the degeneracy between the two possible explanations in this specific case," says Maria Grazia Bernardini (Brera Astronomical Observatory and National Institute for Astrophysics, Italy), a GRB expert not involved in the study. "It would provide the long-sought smoking gun of the magnetar scenario [for producing short GRBs], and the first direct evidence of a stable magnetar associated with a GRB."

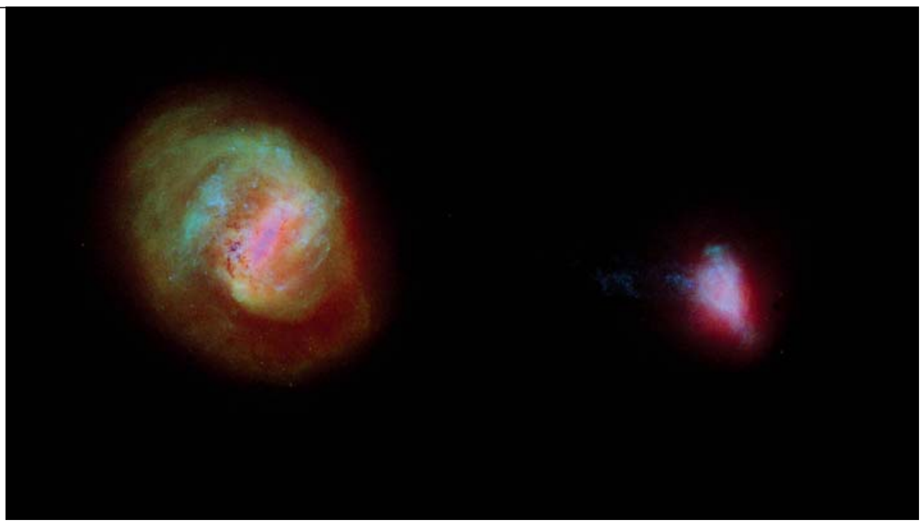
■ MONICA YOUNG

Watch the simulation at **https://is.gd/magnetarbirth**.

still be missing). The new data paint a more precise picture, for example, of how the Milky Way's tidal gravitational forces are slowly dispersing the stars in the nearby Hyades cluster.

"Almost every field is benefitting from this mission," says Amina Helmi (University of Groningen, The Netherlands). "Gaia is transformational. It is revolutionizing astronomy."

■ GOVERT SCHILLING



▶ This image based on Gaia data shows the stellar density of the Large and Small Magellanic Clouds. Red, green, and blue trace mostly the older, intermediate-age, and younger stars.

NEUTRON-STAR COLLISION: NASA / ESA / D. PLAYER (STSCI); LMC AND SMC: ESA / GAIA / DPAC / CC BY-SA 3.0 IGO; ACKNOWLEDGEMENT: L. CHEMIN; X. LURI ET AL (2020)

STARS

The Decline of the Youngest Planetary Nebula

THE YOUNGEST PLANETARY NEBULA ever found is fading away, shedding light on its star's unique evolution.

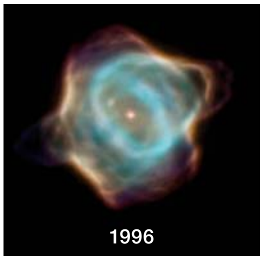
Dying low-mass stars emit harsh radiation that causes previously ejected gas to fluoresce in colorful displays known as *planetary nebulae*. These typically last a few thousand years as the central star radiates the last of its heat into space.

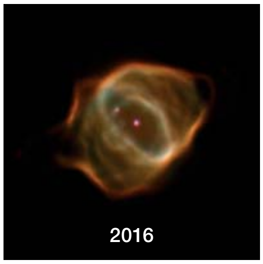
But the Stingray Nebula (Hen 3-1357) has other ideas. It likely appeared sometime in the 1980s, but it wasn't imaged until 1993 when Matthew Bobrowsky (then at Orbital Sciences Corporation) captured it using the Hubble Space Telescope. It's the only planetary nebula caught shortly after it brightened.

Now, my colleagues and I — Martín Guerrero (Institute of Astrophysics of Andalusia, Spain) and Gerardo Ramos-Larios (University of Guadalajara, Mexico) — have found that the Stingray seems destined to vanish in the next few years: start to finish in only two human generations!

Observations of the central star showed it had unexpectedly contracted in the early 1980s, dimming its visible light. This likely happened because it underwent a *helium flash*, in which some unburned helium suddenly reignited, contracting its core and heating its surface, as suggested previously by Nicole Reindl (University of Potsdam, Germany) and colleagues.

Over the next decade, the star's surface heated up by a factor of five, to 60,000 K (100,000°F), and it began emitting intense UV radiation, ionizing previously ejected gas and producing the Stingray Nebula. The nebula and the shrunken star have been fading in tandem ever since. By 2016, the blue-green light emitted by doubly ionized oxygen in the nebula was 900 times fainter than in 1990; the reddish light emitted by ionized hydrogen is fading more slowly.





▲ Stingray Nebula

Now that the helium flash has ended, Reindl's team has predicted that the star will resume its previous evolutionary path. The fluorescence of the nebula may one day resume, and the revived nebula will be "born again."

■ BRUCE BALICK

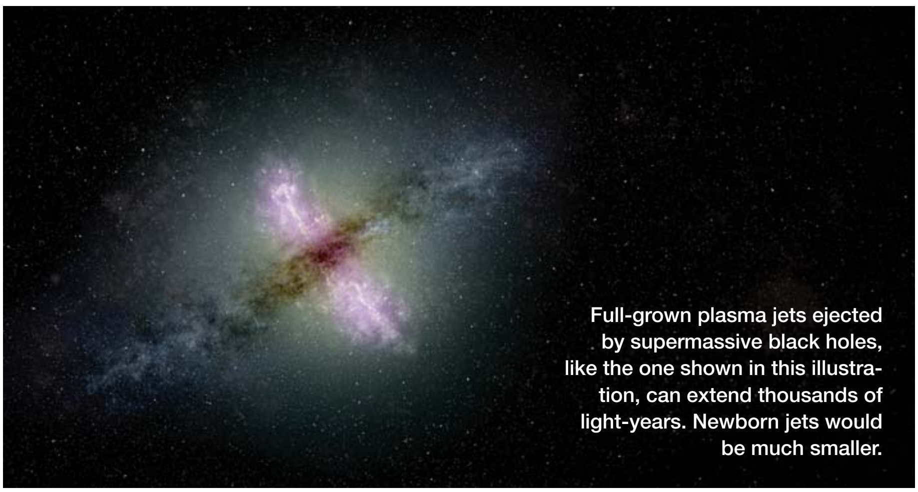
BLACK HOLES

Newborn Black Hole Jets Found in Distant Galaxies

ASTRONOMERS HAVE SPOTTED a dozen *quasars* — gargantuan black holes munching on gas at the centers of galaxies — that appear to have launched jets within the last couple of decades.

Kristina Nyland (U.S. Naval Research Laboratory) and collaborators found them by investigating radio sources detected in an ongoing sky survey by the Very Large Array (VLA) but missing from the same telescope's older FIRST survey, which ran from 1993 to 2011. Out of about 2,000 new sources, 167 appeared in known quasars.

The team followed up on 14 of the brightest sources with additional VLA observations. The quasars' radio emissions appear to come from young jets that turned on in the last 10 to 20 years. It remains unclear, though, if the jets are truly newborn, or if they're slightly older and larger ones that have only recently bent toward Earth.



Full-grown plasma jets ejected by supermassive black holes, like the one shown in this illustration, can extend thousands of light-years. Newborn jets would be much smaller.

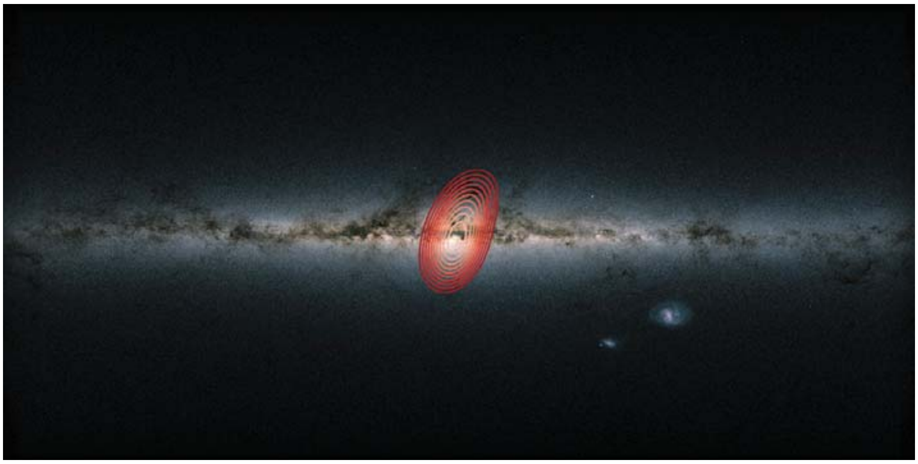
If they *are* newborns, they've launched recently from pre-existing quasars. While a decade or two is probably too short for a wholesale change to the accretion disk feeding the central black hole, quasars could have reactivated on that time scale, says accretion expert Sera Markoff (University of Amsterdam, The Netherlands).

The result, which appeared in the December 10th *Astrophysical Journal*, adds to an accelerating shift in our understanding of *active galactic nuclei* (AGN). Although AGN constantly flicker at low levels, astronomers have nevertheless thought of them as relatively stable on human time scales. Yet numerous studies have revealed large, rapid changes in quasars' light (e.g., *S&T:* May 2016, p. 14), and observations suggest most radio jets never make it into old age. The data paint a picture in favor of intermittent snacking behavior for these gargantuan black holes.

■ CAMILLE M. CARLISLE

Read more at https://is.gd/newbornjets.

STINGRAY NEBULA (2): NASA / ESA / B. BALICK (UNIVERSITY OF WASHINGTON) / M. GUERRERO (INSTITUTO DE ASTROFÍSICA DE ANDALUCÍA) / G. RAMOS-LARIOS (UNIVERSIDAD DE GUADALAJARA); BLACK HOLE JET: SOPHIA DAGNELLO / NRAO / AUI / NSF



▲ Red rings superimposed over an image of the Milky Way show the approximate extent of the stars that came from the fossil galaxy known as Heracles. (To the lower right are the Large and Small Magellanic Clouds.)

DANNY HORTA (LIVERPOOL JOHN MOORES UNIVERSITY) / ESA / GAIA / SDSS

GALACTIC

The Galactic "Fossil" Inside the Milky Way

THOUSANDS OF STARS that once belonged to an ancient dwarf galaxy are inside our own.

Graduate student Danny Horta and his advisor Ricardo Schiavon (both at Liverpool John Moores University, UK), with an international team of colleagues, reached this conclusion using two surveys that catalog millions of stars: The Gaia mission, which pinpoints stars' positions, distances, and velocities, and the APOGEE sky survey, which provides chemical compositions.

Horta and colleagues zeroed in on 1,032 pristine and therefore ancient stars within 13,000 light-years of the galactic center. Gaia data reveal unique, highly eccentric orbits for a third of them, and APOGEE observations showed that those same stars have unusual compositions.

In the January *Monthly Notices of the Royal Astronomical Society*, the researchers concluded that the stars are the fossilized remains of an ancient galaxy that collided with the Milky Way 10 billion years ago. The research team nicknamed the galactic fossil "Heracles."

While some of the 300 or so stars actually traveled in with Heracles, the researchers speculate that the others were born within the Milky Way, their birth stimulated by the galactic merger. They make up a sizable fraction of the stellar halo that now surrounds our galaxy's disk.

Heracles sounds similar to another recently discovered ancient galaxy dubbed "The Kraken" (*S&T:* Mar. 2021, p. 11). Both would have encountered our galaxy about 10 billion years ago on a similar orbital path, and their stars would have had similar chemical compositions.

But Horta and Schiavon caution that Heracles is about three times as massive as the Kraken is thought to have been, and they argue that the association between the two isn't yet clear. A convincing identification awaits additional data and simulations.

■ MONICA YOUNG

IN BRIEF

Hayabusa 2 Returns Asteroid Sample to Earth

After a six-year journey of 5.24 billion kilometers (3.26 billion miles), the Japanese Hayabusa 2 mission passed by Earth on December 5th, jettisoning its sample-return capsule for a landing in the Woomera Prohibited Area in southern Australia. The capsule carried pieces of asteroid 162173 Ryugu. The team located and collected the capsule after a brief helicopter search, then transported it to a facility in Woomera for a "quick-look" inspection. That inspection revealed that the capsule contained gases from Ryugu. The capsule and its contents then headed to Japan, where the first chamber opening revealed charcoal-colored rocks and dust. Study of this pristine asteroid material will give scientists a look back at the early solar system. After releasing the sample, Hayabusa 2 performed trajectory correction maneuvers to fly past Earth as it continues on an extended mission to two additional asteroids, including 1998 KY_{26}, a fast rotator that spins every 11 minutes.

■ DAVID DICKINSON

Surprisingly Mature Infant Galaxies

Eight studies published in the November *Astronomy & Astrophysics* show that long before star formation peaked in the universe, which occurred around 3 billion years after the Big Bang, galaxies were already churning stars out at prodigious rates, and changing their environments as they did so. An Atacama Large Millimeter/submillimeter Array (ALMA) program dubbed ALPINE has gauged the dust, gas, and star formation in 118 distant galaxies. The observations show that even when the universe was only 1–1.5 billion years old, galaxies' starbirth was already half-obscured in dust clouds. Dust takes time to make — any atoms heavier than hydrogen and helium have to be forged in stars first — so astronomers didn't expect to see so much dust and heavy elements in these distant galaxies, says co-principal investigator Andreas Faisst (Caltech). ALPINE observations also show that these youngsters were rambunctious: The team classified 40% of the galaxies as mergers. Yet, another 11% of the galaxies were stable rotating disks. These orderly young'uns confirm what other observations (*S&T:* Apr. 2018, p. 12; Sept. 2020, p. 12) had already shown — that a number of galaxies stabilize into disks early on, even as others appear more chaotic and swirly from previous or ongoing mergers.

■ MONICA YOUNG

How Well Do We Know the Sun?

Even though the Sun is our nearest star, we may not understand it as well as we thought.

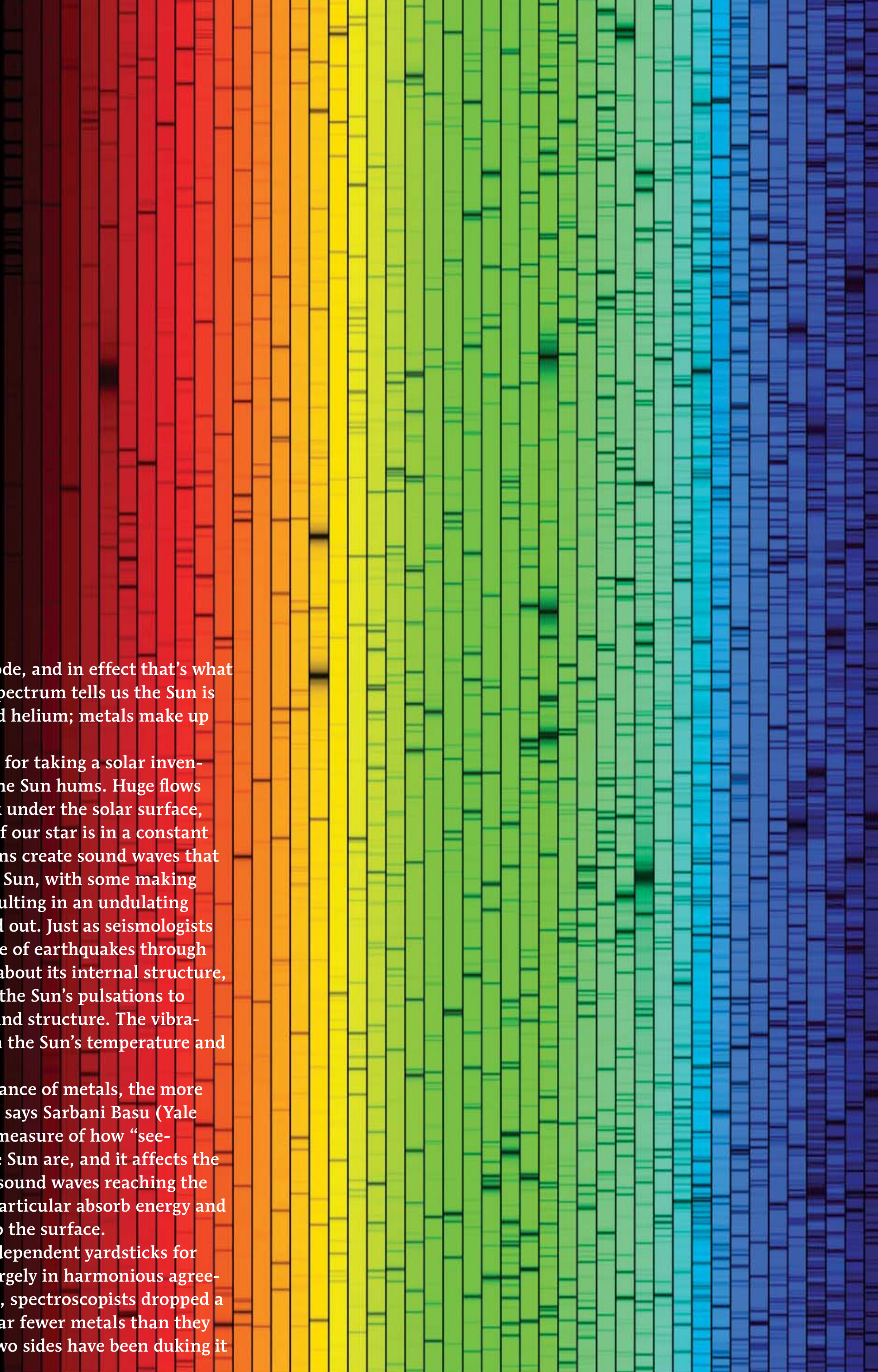
NASA / SDO

There's a problem with the Sun — or at least, a problem with our understanding of it. Rival groups of astronomers are racing toward a solution, adamant they each have the correct answer. Who turns out to be right could have huge consequences for the way we understand the Sun, other stars, and their planets.

At the heart of the issue is what the Sun is made of. Our nearest star is 1.4 million kilometers (870,000 miles) wide, a goliath of roiling, churning, seething plasma that has a surface temperature approaching 6000 kelvin (5500°C). This plasma is mostly hydrogen and helium but has a smattering of heavier elements, which astronomers call *metals*. The question is, how many?

Taking a sample is, of course, impossible. Instead, astronomers have turned into detectives, teasing out clues about the Sun's composition from the evidence provided by a suite of solar observatories both on the ground and in space and the sophisticated models of the Sun they help inform.

Those dedicating their careers to finding out the Sun's makeup fall into two camps. The first — the *spectroscopists* — rely on the sunlight we receive from the *photosphere*, the Sun's visible surface. Passing sunlight through an instrument called a spectrograph separates out all the familiar colors of the rainbow, but they're strewn with a series of dark bands called absorption lines. They are simply missing colors — precise frequencies of light swallowed by the 67 different elements found in the Sun. At first glance it



▶ The Sun emits every wavelength of visible light, but elements in the solar atmosphere absorb specific wavelengths, imprinting the spectrum with dark bands. While these absorption lines provide insight into the Sun's chemical composition, understanding the interior is a far more difficult task.

NIGEL SHARP (NSF) / FTS / NSO / KPNO / AURA / NSF

looks like a colorful barcode, and in effect that's what it is. Scanning the solar spectrum tells us the Sun is at least 98% hydrogen and helium; metals make up the remaining 2%.

An alternative method for taking a solar inventory focuses on the way the Sun hums. Huge flows of material swell and sink under the solar surface, meaning the underbelly of our star is in a constant state of flux. These motions create sound waves that bounce around inside the Sun, with some making it to the photosphere, resulting in an undulating surface that throbs in and out. Just as seismologists on Earth track the passage of earthquakes through the planet to learn more about its internal structure, *helioseismologists* can use the Sun's pulsations to uncover its composition and structure. The vibrations are sensitive to both the Sun's temperature and its composition.

"The higher the abundance of metals, the more opaque solar material is," says Sarbani Basu (Yale University). Opacity is a measure of how "see-through" the layers of the Sun are, and it affects the speed and pattern of the sound waves reaching the solar surface. Metals in particular absorb energy and impede the waves' path to the surface.

For years these two independent yardsticks for the Sun's makeup were largely in harmonious agreement. Then, in the 2000s, spectroscopists dropped a bombshell: The Sun had far fewer metals than they had originally said. The two sides have been duking it out ever since.

Astronomical Standoff

Nicolas Grevesse (University of Liège, Belgium) was a coauthor on what is now a landmark paper. He explains that the change in abundance measurements was due to advances in calculations. "Twenty years ago, we were only using one-dimensional models of the photosphere," he says. Computing restrictions forced astronomers to simplify their models and assume that the photosphere was in thermal equilibrium, with no sudden changes in temperature.

However, the surface layers of the Sun are constantly evolving, with hot, new material bubbling up all the time. Once Grevesse and his colleagues started using 3D models and dropped the equilibrium requirements, it became clear to them that their original abundance estimates of carbon, nitrogen, and oxygen were wrong. The overall metal content of the Sun dropped from 1.8% to 1.3%; a revision to oxygen abundances accounted for almost half of that shift.

Suddenly, spectroscopists were at odds with helioseismologists, and the so-called *solar abundance problem* was born.

The consequences are dramatic. The mass of metals sliced from solar models is equivalent to around 1,500 Earths. Stars with fewer metals burn through their nuclear fuel much faster. If the spectroscopists are right, the Sun will die a billion years earlier than we'd anticipated.

It isn't just our understanding of the Sun and its longevity that are in jeopardy, though. The Sun is the only star we get to see up close; the next-nearest star is more than 268,000 times farther from Earth, more than 4 light-years away. As a result, we use the Sun as a benchmark for understanding every other star in the universe. "It affects the precision with which we infer the mass, age, and radius of other stars," says Gaël Buldgen (University of Geneva, Switzerland). If we've misunderstood these parameters for the Sun, then we've got them wrong for *all* stars. According to Buldgen, fewer metals would mean a decrease of up to 10% in mass and radius and up to 20% in age for Sun-like stars.

These differences affect our studies of planets beyond the solar system, too. Astronomers estimate exoplanets' masses and radii from those of their host stars. In recent decades we've found potentially habitable planets around distant stars. But a planet previously thought to have a rocky surface and a nice warm temperature — and possibly liquid water — may turn out to be very different if the size of its host star is not what it seems.

The stakes are clearly high, so who's right? Both sides are stubbornly sticking to their guns in an astronomical standoff.

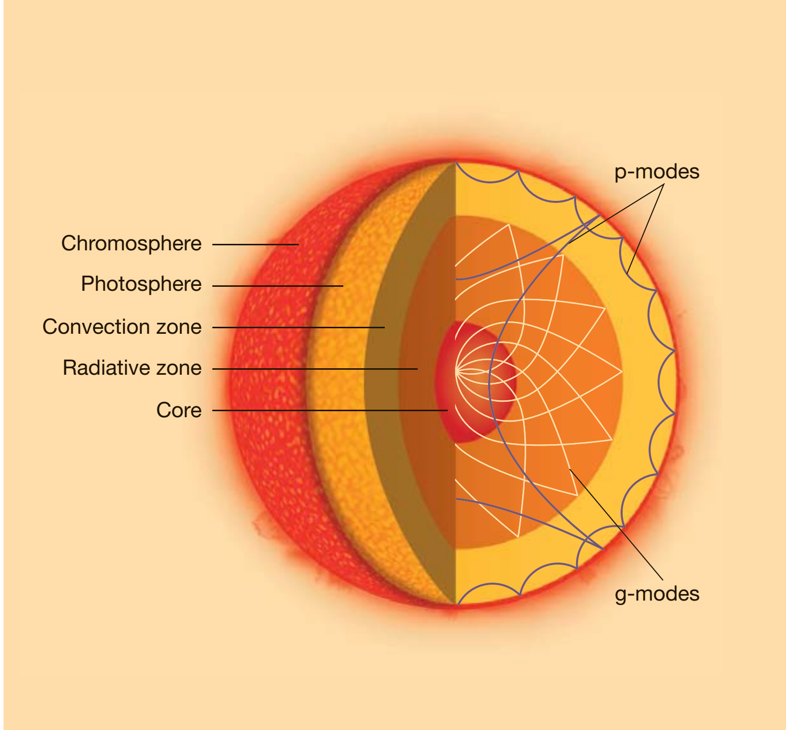
"It shouldn't even be called the solar abundance problem," says Anish Amarsi (Uppsala University, Sweden), who is on the spectroscopists' side. "You should call it the 'solar modeling problem,' as the abundances are sound." Different spectroscopic indicators all point to the same abundances, he says: "We have checked them again and again, and we keep landing at the same answer."

The spectroscopists also point to meteorite samples containing pristine material from the same cloud of gas and dust that formed the Sun. These, they claim, show generally good agreement with the revised solar abundances.

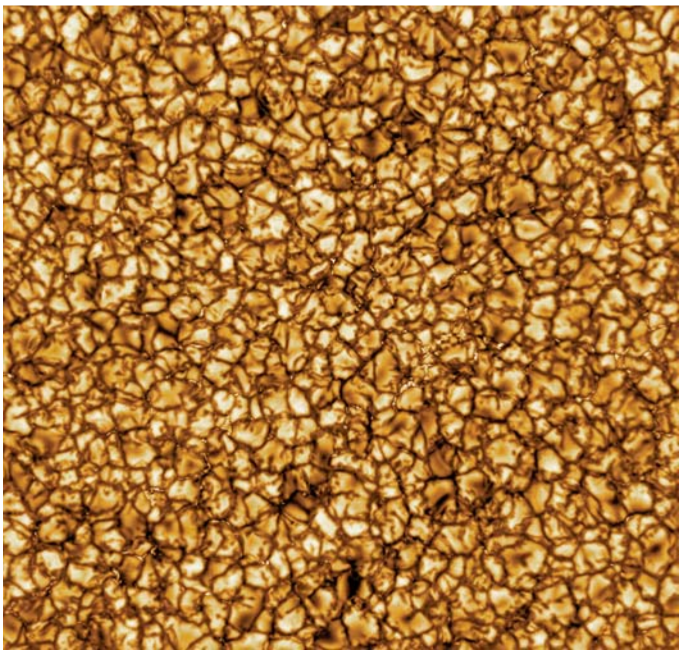
The real problem is that helioseismologists are underestimating the opacity of the solar plasma, Grevesse and Amarsi both say. "This missing opacity acts in the same way as changing the abundance," says Amarsi.

For her part, Basu isn't having any of it. "To me, this is a spectroscopists' dispute," she says. "Every helioseismic measurement gives a higher abundance."

The opacity would have to change by around 15% at the base of the convection zone (the layer of the Sun directly



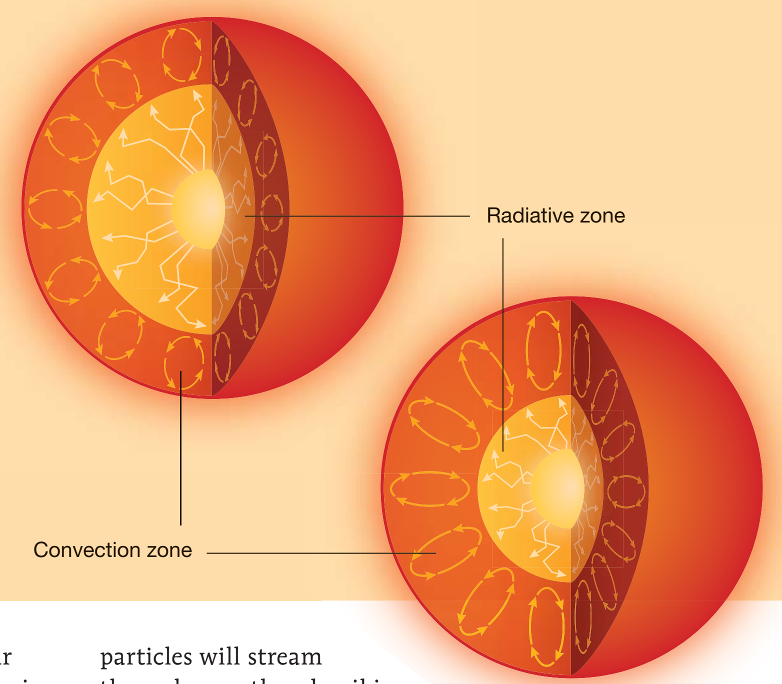
▼ **SOLAR SURFACE** Plasma on the visible surface of the Sun churns within cells, each roughly the size of Texas.



SOLAR SURFACE: NSO / AURA / NSF; SOLAR INTERIOR: LEAH TISCIONE / S&T, SOURCE: ESA

◀ **INSIDE THE SUN** This cutaway diagram shows key regions of the solar interior. The *chromosphere*, part of the Sun's atmosphere, is outermost. Beneath that is the visible surface or *photosphere*. Within the Sun, a turbulent *convection zone* surrounds the more stable *radiative zone*. Deep inside is the core, where hydrogen fuses into helium. Waves slosh within the Sun, some of them (known as gravity waves) restricted to the inner regions. Other waves, known as pressure waves, connect the interior to the visible surface.

▶ **DEPTH CHANGE** The new solar abundances imply a shallow convection zone *(left)*, but sound waves indicate a deeper convection zone *(right)*. (The change in depth of the convective zone in this diagram is exaggerated for clarity.)



LEAH TISCIONE / *S&T*, SOURCE: APS / ALAN STONEBRAKER

below the photosphere) and 5% in the core to bring solar models in line with the revised abundances, she says. Upping the opacity would change our understanding of the Sun's interior structure. Solar energy travels outward from the Sun's core by the process of radiation, before it transitions into being carried by convection as the temperature and density of material drops closer to the surface.

The chance that the helioseismologists' numbers are a fluke outlier of the spectroscopists' numbers is just 1 in 20 million. If they are wrong, then they are spectacularly wrong.

"That boundary depends on how opaque solar material is," Basu says. "If we use the new abundances, then the convection zone is very shallow." It would begin at 72.5% of the way from core to surface. But the way the sound waves bounce around suggests the convection zone is deeper, starting at 71.3% of the Sun's radius. That may sound inconsequential, but the helioseismologists claim their work is accurate to 0.1%. The chances that the helioseismologists' numbers are a fluke outlier of the spectroscopists' numbers are just 1 in 20 million. If they are wrong, then they are spectacularly wrong.

The Neutrinos Will Decide

According to Basu, there is a way to settle this impasse: solar neutrinos. Neutrinos are tiny, almost massless particles generated in the same nuclear fusion reactions that produce sunlight deep in the Sun's core. Each and every second, 683 million tons of hydrogen are churned into 679 million tons of helium. Solar fusion generates so many neutrinos that if you hold your thumb up to the Sun, 65 billion of these ghostly particles will stream through your thumbnail in a second. A billion trillion will pass through your body over your lifetime, approximately the same as the total number of stars in the entire observable universe.

Elaborate experiments around the world have been snaring solar neutrinos since the 1960s, allowing us to be confident of the Sun's inner workings. Labs go to great lengths to achieve this by sheltering underground, shielding themselves from other kinds of particles that can't make it through the bedrock. Most neutrinos, on the other hand, pass straight through Earth and continue onward into space unhindered. In fact, a light-year of lead — some 9.5 trillion kilometers long — would only have a 50:50 chance of halting a neutrino.

For decades, these unusual experiments have picked up solar neutrinos produced as part of the *proton-proton* (pp) chain — the main set of nuclear reactions that generate the Sun's energy. The vast majority of these reactions only involve hydrogen and helium, but a rarer set includes the metals beryllium and boron. In 2018, the team conducting the so-called Borexino experiment in Italy announced they had picked up neutrinos produced by all possible pp-chain reactions, including the rarer two involving metals, and so could infer their abundances. What they found favors the helioseismologists' higher metallicity estimate. Maybe it is a solar abundance problem, after all.

Borexino could provide a more definitive answer in the years ahead. A rarer form of fusion called the *carbon-nitrogen-oxygen* (CNO) cycle generates less than 2% of the helium created in the Sun. In June 2020, Borexino scientists announced that they had also picked up neutrinos produced by the CNO cycle for the very first time. Working out how many of these scarcer neutrinos the Sun produces will offer up an independent and invaluable way to work out the solar abundances of carbon, nitrogen, and oxygen.

"Carbon-nitrogen-oxygen neutrino fluxes will be the cleanest test," Basu says. But she cautions against a quick answer. Although the first tentative results don't look good for the spectroscopists, she says "it may take a few decades to get the error bars down. It's a waiting game."

The Devil's in the Details

In the meantime, others have been searching for alternative solutions — some of them highly speculative. Qian-Sheng Zhang (Chinese Academy of Sciences) thinks that we can keep spectroscopists' lower abundances and match helioseismic measurements if we revise the way we model the Sun. This requires resolving the entire abundance problem, which isn't solely about a discrepancy in the amount of metals — the amount of helium is also in question.

Standard solar models using spectroscopists' lower metal abundances usually result in a lower amount of helium in the convection zone; otherwise the Sun would be the wrong brightness. But less helium is at odds with helioseismic measurements. In August 2019, Zhang's team presented a revised model of the Sun's interior that employs lower metal abundances while also increasing the amount of helium in the outer convection zone.

Currently, our picture of the convection zone is that material at its base heats up, rises to the surface, then cools and sinks back down. As the plasma boils, some helium settles out due to gravity, dropping into the radiative zone. But Zhang's team suggests that if some boiling material overshoots the lower boundary, it will drag the base of the convection zone deeper inside the Sun, preventing helium from settling as much and keeping the convection zone richer in helium. Accounting for this process allows the Sun to have lower metallicity while still maintaining the deep convection zone that helioseismologists measure.

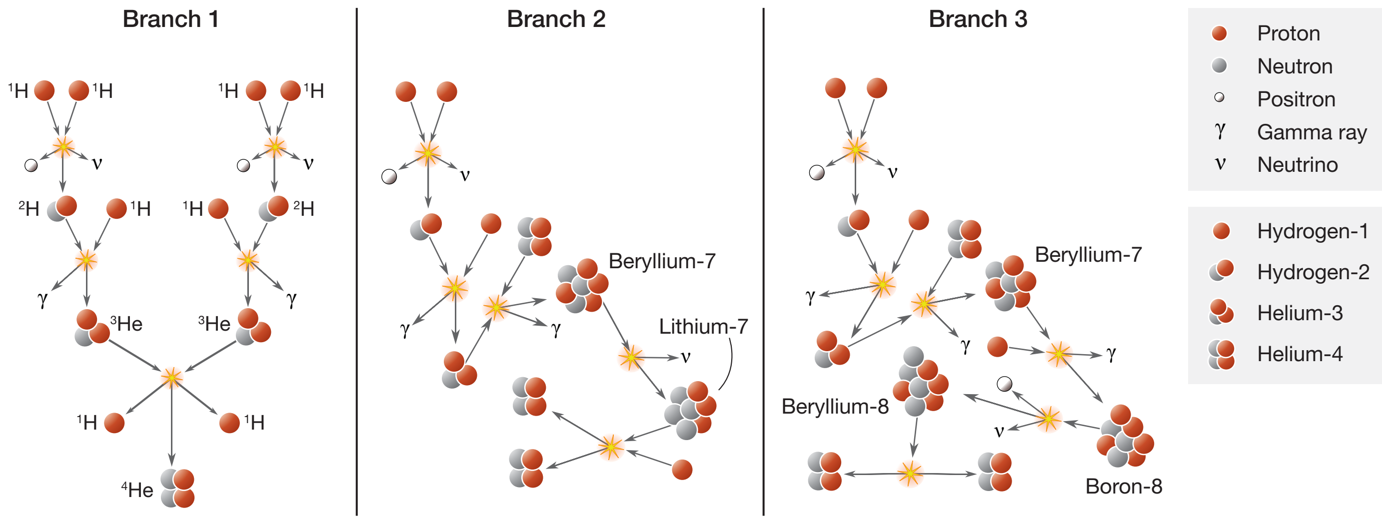
Helium was discovered by spectroscopists on the Sun before chemists identified it on Earth. That's why it's called helium: Helios was the Greek god of the Sun.

Another factor to consider is the solar wind, the stream of material blown outward by the Sun. Solar models don't typically include it, but it also affects helium abundance. Evidence from missions such as Ulysses suggests the solar wind is helium-poor compared to the normal solar surface composition. If models incorporate this effect, they see a boost in helium's abundance in the convection zone.

Finally, Zhang and colleagues found they also needed to reduce the amount of helium in the radiative zone, deep inside the Sun — a fundamental change likely made early on: The material falling onto the infant Sun would have had to be

VOLKER STEGER / SCIENCE SOURCE

▲ **LITTLE MESSENGERS** The Borexino experiment is housed underground in the Gran Sasso National Laboratory in Italy. Photomultiplier tubes line the walls of the chamber pictured here. The flashes of light they detect within a central sphere of liquid signal neutrinos coming from the Sun.



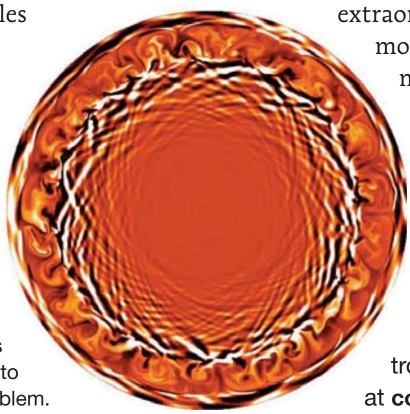
RARE REACTIONS Most solar fusion occurs through the proton-proton chain, which fuses hydrogen into helium. About 70% of proton-proton fusion occurs through the string of reactions in Branch 1, with the rest following Branches 2 and 3 (30.9% and 0.1%, respectively). By detecting neutrinos coming from the latter two sets of reactions, the Borexino experiment has provided tentative evidence that helioseismologists are right and that the new solar metal abundances are too low. Detections of neutrinos from another, even rarer set of reactions involving carbon, nitrogen, and oxygen would provide more definitive evidence.

helium-poor. "We've already seen evidence of this happening with other young stars," Zhang says.

Combined, the three processes create a complex interplay that explains observations from both sides of the standoff.

"Our model gives a perfect match to the results from helioseismology," Zhang says. The catch is that these processes have to happen in just the right proportions to make all the pieces fit. "The range of values needed to make it work is small," he says, "but we think it is reasonable." It's a rare suggestion that would see both the spectroscopists and the helioseismologists vindicated.

Anton Sokolov (Institute for Nuclear Research of the Russian Academy of Sciences) believes he has another solution, albeit one that relies on an idea far from mainstream scientific thinking. He looked for ways to change the opacity of solar material without tweaking the abundance of metals. One option is to make the radiative zone a little cooler and denser, in turn making it opaquer. To achieve this, Sokolov looked beyond the Standard Model of particle physics — scientists' cookbook for the way particles and forces interact with one another. Physicists have long suspected there are particles beyond what the Standard Model prescribes, not least because they need them to explain dark matter, the invisible glue thought to bind galaxies like our Milky Way together.



DEFINING BOUNDARIES A 2D slice from a computer simulation shows the convection and radiative zones in the Sun. Some of the convective plumes spill past the boundary between the zones, carrying material deeper into the radiative zone. This phenomenon is known as *overshoot*, and taking it into account could help resolve the solar abundance problem.

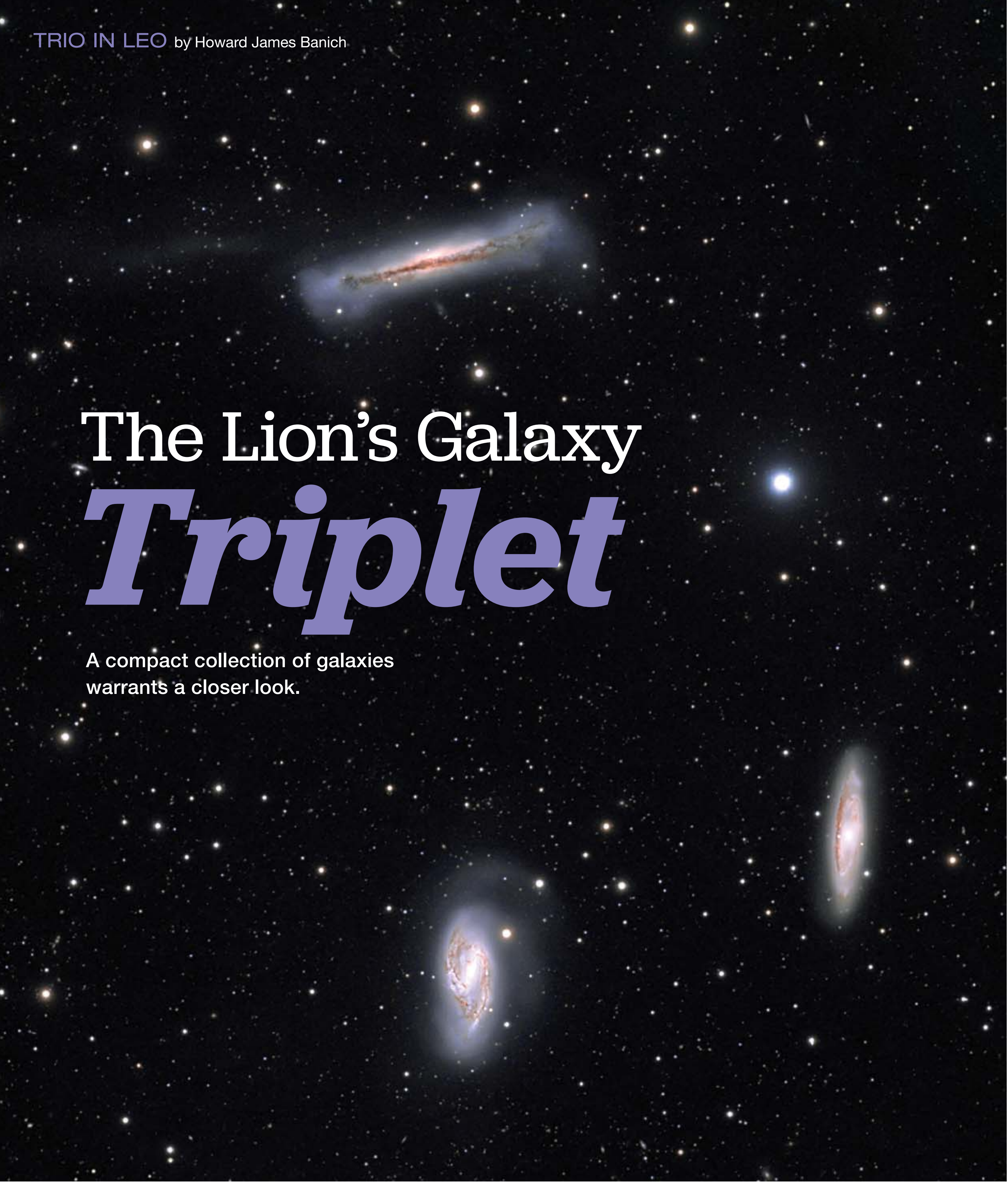
According to Sokolov's calculations, conditions at the top of the radiative zone are ideal for turning some of the ordinary photons the Sun creates into particles called *dark photons*. Crucially, dark photons don't interact with ordinary solar material; instead, they stream out freely in all directions, robbing the radiative zone of energy. However, this energy loss needs to be compensated for elsewhere in the Sun to tally with observations.

For that, Sokolov turned to another so-far-hypothetical entity: *millicharged particles*. They are the product of dark matter that has settled in the solar core after being hoovered up by the Sun as it journeys through the Milky Way. According to Sokolov's theory, these particles produce energy that warms the core and balances the heat lost farther up in the radiative zone. "Such a process would solve the solar abundance problem," he says.

Sokolov's solution is an extreme one. After all, as Carl Sagan famously espoused, extraordinary claims require extraordinary evidence. Yet the solar abundance/modelling problem has been a thorn in astronomers' collective sides for nearly two decades. Although the recent Borexino CNO neutrino haul has provided a real shot in the arm, it's clear there is much work left to do to resolve one of the trickiest issues in modern astronomy. Nothing short of our understanding of stars depends on it.

COLIN STUART (**@skyponderer**) is an astronomy author and speaker. Get a free ebook at **colinstuart.net/newsletter**.

PP CHAINS: LEAH TISCIONE / *S&T*, SOURCE: NASA / JPL-CALTECH; OVERSHOOT SIMULATION: T. ROGERS ET AL. / *ASTROPHYSICAL JOURNAL* 2006 by Howard James Banich



The Lion's Galaxy *Triplet*

A compact collection of galaxies warrants a closer look.

Leo was the first constellation my dad pointed out to me when I was very young.

As he held me in his arms with my older sister standing at his side, he tried to show us which stars belong to Leo, the Lion. Almost instantly, my three-year-old brain began panicking at the idea of a wild animal in the sky. My father tried to calm me by saying they're not real animals — and then proceeded to point out that Ursa Major and Ursa Minor are big and little bears. Now I was really scared.

I was carrying on so much that my braver sister was starting to wonder if she should be afraid, too. Dad promptly took us inside, to the safety of the house, all the while reassuring us that the animals in the sky were just make-believe. Once we were back indoors, he managed to gently calm us down.

This early memory, possibly my first, left its mark. Even now, that long-ago night comes to mind while star-hopping through Leo to one of my favorite telescopic sights, the three galaxies of the **Leo Triplet**.

The Trio in Leo

Finding the Triplet, which is located about 2° south-southeast of the star Theta (θ) Leonis and almost halfway along a nearly straight line from Theta to Iota (ι) Leonis, is pretty straightforward. But even though all three galaxies are obvious in backyard telescopes, the Triplet wasn't discovered all at once.

Charles Messier discovered **M65** and **M66** in 1780, and William Herschel completed the triplet in 1784 with his discovery of **NGC 3628**. All three galaxies are gravitationally interacting with one another, although only the distorted shapes of M66 and NGC 3628 make this apparent. Studies of NGC 3628's tidal tail have even revealed the formation of a rare *tidal dwarf galaxy* within its plume.

M66 is the closest to us at 33 million light-years (Ml-y), with M65 next at 36 Ml-y and NGC 3628 the farthest at 40 Ml-y. They're a tight clustering, tighter than the Local Group according to current distance estimates. Astronomically inclined inhabitants on M66, say, would likely see M65 the way we view Andromeda — or even larger.

◀ **COSMIC TRIO** The Leo Triplet consists of NGC 3628 (top right), M66 (bottom left), and M65 (bottom right). Note the tidal tail of NGC 3628 stretching eastward toward the top left of the image, as well as the subtle X pattern of its core. Also note the distant galaxies in the far background. The three Triplet galaxies are less than a half degree apart and together fit into the low-power eyepiece field of view of most amateur telescopes. All images have north up.

▲ **TIGHT FIT** This sketch of the Leo Triplet hints at the low-power (155×) view on a dark, transparent night through my 28-inch scope, and shows how they barely fit into the field of view. A short focus instrument is better suited to observe all three galaxies at once.

Halton Arp's *Atlas of Peculiar Galaxies* (published in 1966) lists the Triplet as Arp 317, due to the interaction between M66 and NGC 3628. M66 gets its own designation — Arp 16 — because of a "large concentration at end of the S. arm." Cryptic, but concise.

There are other bright galaxies in the area that are gravitationally bound to the Triplet. For instance, **NGC 3593** is located about a degree to the west-southwest of the trio,

Triplet in the Lion

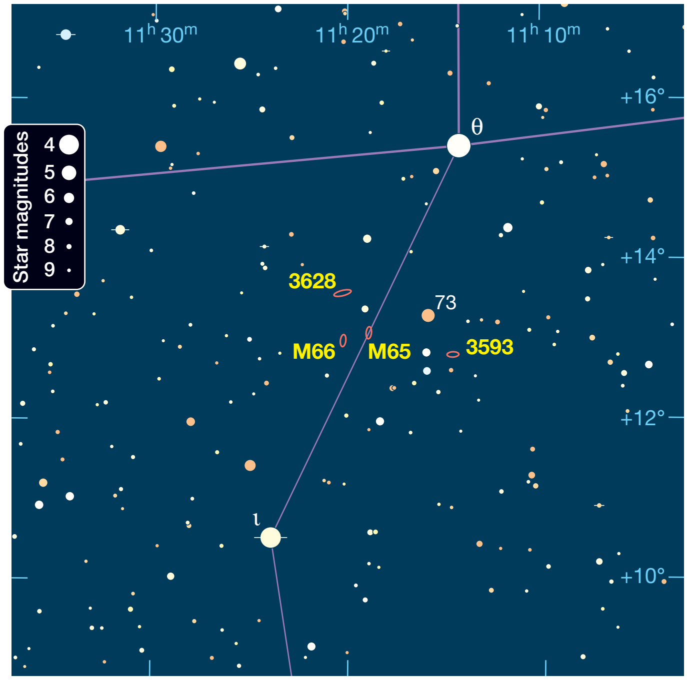
Triplet Member	Other Designation	Distance (million l-y)	Surface Brightness	Mag(v)	Size/Sep	RA	Dec.
M65	NGC 3623	36	12.8	9.3	9.8′ × 2.9′	11^h 18.9^m	+13° 06′
M66	NGC 3627	33	12.7	8.9	9.1′ × 4.2′	11^h 20.3^m	+12° 59′
NGC 3628	—	40	13.4	9.5	14.8′ × 3.0′	11^h 20.3^m	+13° 35′
NGC 3593	—	30	13.3	10.9	5.2′ × 1.9′	11^h 14.6^m	+12° 49′

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.

COSMIC TRIO: STEFAN BINNEWIES / JOSEF PÖPSEL / CAPELLA OBSERVATORY; SKETCH: HOWARD BANICH and is at a distance of 30 Ml-y. Also, the Triplet is possibly a subgroup of the M96 galaxy group, also known as the Leo I Group. This collection is 8° west of the Triplet, and its members are at comparable distances to M65, M66, and NGC 3628. Other galaxies in this area are probably part of this gravitational neighborhood, and if you're curious to find out for yourself, there are several resources you can turn to for obtaining their distances — see the box on page 21 for details.

The Leo Triplet fits in my 28-inch scope's widest field-of-view eyepiece, though its components are arrayed around the edge of the apparent 100-degree field of view, making it difficult to appreciate them as a group. However, one of the great things about the Triplet is that you don't need a huge scope to appreciate them, and a wide-field instrument is preferable for seeing all three together. I had a memorable view through my 8-inch f/4 scope in April 1984:

> *"Nifty trio of galaxies in Leo — the Deep Sky filter improved their contrast about 2× — M65 and 66 were the brighter of the 3, but 3628 was thinner and longer — still obvious. All 3 fit into the field at 41×. 65 and 66 stood out better at 102× than 3628."*



Few galaxy groups can surpass the visual impact of M65, M66, and NGC 3628, neatly posed in an eye-catching isosceles triangle that points almost due north, through a wide-field scope like this.

On the other hand, detecting the subtle nuances in each Triplet galaxy requires medium to high magnifications and dark, transparent nights, regardless of what scope you use. A closer examination of each galaxy starts to show how different they are, and yet hint at how they relate to one another.

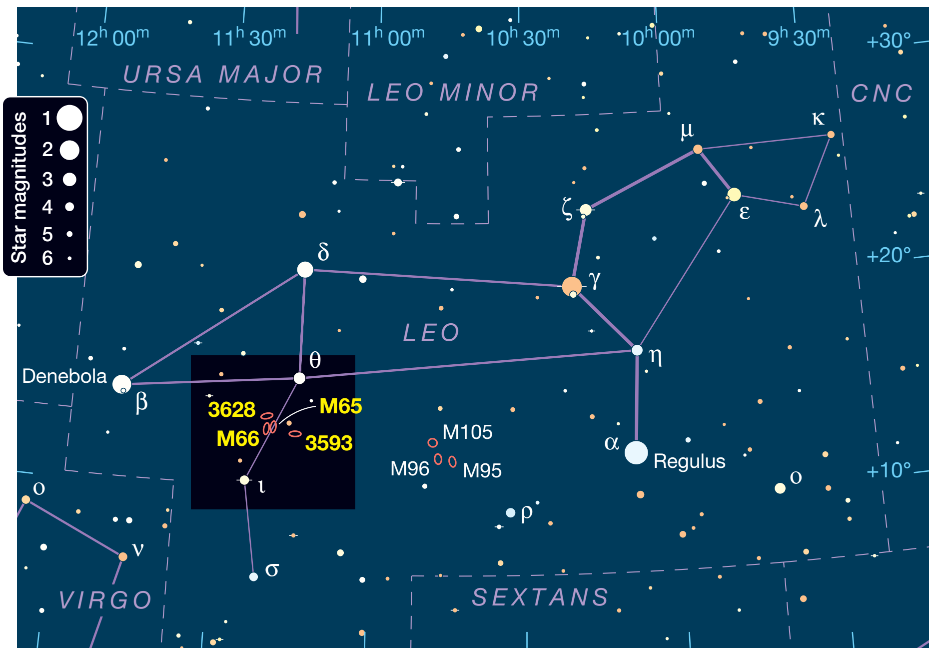
M65

To my eye, M65 is the least visually interesting galaxy of the trio, even though it's well defined and stands out well from the sky background. Internal detail is hard to come by, though, even in large scopes. To my surprise the view is only slightly less detailed in my 28-inch compared to Jimi Lowrey's 48-inch scope — which makes it a rare object indeed!

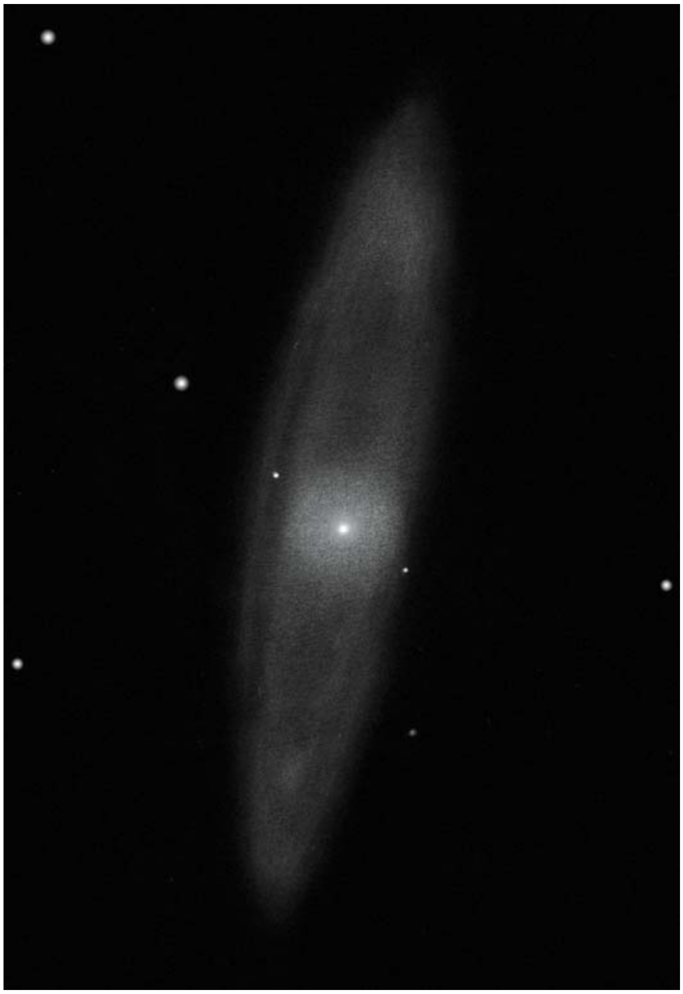
Perhaps that means smaller scopes can present much the same view. Other observers have seen extensive detail in M65. Take Stephen James O'Meara — his sketch of this galaxy in his book *Deep-Sky Companions: The Messier Objects* (Cambridge University Press, 1998) shows a nearly photographic level of detail, and with a 4-inch refractor no less. He's not the only one to see more than I have, so give it your best shot and you may be pleasantly surprised.

With its well-defined periphery, bright core, and starlike nucleus, M65 is tipped at a relatively sharp angle to our perspective — and looks much like I imagine M31 would appear from 36 Ml-y away if it were tilted at the same angle. Recent research suggests M65 may be a barred spiral, but the bar is not a visual detail.

However, I have been able to see the dust lane on the galaxy's near side. It's about as subtle as the dark lane that arcs across the core of M81 — so the feature is as much a test of your observing skill as a barometer of the observing condi-



◀ **IN THE LION'S DEN** The Leo Triplet is neatly clustered below Theta (θ) Leonis.



▶ **CELESTIAL DISK** Details beyond its bright core and overall shape are tough to discern in M65. The contrast in this sketch has been boosted to make these subtle details more apparent than they appear in the eyepiece. Perhaps the easiest of these features is the dust lane on the east (left) side of M65.

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tions. There are a few slightly more distinct areas across its tilted disk that I've been able to see with effort — these areas become more distinct on a really dark and transparent night.

My most detailed view of M65 is from April 2019:

> *"Nice view of M65, the least examined (by me at least) of the Leo Trio. There are a handful of subtle variations along its arms and core, more than I remember, but then I usually don't look at it all that closely! 253×, 21.45 SQM* [Sky Quality Meter]*."*

There are two reasons I haven't looked at M65 "all that closely" through the years. Aside from its frustratingly subtle details, M66 and NGC 3628 are considerably more interesting visually.

M66

This spectacular barred spiral galaxy is my favorite of the Triplet. M66 has nearly the same angular diameter as M51, the Whirlpool Galaxy, but is stretched thinner by its gravitational interaction with NGC 3628. For what it's worth, M66's barred spiral shape is as obvious to my eye as M51's more famous spiral arms.

The sketch on page 22 was made under nearly ideal conditions using my 28-inch scope, and is one of my favorite galaxy drawings. I spent only about an hour creating this sketch at the eyepiece, and the amount of detail I saw blew me away. What really made an impression was how dynamic the galaxy looked, and its stretched-out shape practically screamed tidal disruption.

Tracing the limits of the spiral arms became easier the longer I looked with averted vision. My brain was tempted to trace the arms farther than my eye was actually seeing, so I've been careful to only include what I could definitely detect. Observing as much of the faint outer extensions as I did was a surprise, and they were visible only because the conditions were so good.

The thin central bar and its starlike core are rather bright and pop out well during moments of steady seeing, as did all the other small-scale details along the spiral arms, such as H II regions and dust lanes. I have a soft spot for barred spirals, and to me M66 is one of the most visually interesting because of its wealth of detail and wonderfully energized shape.

> *"No obvious supernova* [ASASSN-16fq, June 2016]*, but I did see several star-like dots within the galaxy. The one at the end of*

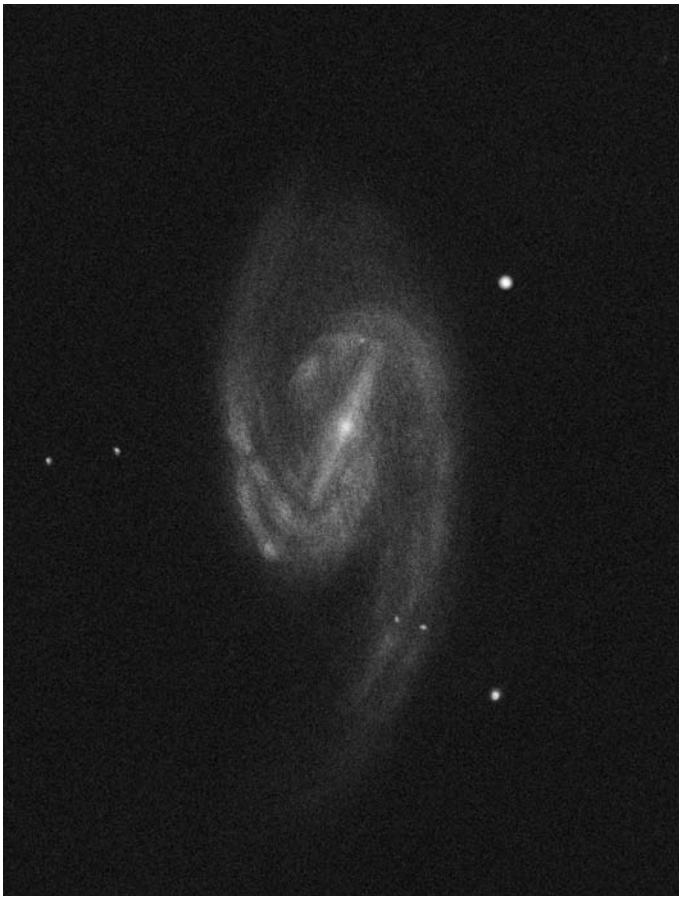
Distances to Galaxies

The internet is replete with resources for obtaining distances to galaxies. The SIMBAD database (**https://is.gd/simbad_id**) returns redshifts in the main body of information and often also a selection of distance estimates expressed in megaparsecs.

If you prefer to visualize your data, head over to Aladin Lite (**https://is.gd/AladinLite**). After pulling up the SIMBAD catalog from a menu, you'll need to click on your target to get the redshift.

Redshifts should be converted to something more tangible, and for that you can turn to Ned Wright's Javascript Cosmological Calculator at **https://is.gd/CosmoCalc**. After entering the redshift, the program will return distances in megaparsecs and giga-light-years. Just note that the resulting distances will depend on which cosmological model you select.

The NASA/IPAC Extragalactic Database (**https://is.gd/nasa_ipac**) also proposes a comprehensive selection of distances based on various cosmological models.



◀ **DELICATE SPIRAL** By far the most detailed galaxy of the Leo Triplet, M66 exudes dynamism from its close encounter with NGC 3628. I used 408× with the 28-inch scope on the night of June 3, 2016, at the site of the Oregon Star Party to make this sketch.

▶ **GALAXIES HAVE TAILS, TOO** Note how NGC 3628 has a thick envelope of galactic fuzz surrounding it, almost like it's wobbling along its major axis and shaking stars out of its spiral arms. Look closely to see the X-shaped core, an indication that NGC 3628 may be a barred spiral. The long tidal tail stretches about three times the length of NGC 3628 to the east (left) in this image, with the tidal dwarf galaxy (Leo-TDG), marked with the gold lines just north of the background galaxy IC 2787. I know of only one visual observation of this object — by Jimi Lowrey with his 48-inch scope from West Texas. Also, the inset box shows the objects Halton Arp claimed were ejected from the core of NGC 3628.

the [northern] *arm seems a likely suspect…* [it wasn't] *Lots of galaxy detail at 408×. 21.82 SQM."*

Sometimes my sketches do most of the talking in my notebooks, and I only write down what the drawing doesn't show. My notes imply that my priority that night was seeing the supernova, but I stopped looking for it after about five minutes or so and concentrated on sketching the galaxy. In retrospect, I'm not surprised I couldn't spot the 16th-magnitude supernova since it turned out to be in a relatively bright part of the galaxy, but so what — this turned out to be far-and-away the finest view of M66 I've had so far.

NGC 3628

I also have a soft spot for edge-on galaxies and tidal tails. At the northern tip of the Triplet, NGC 3628 fits the bill on both counts. But it also has the lowest surface brightness of the three galaxies, making it the most difficult to see well. Under a light-polluted suburban sky NGC 3628 may even be invisible, but it blossoms wonderfully under a truly dark sky.

The first thing that's noticeable is the galaxy's elongated east-west shape. Next you might see the fairly wide, diffuse dark lane running through its center. The northern slice of NGC 3628 above the dark lane is much brighter than the slice below, and on some nights the southern portion may be difficult to detect at all. The dust lane often fades into the sky background under such conditions.

However, on the best nights the apparent length and width of the galaxy is noticeably increased by a faint envelope of fuzziness — an effect of tidal disruption by M66. You'll need dark and transparent skies to see this feature.

Interestingly, NGC 3628 may also be a barred spiral galaxy. This is based on the subtle X pattern of its core, which is evident in many images but to my knowledge hasn't been seen visually. Although the X pattern isn't absolute proof this is a barred spiral, it's an intriguing clue.

The portion of the tidal tail depicted in my sketch is only the brightest part of a much longer stream. As you can see in the deep-exposure photo at right, it extends to the east at least three times the length of NGC 3628. Toward the end is a knot that's recently been identified as the tidal dwarf galaxy Leo-TDG. The formation of a dwarf galaxy within a tidal tail is a wonderfully exotic phenomenon. Leo-TDG most likely formed when NGC 3628 and M66 had their closest encounter approximately 800 million years ago, when they came within only 82,000 light-years of each other. That must have been quite a sight! In addition, radio observations have shown that NGC 3628 resides in a vast pool of neutral hydrogen that also reaches toward M66, another clue supporting the tidal interaction of these two galaxies.

Although much too faint for me to see, there's an intriguing string of objects just south of the core of NGC 3628 that Halton Arp described in a 2002 paper. Two of these objects are quasars, which he claimed were ejected from the nucleus of NGC 3628 due to their curious alignment with the galaxy's core and various associated outflows. The redshifts of these quasars are quite different from each other, but Arp maintained that redshifts aren't always an indication of distance when applied to quasars. Unfortunately, his insistence on this may have contributed to toppling him from the ranks of top-level astronomers.

Back in the brightness range I can actually see, my best sketch of NGC 3628 was made from a dark site with my 28-inch scope:

"An excellent view, especially considering that it's ⅔ of the way to the western horizon. The dark lane is prominent, and long,

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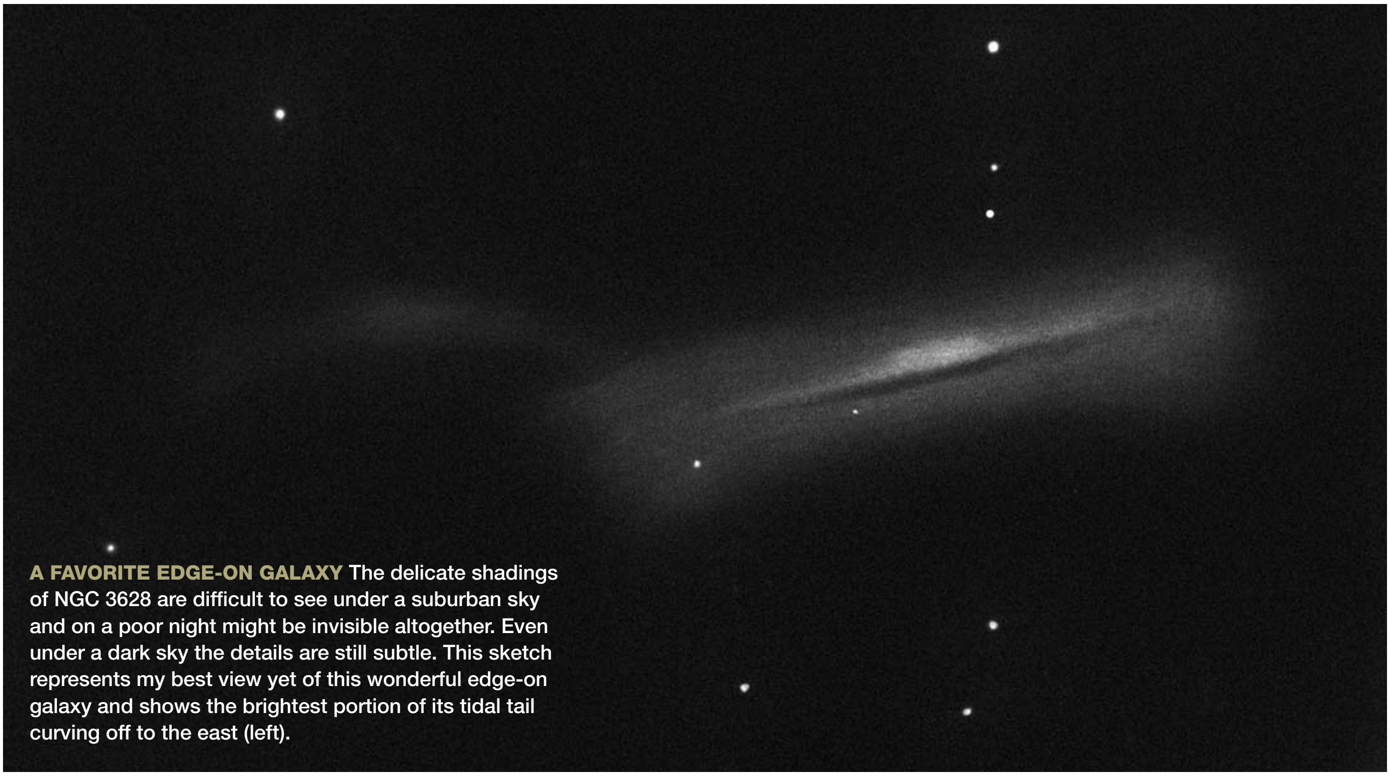


A FAVORITE EDGE-ON GALAXY The delicate shadings of NGC 3628 are difficult to see under a suburban sky and on a poor night might be invisible altogether. Even under a dark sky the details are still subtle. This sketch represents my best view yet of this wonderful edge-on galaxy and shows the brightest portion of its tidal tail curving off to the east (left).

NGC 3628: ROGELIO BERNAL ANDREO; SKETCH: HOWARD BANICH

with the tidal tail readily seen. Low contrast except for the brightest part of the [core's] *central area, which also delineates the sharpest edge of the dark lane. 253×, 21.47 SQM."*

I have a hunch NGC 3628 and its tidal tail would look longer and more detailed at a high-altitude dark site on a good night. Would Leo-TDG be visible? I hope to find out.

The Distant Background

Scattered all around the Triplet are numerous galaxies far in the background. The brighter ones have IC designations and are between magnitudes 14.5 and 16. You'll need high power to see most of these small and faint galaxies, which are 70 to 600 Ml-y away. They take significant effort and excellent observing conditions to detect, but those are also the best conditions for observing M65, M66, and NGC 3628. Your choice.

Because NGC 3628 and M65 may also be barred spirals similar to M66, perhaps the Leo Triplet looks even more striking from a different perspective. We'll probably never know, but it's a sure bet that observing them on the best spring nights from this planet will not only be irresistible, but time well spent.

■ Contributing Editor **HOWARD JAMES BANICH**'s dad, James Howard Banich, eventually did impart his fascination with the sky to his son and daughter — even though the first attempt was an unforgettable disaster. Howard can be reached at **hbanich@gmail.com**.

PAST AND PRESENT
Photographer Kara Hollenbeck is preparing to view the Moon with the University of Washington's 6-inch refractor. Installed at the end of the 19th century, it has been used for visual observing by the public and students for much of the last 125 years.

RESURRECT a Classic

It took an astronomer who refused to give up on herself to save a historic observatory for a new generation.

WOMAN AT TELESCOPE: BENJAMIN BENSCHNEIDER; CATALOG SKETCH OF SCOPE: COURTESY OF THE UNIVERSITY OF WASHINGTON

ING Refractor

What is so good in a college as an observatory? The sublime attaches to the door and to the first stair you ascend . . . this is the road to the stars . . .

— Ralph Waldo Emerson journal excerpt, November 14, 1865

The tiny, domed building sits on a grassy meridian sandwiched between a parking attendant's booth, a visitors lot, and the past and present of American astronomy.

This is the Theodor Jacobsen Observatory on the Seattle campus of the University of Washington. The entrance leads to a narrow staircase that winds up to the dome. There, visitors stand in the presence of an extraordinary telescope — a 6-inch refractor built in 1892 and in perfect working order. It's here today because of one astronomer's insistence on purchasing it, and another who spent nearly four decades managing the observatory alone so that thousands of Seattleites could peer through the scope into the heavens. It survived an upheaval in the field of astronomy because of yet another remarkable scientist who understood the difference between what academic researchers require and what students entranced by the night sky really need.

A Telescope Is Born

The telescope's story began in 1891, when Professor Joseph M. Taylor offered the University of Washington's first astronomy course. Faced with a windfall of cash and a spending deadline, the university's Board of Regents granted Taylor $3,000 (approximately $86,000 today) to purchase a telescope, dome, and weight-driven equatorial mount. Taylor, a veteran of Lick Observatory in California, procured a 6-inch refractor from the famed John A. Brashear Company in Pittsburgh,

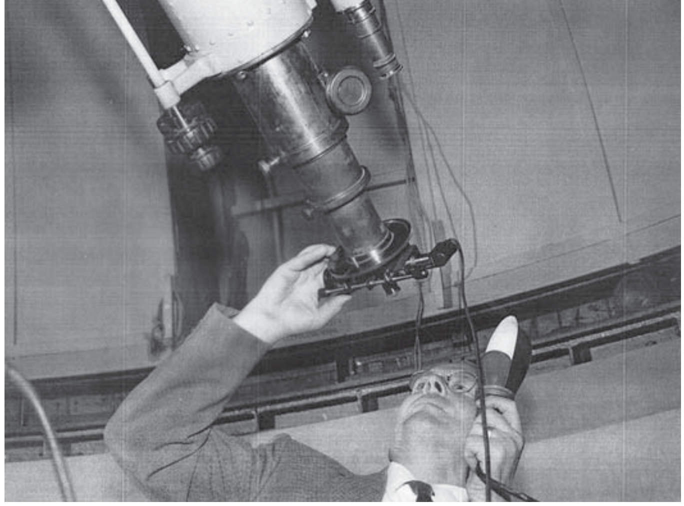
▶ **CATALOG SHOPPING** The 6-inch refractor with 90-inch focal length, as pictured in a 1911 Brashear catalog. The kit included "equatorial mounting, driving clock, coarse and fine circles, R.A. and declination clamps and slow motions at eye end, 6-inch objective in cell, 2-inch finder objective in cell, five eyepieces, one for finder, at $5 each, and diagonal prism." Total price: $1,590.

Pennsylvania. The Warner & Swasey Company of Cleveland, Ohio, built the mount and a small dome to house the instrument at 4th Avenue and University Street in what is today the bustling downtown core of Seattle.

Three years later, the university laid the cornerstone for Denny Hall, the first building of its new campus on the shores of Lake Washington. Sandstone left over from Denny Hall was used to construct the new home for Taylor's telescope. The observatory included several small offices and a narrow, winding staircase leading to the dome. (A lecture hall would be added later.) By 1895 the observatory was ready to house its prized possession.

The telescope quickly became well known to residents of the area. As reported in the *Seattle Post-Intelligencer* on October 27, 1907: "On every clear night, the big telescope at the observatory is in use, and excellent work has been done at the state university." University of Washington Professor James E. Gould acquiesced to the demands of the public, who had protested that they were only allowed to visit the observatory on Wednesdays. "This year, Prof. Gould will admit the public on any clear night to conduct observations with his regular students," the article confirmed.

In the autumn of 1928, Theodor Siegumfeldt Jacobsen arrived on campus. A native of Nyborg, Denmark, Jacobsen had immigrated to the United States in 1917 and earned a PhD in astronomy at the University of California before beginning work at Lick Observatory. "On account of a *muscular strain*," he wrote to the University of Washington, he had decided to retire from the heavy labor of a large observatory



▲ **IN ACTION** The campus newspaper described Theodor Jacobsen as a "kindly Scandinavian" welcoming all visitors who wished to experience observational astronomy as it was performed in the late 19th century. Jacobsen himself was fortunate enough to see Halley's Comet twice. He distinctly recalled viewing the famed comet from a hillside in Denmark as a child in 1910. He saw the comet on its 1986 return as well.

and dedicate himself to teaching and research.

It was a fortuitous hire. For decades, the soft-spoken Dane was the university's lone astronomy professor. He personally staffed the tiny observatory, guiding untold numbers of students and visitors, "with the exception of possibly 20 times when my advanced students have volunteered this service for the sake of experience."

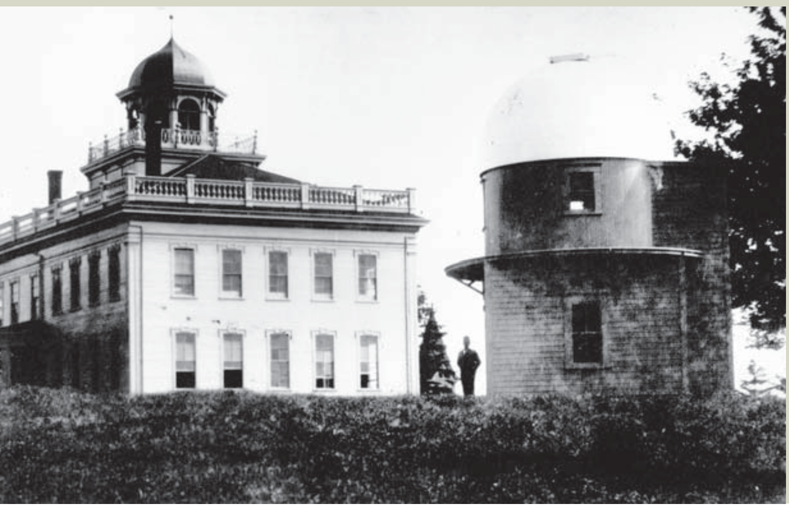
Times of Change

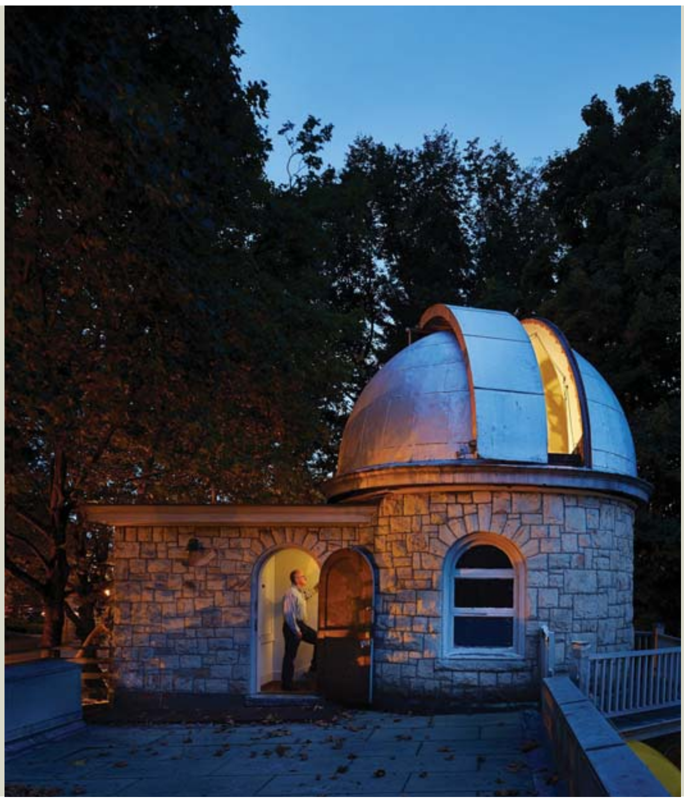
The launch of Sputnik in 1957 catalyzed a massive explosion of interest in astronomy. By 1965, the University expanded

JACOBSEN AT EYEPIECE AND B&W SHOT OF DOME EXTERIOR: COURTESY OF THE UNIVERSITY OF WASHINGTON; PRESENT-DAY EXTERIOR SHOT: BENJAMIN BENSCHNEIDER

▶ **A TINY DOME** The observatory building as it appears today on the University of Washington campus. This photo was captured from the roof deck of the observatory's lecture hall, which was added several years after the dome was completed in 1895.

▼ **FIRST LIGHT** The buildings of what would eventually become the Theodor Jacobsen Observatory shortly after completion. It is believed to be the smallest observatory dome ever constructed by the Warner & Swasey Company.





the department's faculty and began offering formal degree programs. One of the earliest doctoral students was Paula Szkody (SKO-dee), an astrophysics graduate from Michigan State University, who today is the current president of the American Astronomical Society.

In 1972 (after Szkody's arrival) the University dedicated a new research observatory equipped with a 30-inch Ritchey-Chrétien Cassegrain telescope on Manastash Ridge in eastern Washington. Yet public nights with the 6-inch refractor remained popular. Szkody remembers working as a volunteer guide. "We would do the open houses," she recalls. "That's when I first started to use the telescope. One quarter I taught an observing class at the observatory. We put an objective prism on it. We actually used the telescope a lot."

In 1975, Szkody became the first woman to earn an astronomy PhD in the department, and she joined the University of Washington faculty the same year. In 1988, she welcomed a new undergraduate, a 40-year-old transfer student from Seattle Pacific University named Ana Larson.

Had Larson stuck with her career in education, no one would have been the wiser. Like Szkody, she loved science. But whether it was an admitted lack of confidence, or the subtle messages female students often received about what constituted a suitable career path, Larson did not pursue astronomy in college. Instead, she earned a business degree at the University of Washington in 1970, garnered a teaching credential, married, and raised two children.

Sixteen years after graduating from college, Larson enrolled in a physics course at Seattle Pacific University so that she'd be qualified to teach science classes. "And that pretty much sealed my future!" Larson laughs. "It just clicked."

Larson transferred to the University of Washington and earned dual bachelor's degrees in physics and astronomy. She became one of the first five amateur astronomers to have an experiment accepted for the Hubble Space Telescope. (Sadly, the experiment was never completed due to the flaws discovered in the HST's optics after launch.) And she tore her way through the curriculum.

"Ana was a great student," Szkody remembers. Larson particularly excelled at observational astronomy. "She was nervous about coming back as an older student," Szkody says. "But we've had older students in our PhD program — they're very motivated, they're very solid, whereas some of the younger kids have nothing else to do so they just go to school. The older students know that this is what they want."

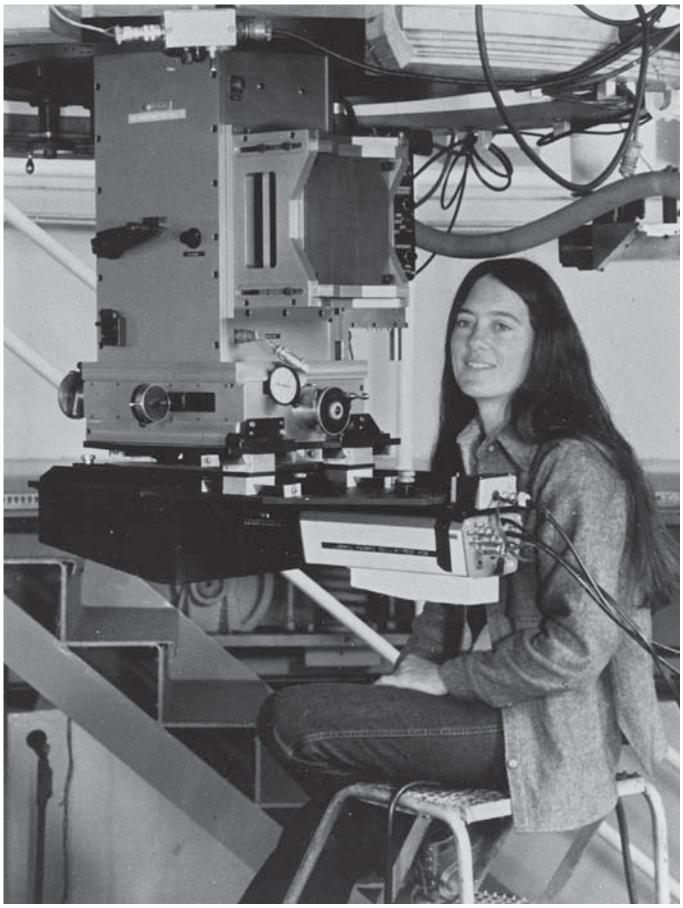
With encouragement from pioneering astrophysicist Erika Böhm-Vitense, Larson earned a PhD at the University of Victoria, British Columbia, in 1996. She was a member of the research team that examined radio-velocity data of "wobbling" stars and concluded that exoplanets likely orbit Gamma Cephei, Pollux, and Aldebaran. To keep her family in the Pacific Northwest, Larson accepted a part-time teaching assistant position at the University of Washington. She was promoted to lecturer, then to senior lecturer.

In late 2000, Larson started asking questions about the old observatory building and its telescope.

Beginning the Renewal

By the mid-1990s, the 6-inch Brashear had begun to fall into disrepair. "There was a combination of things that shifted attention away from the observatory," Szkody says. "The undergraduates started using the 30-inch telescope in eastern Washington. We got a 3.5-meter telescope at Apache Point in New Mexico. And in our new building on campus, we had a planetarium and telescopes you could place on the deck outside, where you could see the sky better." Even the alumni magazine concurred. "[T]he observatory's future could be in doubt. The building and its equipment are showing their age, and haven't been maintained very well. The hand-operated dome — which years ago rested on Civil War cannonballs used as bearings — is difficult to operate."

Crumbling infrastructure was only one of the problems facing the telescope. Academic tension had bubbled up between observational astronomers who saw value in a simple telescope, and theorists whose attention ran to ideas and equations instead of observing runs. To the theorists, the



COURTESY PAULA SZKODY

▲ **PROFESSOR AND COLLEAGUE** Paula Szkody was both Ana Larson's professor in the late 1980s and her University of Washington colleague starting a decade later. This 1980s photo shows Szkody working at Kitt Peak.

small refractor was simply a forgotten relic unsuited to modern research activities. By October of 2000, the department chair (a theorist) had resolved to keep the already long-locked observatory closed. Perhaps moving the scope to the astronomy department and placing it in a glass case would be a proper way to honor its service, the department chair concluded.

◀ **A CAREER RESURRECTION** Ana Larson returned to school at age 40 to earn bachelor and doctoral degrees in astrophysics. She's pictured here on a recent hike up the Methow River in north-central Washington State.

When Szkody heard the observatory was to be shut down and the scope relegated to museum showpiece, she was furious. "I was so mad about it being closed that I stormed into the chair's office," she says. "I was so angry!"

Szkody emailed the astronomy faculty, imploring them to consider the wider view. "The best thing about that old telescope is the feeling you get in climbing up those narrow, winding stairs and pulling the dome on the old cannonballs," Szkody wrote. "It is the best way to understand how astronomy used to be a long time ago and to realize the challenges involved in non-computer operation . . . If you have not ever been there at night, I recommend you try it out before deciding on closing or giving this unique instrument away. It is only one of a few scattered around the country."

With the support of Szkody and others in the department, Ana Larson emailed her colleagues. She didn't mince words when it came to the difficulty of the task at hand. "The [clock] drive is broken, the rooms are dirty and disorderly. Paint is chipping off on the outside, and the outside of the dome is rusty. . . We are probably looking at organizing a committee to oversee the repairs, clean-up, archiving, and all else that comes up." A wasp nest inside the telescope's six-foot tube was among the things that would "come up."

Larson concluded, "I'm almost afraid to ask: What do each of you think about all this?"

She needn't have worried. Her colleagues lined up to help, and the tide began to turn in the scope's favor. Eventually they received the green light from the department: The undergraduate astronomy students would adopt the observatory, with faculty supervision and, eventually, for class credit. "Ana had the right approach," Szkody says. "She got the students together to keep it going."

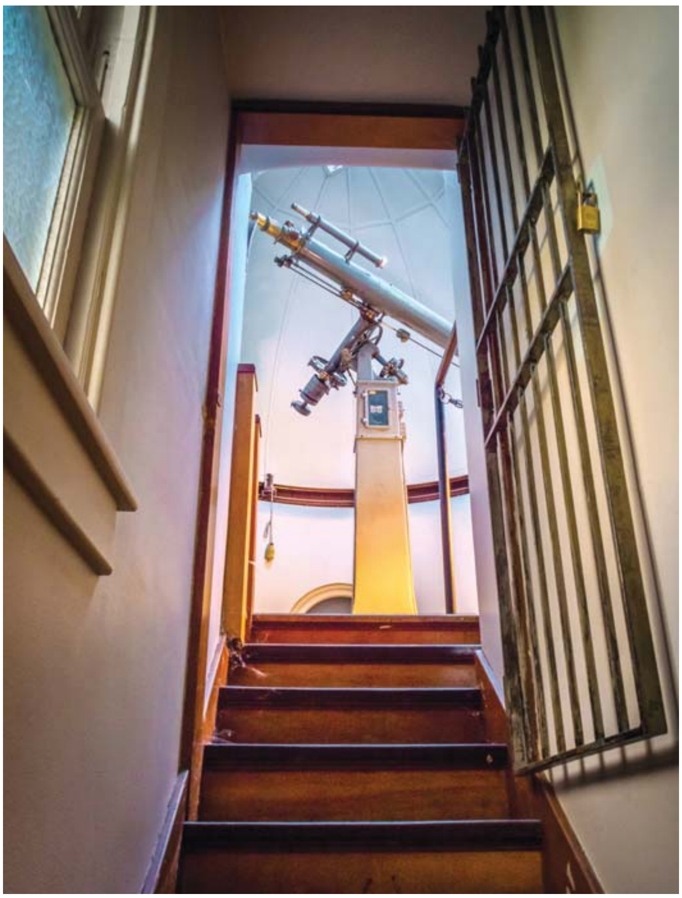
Larson assembled a faculty team to address the myriad issues involved in getting everything back up and running. She cajoled the university's groundskeepers into trimming and weeding the building's lot. Most importantly, she enlisted the help of a telescope specialist to fix the broken clock drive and give the entire instrument a solid workout to ensure it would again be up to the rigors of public viewing nights.

A New Lease on Life

A scrappy, self-taught shipyard machinist with a knack for building complex instruments, Peter Hirtle had run telescope-making seminars for the Seattle Astronomical Society for many years. He had also visited the dome decades earlier. "It's a typical long-focus refractor," he remembered. "It just works really well on fine-detail, low-contrast stuff."

Hirtle took apart the clock-drive mechanism, cleaned and lubricated it, and discovered that it was in surprisingly fine working order. Next came the objective lens. "That thing had not had a dust cover in years," he says. After a thorough cleaning, he bench-tested the optic and found it to be an excellent lens. "It's amazing how well corrected it is — very smooth," he recalls. By Larson's estimation, Hirtle devoted more than 200 hours without pay to restoring the antique scope.

Finally, on May 12th, 2001, the astronomy department hosted a grand reopening billed as "110 Years of Astronomy at the UW." On January 15th, 2004, the Regents voted to



◀ **STAIRWAY TO THE STARS** Ascending a flight of stairs brings visitors fact-to-face with the historic telescope of the Theodor Jacobsen Observatory. Newly restored, the instrument once again collects starlight just as it first did in 1895.

OBSERVATORY INTERIOR: KARA HOLLENBECK; LARSON: COURTESY ANA LARSON rename the building in honor of Theodor Jacobsen, who had died in 2003, at age 102. It was a fitting tribute to the professor who had devoted his life to the observatory and its goals. The dedication ceremony on October 27th that year featured a host of dignitaries *and* a total lunar eclipse. The Theodor Jacobsen Observatory was in business.

To handle the expected crowds, Larson turned again to the Seattle Astronomical Society. Amateur astronomer Mike Langley couldn't raise his hand fast enough. An experienced star-party host, he became the docent for the public outreach program — a position he held for 15 years until turning over the reins to fellow SAS member Jon Minnick three years ago.

Today, the Theodor Jacobsen Observatory public outreach program is jointly managed by undergraduate students at the University of Washington and by the Seattle Astronomical Society. Students prepare lectures for class credit, while the SAS manages the scope. They encourage the public to experience astronomy as it was performed over a century ago.

A Stellar Source of Inspiration

My first encounter with the telescope came on a rainy evening in September 2019. The cloudy skies meant no stargazing, but Jon Minnick demonstrated the clock drive and explained how, on clear nights, the dome's slit opens, and the drive is wound up manually to track the night's target. A senior astronomy undergraduate provided an outstanding lecture on star life cycles. At one point, she mentioned the star Betelgeuse. Behind me, a little girl celebrating her 10th birthday at the observatory piped up: "That's my favorite star!"

Bruce Balick, a professor emeritus of astronomy, was also there that rainy September night. He had become Observatory Director when Larson retired in 2018.

Balick told me Larson's story, adamant that she be given her due. "Ana was the most influential person in the modern history of the observatory by far," he said, with emphasis. "It was a locked-up building, almost never used, and she resuscitated the whole thing."

In October 2020 I drove to Mukilteo, Washington, to meet Ana Larson in person. We sat socially distanced, masked, on opposite picnic tables underneath an outdoor gazebo near the ferry that brought Larson from her home on nearby Whidbey Island. I told her about that little girl at the observatory and her favorite star. "That happens all the time," Larson said. I could almost see her smiling behind her mask.

However, she was clear: In her view, the real credit for the resurrection of the 6-inch refractor belonged to the undergraduates who relaunched the public nights. Larson's colleagues, though, sing her praises. If it hadn't been for her, they told me, the scope could well have been scrapped.

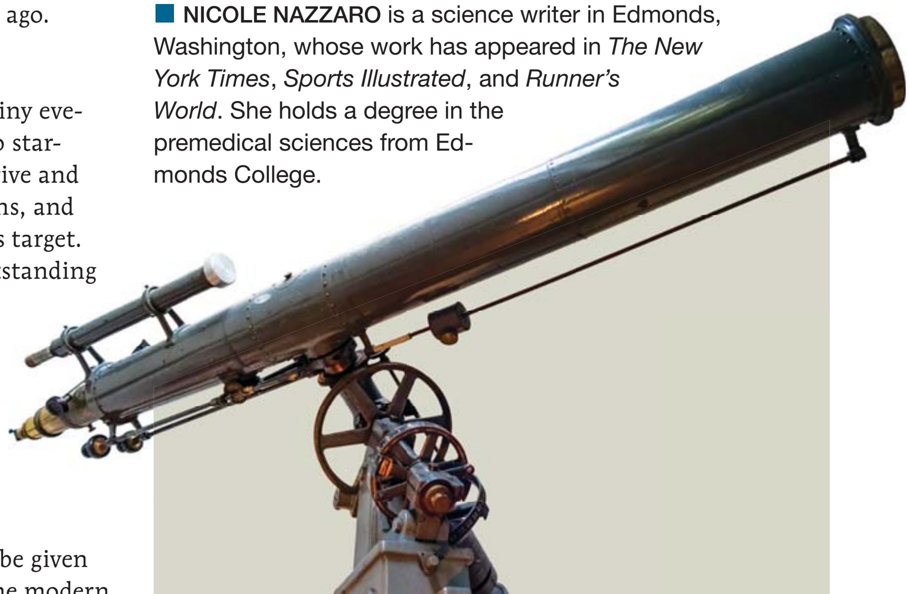
As we wrapped up our conversation, Larson paused, then suddenly made a connection. "People [asked] me way back then, why do you want to be an astronomer? What are you going to do with it? Why waste your time getting a PhD in astronomy?" Then the connection. "Why put the telescope back in use? What's gonna happen?"

She paused again. We both knew the answer.

All the astronomers whose work I've followed trace their interest back to a moment in childhood when they looked up at the night sky and were amazed at what they saw. Who knows what the true impact of this humble refurbished telescope will be? By seeing the value in something that others had dismissed, Larson resurrected a classic refractor for a new generation of astronomers.

"Paula was important," she concludes. "There were many people who helped. It just takes important people." And perhaps some of them, as both of us had seen, are only 10 years old. Perhaps this antique telescope, like the educators who fought to save it, is one that not only shows us the heavens, but points to the future.

■ **NICOLE NAZZARO** is a science writer in Edmonds, Washington, whose work has appeared in *The New York Times*, *Sports Illustrated*, and *Runner's World*. She holds a degree in the premedical sciences from Edmonds College.



KARA HOLLENBECK

▲ **A SCOPE RESTORED** The 6-inch refractor as it appeared in 2001. Peter Hirtle of the Seattle Astronomical Society repaired the clock drive and tested the objective lens. Unnamed brave souls removed the wasp nest they found inside the telescope tube.

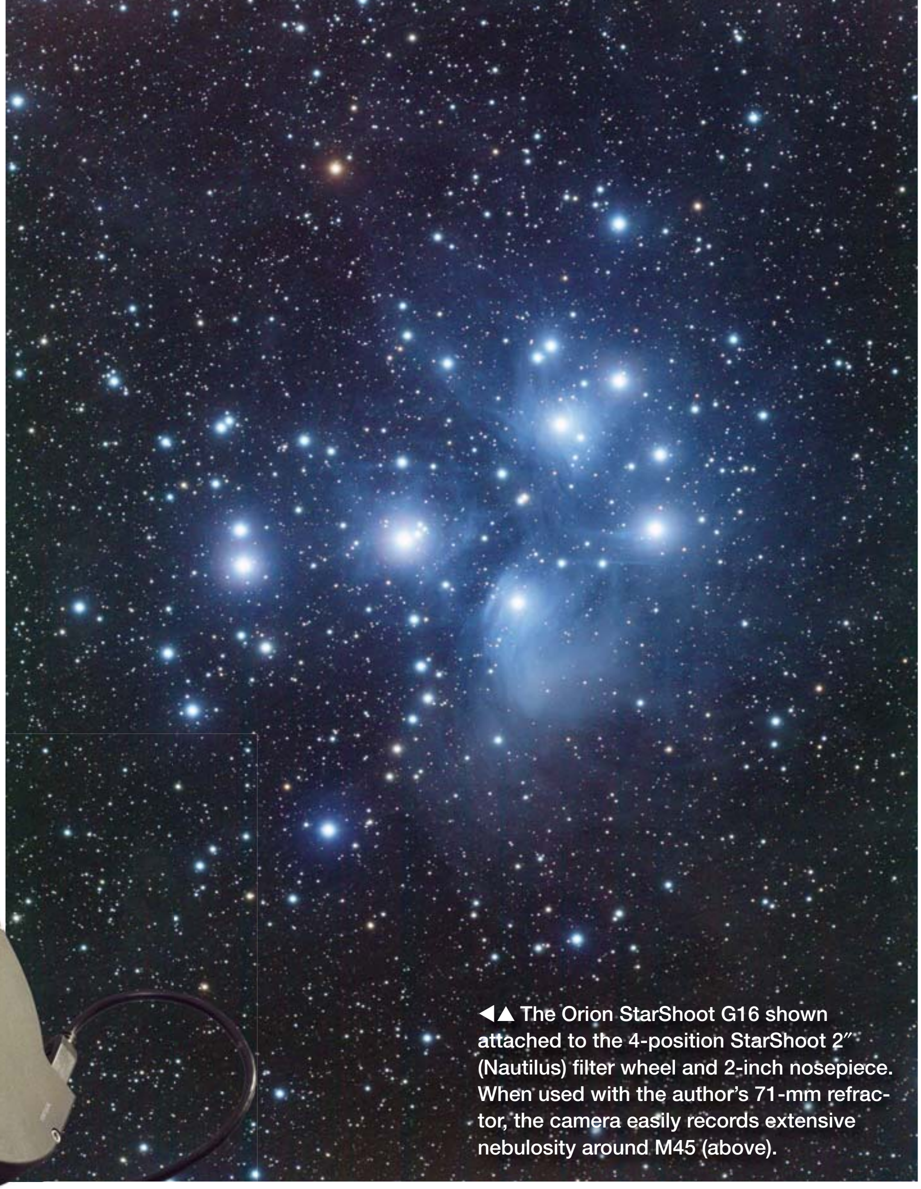
Public Viewing at the Theodor Jacobsen Observatory

The Observatory was closed for the entire 2020 season due to COVID-19. For information on 2021 visitation dates and to make reservations, visit **https://is.gd/jacobsenobservatory**.

The regular viewing season runs from April through September, two evenings per month when the university is back in session. Reservations are free, but booking several months in advance is essential as the lecture hall only accommodates 45 visitors at a time.

Orion's StarShoot G16 Deep Space Camera

We look at one of the latest offerings for budget-minded imagers.



◀▲ The Orion StarShoot G16 shown attached to the 4-position StarShoot 2″ (Nautilus) filter wheel and 2-inch nosepiece. When used with the author's 71-mm refractor, the camera easily records extensive nebulosity around M45 (above).

Orion StarShoot G16 Deep Space Mono Imaging Camera with Orion StarShoot 2″ Filter Wheel and LRGB Filter Set Package

U.S. Price: $1,299.99 (camera), $629.99 (filter wheel with LRGB filters)
telescope.com

What We Like

Small, sensitive pixels

Attractive pricing

What We Don't Like

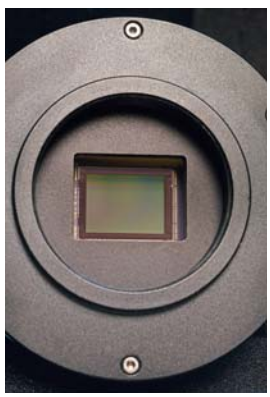
Filter-wheel software independent of camera control

No mechanical shutter

IF THERE WAS EVER ANY DOUBT about the popularity of astronomical imaging today, you only have to look at the range of new cameras being produced by several vendors, including Orion Telescopes & Binoculars in Watsonville, California. Orion has long offered beginner and intermediate-level astronomical cameras, including both one-shot-color and monochrome models suitable for deep-sky imaging as well as lunar and planetary photography.

Orion recently introduced the StarShoot G16 Deep Space Mono Imaging Camera. This thermoelectrically cooled, deep-sky imager features a 4/3-format, 16-megapixel Panasonic MN34230 monochrome CMOS detector with 3.8-µm pixels in a 4,640 × 3,506 array measuring 17.6 × 13.3 mm, or 22.1 mm corner to corner. For this review we borrowed the G16 along with Orion's 4-position StarShoot 2″ (Nautilus) filter wheel, which includes a set of Orion's LRGB filters.

Given the G16's small pixels, it pairs particularly well with short-focal-length instruments, and



◀ The camera's 16-megapixel monochrome sensor measures 21 millimeters from corner to corner and is mounted precisely 17.5 mm behind its T-threaded flange.

ALL IMAGES COURTESY OF THE AUTHOR

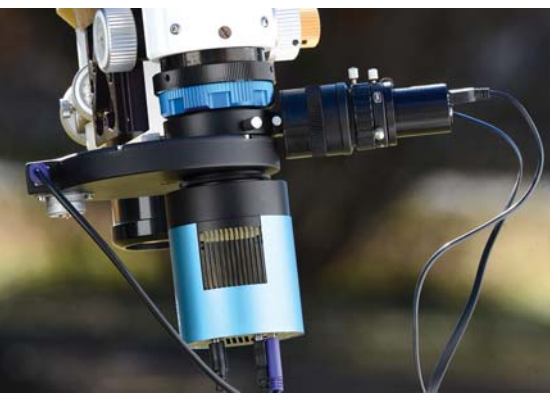
the pixels can be *binned* (electronically grouped) to better match scopes with longer focal lengths. I did most of my tests with a William Optics 71-mm apochromatic refractor, which has a 350-mm focal length (f/4.9). This combination yields a resolution of 2.4 arcseconds per pixel and a generous field of view measuring 174 × 132 arcminutes — fairly high resolution for such a short focal length.

The camera itself has a back-focus distance of only 17.5 mm, measured from the front flange. This permits it to come to focus on instruments with limited focus travel such as my 8-inch Celestron Rowe-Ackermann Schmidt Astrograph (RASA 8). However, the Nautilus filter wheel with its 7-inch diameter is seated off-center, preventing its use with the G16 for color imaging with the RASA or other astrographs where the camera resides directly within the light path of the instrument. The entire setup with the filter wheel attached and 2-inch nosepiece weighs just 1 kilogram (2.2 pounds).

The camera's 10 × 7.5-centimeter (4 × 3-inch) cylindrical shell appears mostly empty inside as viewed through its two louvered vents. This provides lots of room for air movement assisted by the enclosed cooling fan at the rear of the housing.

The back of the camera features a two-port USB 2.0 hub, which can accept

▼ The camera seen attached to the author's William Optics 71-mm f/4.9 refractor. The G16's generous back-focus requirements permit the inclusion of both the filter wheel and an off-axis guider while still retaining the correct spacing for the telescope's field flattener.



▲ *Left:* The back of the Orion G16 is vented to allow the camera's cooling fan to direct air against the back of the CMOS chamber. The USB 3.0 cable that connects the camera to your computer is seen at upper right, and a built-in USB 2.0 hub allows use of two peripheral accessories such as the Nautilus filter wheel and an additional autoguider to help reduce the number of cables dangling from the device. Four LEDs indicate the status of power, data transfers, cooling activation, and power to the fan. *Right:* The 22-mm-thick Nautilus filter wheel is shown here with its cover removed, exposing the four 2-inch-format threaded filters within. At lower right is its USB 2.0 socket to connect it to the camera's USB hub.

most accessories such as the filter wheel and autoguider or focuser. This conveniently reduces the number of cables you need to connect to your computer.

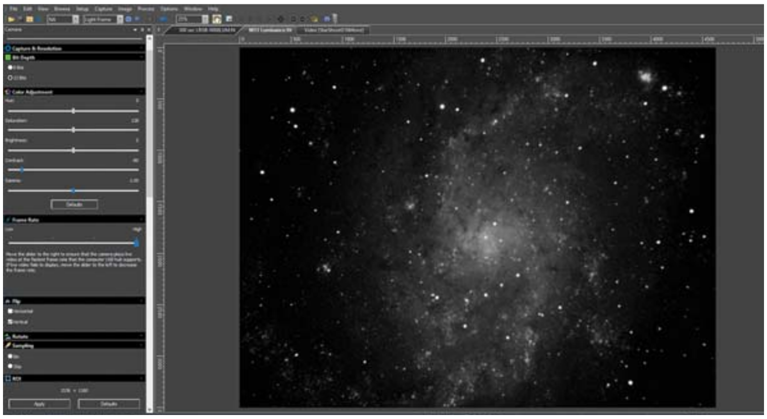
A high-impact, black-plastic storage case is included with the G16 — and it's one of the most protective I've received with any astronomical camera. The case includes a watertight rubber gasket that provides a positive seal. And while it has pick-and-pluck foam cutouts for the G16 camera, cables, and the included 3.3-amp AC power supply, it has no room to store a filter wheel. Additional accessories include a 2-inch nosepiece as well as a USB 3.0 cable.

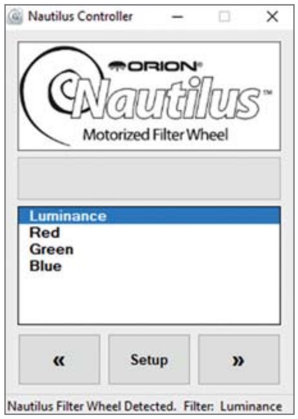
Control Software

Orion offers the free downloadable *StarshootIC* image-capture program for PC and Macs to control the camera and an additional *Nautilus Controller* program to drive the filter wheel, as well as ASCOM drivers to control both with third-party software. Both programs and all device drivers installed without any problems.

StarshootIC provides exposure and gain control as well as a range of display options for the images as they download from the camera, while the *Nautilus Controller* program controls the filter wheel. But, surprisingly, the programs do not communicate with each other. This prevents preprograming a filter change after each exposure, requiring the user to be present whenever a new filter is rotated into the light path. *StarshootIC* permits shooting groups of

▼ Orion includes a rugged, protective case with the StarShoot G16. Inside are pick-and-pluck foam cutouts for the camera, its USB cable, and its AC power supply. The case isn't large enough to accommodate the Nautilus filter wheel, though.





◀ *Far left:* Orion provides the free *StarshootIC* camera-control software (available for PC or Mac) and *Nautilus Controller* program (*near left*) to drive the filter wheel. While adequate for those getting started in astrophotography, the two programs function independently and do not communicate during operation, so they can't be used to program LRGB image sequences.

images through a single filter, but then you must manually switch to the next filter using *Nautilus Controller*. This makes shooting an entire set of LRGB frames unnecessarily tedious.

In order to automate an LRGB image sequence, you'll need to purchase a third-party camera-control program and install the ASCOM drivers for both the G16 and Nautilus filter wheel. I used *Maxim DL* for my color imaging sequences, though other options include *Astrophotography Tool*, *Sequence Generator Pro*, *NINA*, or the camera-control plugin for *TheSkyX*.

The StarShoot G16's 12-bit analog-to-digital converter combined with its 20,000e- full-well capacity is less than a modern DSLR, which is typically 14-bit, or CCD cameras, which often are true 16-bit devices. But while this might sound detrimental, in practice the images looked just as good as other deep-space cameras I've reviewed. The *StarshootIC* software saves single images produced by the camera as 32-megabyte FIT files, and can also save TIF, JPG, or PNG files, or SER video formats.

Performance Under the Stars

Orion claims the G16's 2-stage thermoelectric cooling (TEC) is capable of achieving stable temperatures of up to 40°C below the ambient temperature. This further reduces thermal noise in the CMOS detector to produce smooth, speckle-free images. Setting the TEC value to -25°C when the ambient temperature was 16°C (60°F) produced reliable performance with the cooler operating at 65% power. The manual warns that some dew may form on the chamber window when the camera is operated at the extreme end of the TEC cooling range, though I didn't experience that during my tests.

During operation, the Nautilus filter wheel produces a low hum as each filter rotates into position. I was impressed with the generous aperture of the camera housing and filter wheel. The close proximity of the 48-mm filters to the camera's detector in conjunction with the 48-mm threaded opening on the front of the filter wheel didn't introduce vignetting even with fast optical systems and their inherently steep light cones.

With the filter wheel attached, the camera's total back-focus distance is about 44 mm, which is plenty of room for use with most field flatteners and coma correctors (as well as the necessary adapters), which typically require 55-mm spacing from the detector for best performance. Introducing an off-axis guider (OAG) in the lineup and maintaining optimum spacing may be challenging depending on the depth of the unit. Thinner OAGs mounted between a field flattener or coma corrector will work best.

It should be noted that the StarShoot G16 doesn't include a mechanical shutter, so you need to cover the

▲ When paired with the author's 71-mm refractor, the G16 produces colorful images of deep-sky targets like IC 434, the Horsehead Nebula, seen above. This image consists of 45-minutes exposure through each of four filters for a total of 3 hours.

front aperture of your telescope when recording dark calibration frames.

The G16 is quite sensitive, and when binning its pixels, images of most deep-sky objects were visible on the computer screen with exposures of only a second or two. This is a big help when framing faint objects. I would often center my target using a 1-second exposure with the camera binned 4 × 4 through the luminance filter to allow maximum light transmission, and it was always visible on the monitor with the first exposure.

The camera's USB 3.0 connection allows for fast downloading of images with a full-resolution, 16-megapixel frame taking only about a second (and much less in video mode). Imagers will find the G16's sensor to be a very good match for telescopes requiring 2-inch focusers and field-correctors. The 16-megapixel detector is large enough to provide a generous field of view, but still small enough for an aberration-free and well-illuminated image when paired with most 2-inch-format focal reducers and coma correctors.

Raw, uncalibrated FIT images from the G16 have all the detail that I would expect from a low-noise sensor. Stretched, blue-filtered exposures from the G16 displayed the full extent of the Andromeda Galaxy's spiral arms as well as the bluish reflection nebulosity around the Pleiades. Shots with the red filter showed fine details in emission nebulae when stretched and recorded the H II regions in the spiral arms of galaxies M31 and M33 well.

While the uncalibrated images had little thermal noise, dark-frame calibration cleaned up any residual speckles. Stretching a dark frame from the G16 reveals a generally even pattern of hot pixels and a little glow in the corners of the frame, though calibrated light frames were clean and evenly illuminated. Be sure to apply both dark and flat-field calibration for best results.

Planetary Versatility

Although at first glance most imagers may see the StarShoot G16 as a deep-sky camera, its tiny pixels offer attractive capabilities for lunar and solar imaging. The camera's USB 3.0 connection provides frame rates fast enough to permit lucky-imaging techniques. In the *StarshootIC* control software, under the Capture & Resolution setting, change the format to SER (a common video format used in planetary imaging), then simply adjust your exposure and gain settings and click on the Record button to capture a video file of your target. Later, you can import these videos into a planetary stacking program for sorting and stacking to achieve a sharp result.

While the camera's specifications state that the G16 can capture up to 23 full-resolution frames per second (fps), my computer's older hard drive could only manage at most 15 fps. To be fair, you'd need a hard drive with an extremely fast write speed to take full advantage of the maximum frame rate at full resolution.

I often recorded one-minute videos with several hundred lunar frames that I then processed in *Autostakkert! 3.0* and *Registax 6* with excellent results. The G16's detector allows a full-disk image of the Moon or properly filtered Sun with focal lengths of about 1,300 mm.

The camera also supports region-of-interest (ROI) cropping, which only records the area of the chip you designate in *StarshootIC*. By only using part of the large detector, the camera will record even more frames per second, permitting you to image the planets on larger telescopes, with a limit of about 30 per second.

▲ Utilizing the camera's video mode permits users to capture excellent lunar images, like this fine shot of Copernicus and its surroundings. For this close-up, the author imaged through a Meade 14-inch ACF telescope at f/10. The best 300 frames from a 2,000-frame video sequence were stacked using third-party software.

Summing Up

The camera's sensitivity and tiny pixels can produce high-quality images when paired with short-focal-length optics. The close-mounted Nautilus filter wheel with its large 50-mm filters will ensure good corner-to-corner illumination with little vignetting on even fast optical systems. Though the StarShoot G16 is a very effective deep-sky camera, users can take advantage of its video mode on moonlit nights to capture high-resolution lunar vistas.

Combined with the Nautilus filter wheel, the StarShoot G16 offers an affordable entry into high-resolution imaging with a wide range of telescopes. Astrophotographers making the switch from one-shot-color cameras will find the G16 a very capable performer.

■ Contributing Editor **JOHNNY HORNE** can often be found photographing astronomical events in and around Fayetteville, North Carolina.

 by Javier Barbuzano

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Planetary scientists may soon discover how the Red Planet acquired its two potato-shaped companions.

Phobos — the innermost of Mars's two moons — will provide a beautiful show to anyone lucky enough to be watching in 20 to 40 million years. The small satellite is losing altitude with each orbit, slowly inching towards Mars. But long before it crashes into the surface, tidal forces will shred it to tiny pieces. Its surface already shows signs of its imminent collapse: long faults that run for many kilometers across the landscape, which is covered by a thick layer of powdered rock. When Phobos finally fails, it will turn to rubble — dust, pebbles, and boulders that will stretch out like a spaghetti noodle in a ring around Mars.

The cataclysmic finale of Phobos doesn't puzzle scientists nearly as much as the mystery of its formation. American astronomer Asaph Hall discovered the Martian moons, Phobos and Deimos, in August 1877 and named them after two sons of Ares, the god of war in Greek mythology. Many theories aim to explain their origin, but none of them fully grasps how these small, battered bodies could end up orbiting Mars in perfectly circular orbits, right on the equatorial plane. Are these captured asteroids? Are they as old as Mars? Did they emerge after a giant impact like the one that formed Earth's Moon? Recent research unveils a complex picture.

A robotic mission to the Martian moons could answer these questions, but technical mishaps have doomed the three attempts made so far by the Soviet and later Russian space programs. Now is the turn for the Japan Aerospace Exploration Agency (JAXA), which in 2024 will send a spacecraft to visit both moons and return samples from Phobos to Earth. Its success will reveal how the Martian moons formed, shed light into the chaotic history of the solar system, and — for the first time — bring samples from the Martian system to our planet.

A Strange Pair of Moons

Phobos and Deimos are the first non-spherical solar system

◀ **PHOBOS OVER MARS** The Mars Express orbiter caught this image of Phobos over Mars's limb on March 26, 2010. (The waviness in the background is due to the camera's line-scanning method.)

ESA / DLR / G. NEUKUM (FU BERLIN)

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bodies ever explored up close. When Mariner 9 beamed back the first clear images of the moons, scientists could finally see their lumpy and asymmetric bodies: Their gravity is too weak to mold them into a spherical shape. Compared to Earth's Moon or the Galilean satellites of Jupiter, they are mere boulders. Deimos is just 12 kilometers (7.5 miles) in diameter and lies 23,460 kilometers from Mars. Potato-shaped Phobos averages 22 kilometers in diameter and orbits some 9,380 kilometers from the planet's center — less than 6,000 km above the surface, making it the closest moon to its planet in the solar system. For comparison, our Moon is 3,480 kilometers wide and orbits 384,400 kilometers from Earth. Deimos and Phobos's tight orbits, small sizes, and dark surfaces likely delayed their discovery.

The moons travel in the same direction that Mars spins. Deimos completes an orbit in 30 hours, a bit longer than the planet's 24.6-hour rotation, so as seen from the Martian surface it slowly rises in the east and eventually sets in the west. But Phobos takes just 7.65 hours to complete an orbit — much faster than the planet's spin rate — so it rises in the west and sets in the east, zipping across the sky three times every Martian day.

Both moons are rocky and pockmarked by myriad craters. Phobos, Mariner found, sports a massive, 10-kilometer-wide crater named Stickney on one end. Stickney was the maiden name of Hall's wife, who had been trained as a mathematician and encouraged him to persevere in the search for Martian moons.

Phobos's surface is marred by a series of linear, trench-like grooves, shallow and long fractures that in some cases run for tens of kilometers. Many grooves seem to radiate from Stickney, leading scientists to think that they were formed either by the impact itself or by rolling boulders ejected during the event. While this might be the case for some of the grooves, researchers have recently spotted a population of cracks whose geometry isn't related to Stickney. Instead, they seem to be caused by the gravitational pull between Mars and Phobos, which might be warping Phobos's interior and producing stress faults on the surface.

These faults provide clues about the satellite's internal structure and composition. Phobos is covered by a layer of regolith at least five meters deep — the dusty residue accumulated after millions of years of asteroid impacts. If Phobos were solid all the way through, the tidal stress would be too

DEIMOS (enhanced color)

Approx. Size: 15 × 12 × 10 km

Rotation period: 1.26 days

Density (water is 1): 1.75 g/cm^3

Average distance from Mars: 23,460 km

PHOBOS (enhanced color)

Approx. Size: 26 × 22 × 18 km

Rotation period: 0.319 day

Density (water is 1): 1.90 g/cm^3

Average distance from Mars: 9,380 km

NASA / JPL-CALTECH / UNIVERSITY OF ARIZONA (2) weak to cause fractures. Instead, observations show that internally it resembles a rubble pile, a collection of jumbled materials of varied sizes. Such interiors deform easily under pressure, stressing the mildly cohesive regolith layer and eventually breaking it.

Deimos, on the other hand, looks like a quieter place. It has the overall lumpy and irregular shape of Phobos and is equally covered in craters, but they appear more subdued, suggesting that the regolith layer might be thicker than on its neighbor. It lacks any massive impact feature or signs of structural collapse, but it has two large craters named Swift and Voltaire, two authors that anticipated the existence of Martian moons in their literary work.

Not Asteroids

The origin of Phobos and Deimos is still unclear. More than four decades after the Mariner and Viking probes returned images and spectrographic observations of the moons, scientists are still considering two possibilities.

The spacecraft revealed that the moons are among the darkest known solar system objects. They didn't show spectral signatures that could give away any minerals on their surfaces. They also appeared to be porous, either hollow or filled with water. These characteristics, along with their battered, irregular shapes, led scientists to believe that they could be captured asteroids.

"Those sorts of spectra are usually found in primitive meteorites, the kind of things we think Bennu and Ryugu are made of," says Andrew Rivkin (Johns Hopkins University Applied Physics Laboratory), who has thoroughly studied the moons' spectra.

However, their looks could also correspond to basaltic rocks that have been sitting out in space, bombarded by micrometeorites over time. That would imply a radically different origin, likely a giant impact that blasted Martian material into space, Rivkin explains.

"For quite some time we thought that it was more likely that they were like the carbonaceous-chondrite meteorites, primitive bodies that would have been captured by Mars," Rivkin says. However, "the people who study the orbits, the dynamicists, have always said there's no way you can capture these into an orbit like Phobos's."

Captured asteroids should wind up in highly elliptical orbits and randomly oriented around the planet's spin axis. Instead, Phobos and Deimos describe neatly circular orbits, right above the equator. "Unless [an asteroid] has engines and fires them exactly in the right way, you are not gonna get that," says Matija Ćuk (SETI Institute), an expert in orbital dynamics. "It just looks much less likely than kicking stuff out in an impact."

But the giant-impact theory wasn't seriously considered for the Martian moons until very recently, even after being widely accepted for our own Moon decades ago.

"If you look at the terrestrial planets, you have a big moon only around Earth, you don't have any moons around Mercury, neither around Venus, and you have two very small moons around Mars," says Pascal Rosenblatt (University of Nantes, France). "No one was convinced of the idea that [giant impacts] could be a universal process to form moons around terrestrial planets."

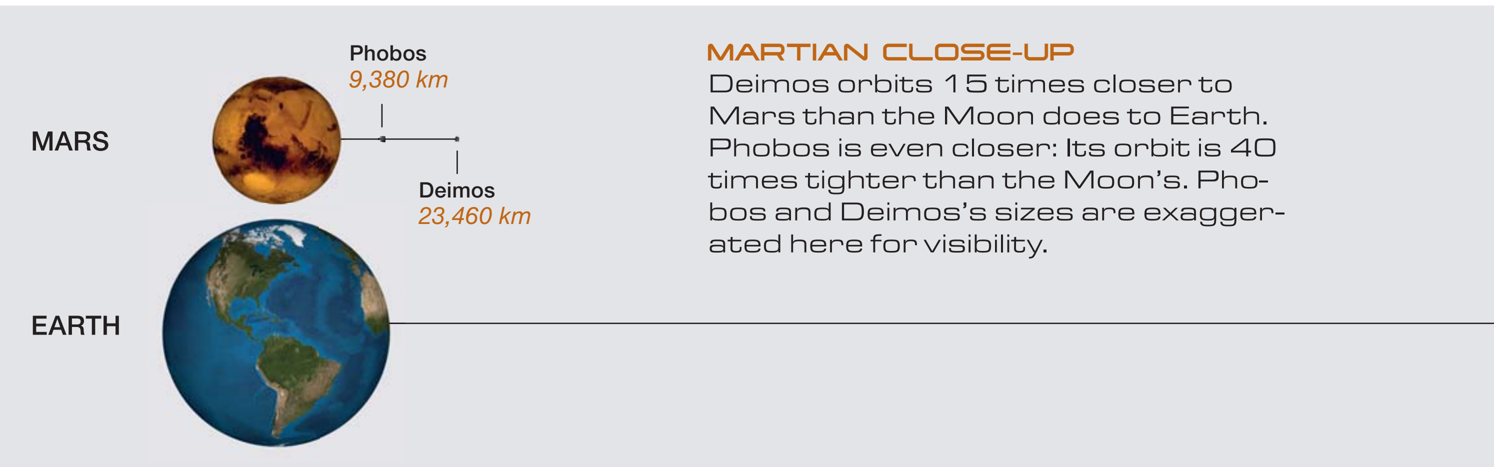
While still on the table, the orbital evidence paints a bleak picture for the capture scenario. "It's a best-of-seven series, and I think the impact theory is up three games to one," Rivkin says. "It's not quite done, but it's looking like it's going to be the impact theory to me."

Same Ingredients, Different Results

But scientists are puzzled. How could the same process that made Earth's Moon also create two satellites so different from our own?

In 2016, Rosenblatt, along with Sébastien Charnoz (Paris Institute of Earth Physics, France) and other colleagues, published the result of a series of computer simulations that, for the first time, showed that Phobos and Deimos could have formed from a giant impact. Rosenblatt got his inspiration after the European Space Agency's Mars Express orbiter approached Phobos in March 2010, confirming that the small moon is barely twice as dense as water — roughly two grams

PHOBOS: ESA / DLR / G. NEUKUM (FU BERLIN); DEIMOS: NASA / JPL-CALTECH / UNIV. OF ARIZONA; EARTH: RETO STÖCKLI / NASA EARTH OBSERVATORY; MARS: ASU / NASA; MOON: NASA / GSFC / ARIZONA STATE UNIV.; INFOGRAPHIC: TERRI DUBÉ / S&T



MARTIAN CLOSE-UP Deimos orbits 15 times closer to Mars than the Moon does to Earth. Phobos is even closer: Its orbit is 40 times tighter than the Moon's. Phobos and Deimos's sizes are exaggerated here for visibility.

per cubic centimeter. This led Rosenblatt to think that Phobos might have accreted in orbit from chunks of rock blasted to space by a powerful impact. These irregular rocks would have left empty voids between themselves as they stuck together, explaining the moon's low density.

A giant-impact origin instantly solves the main problem of the capture scenario: The material kicked into orbit by the impact quickly forms a ring around the equator, where the moons coalesce shortly after.

"This is a good trick," Rosenblatt says. "But you also have to explain the current distance of the moons to Mars and their masses."

The orbits have changed over time due to tidal dissipation. As the moons raise tides on Mars and vice-versa, they transfer momentum between them. Phobos is below the *synchronous orbit*, where objects complete a loop around the planet in the same amount of time that the planet takes to rotate. The tide that Phobos raises in the Martian ground thus lags behind the moon, slowing it down. As a result, Phobos loses velocity and altitude. Deimos is above the synchronous orbit, traveling slower than the planet's surface. In this case, the tide gets ahead of the moon, dragging it forward. This boosts the moon's orbit higher. This is why Deimos is slowly drifting away from Mars — as our Moon does from Earth.

"We have a very stringent constraint just there: We have to form a Phobos more massive than Deimos, and the Phobos has to form below the synchronous orbit and the Deimos above it," Rosenblatt explains.

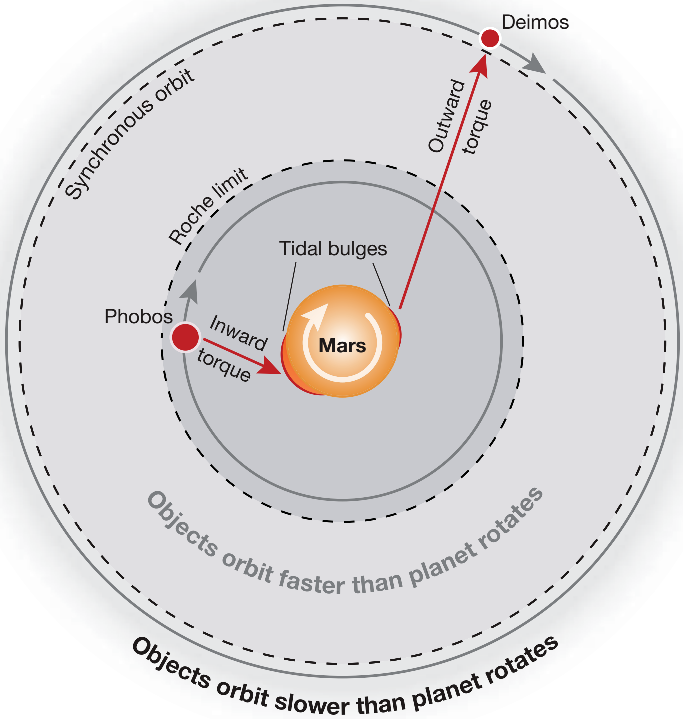
Not knowing how large the protoplanet that hit Mars might have been, Rosenblatt and his colleagues looked at Borealis Basin, the lowlands that cover most of the planet's northern hemisphere. Borealis is thought to have formed after a giant impactor 2,000 kilometers in diameter — one-third the size of Mars — hit the young Red Planet about 4.5 billion years ago. Such an impact could have blasted 100 quadrillion tons of rock into the Martian orbit, or 10,000 times the mass of Phobos and Deimos combined.

After such an impact, the simulations show, the orbiting material assembles into a disk around the equator in little more than a day. Most of the material stays below the *Roche limit*, an invisible boundary where the tidal influence of the planet prevents the formation of moons. Random collisions between particles expand the disk's outer edge beyond the Roche limit, where a large moon 1,000 times more massive than Phobos forms.

As the disk continues to expand, it pushes this large moon outwards, and its gravitational tug produces orbital resonances that "shepherd" the material above it into stable zones where the debris can concentrate. In Rosenblatt´s simulations, Phobos and Deimos form in these zones.

All the moons, including some smaller ones spawned at the Roche limit after the large moon moves out, continue to migrate outwards until the disk runs out of material. Without a driver for outward migration, the moons begin to fall back into the planet, dragged by tides. At this point, only Deimos has been pushed beyond the synchronous orbit, starting its slow outward drift to its current location. All the other moons either crash into Mars or disintegrate in orbit, torn apart by tides.

Phobos could be the last straggler. Formed closer to the synchronous orbit than its siblings, it has made it to our days, although its death date is nigh: It has already crossed the Roche limit, and its cracked surface forecasts its imminent destruction.



▲ **SATELLITE ORBITS** Deimos orbits just beyond Mars's *synchronous orbit*, the distance at which a satellite's orbital period equals the planet's rotation rate. Inside the synchronous orbit, tides will force massive satellites to spiral in toward Mars; outside it, they'll push the satellite away. Within the Roche limit, Mars's tidal influence will tear the satellite apart.

◀ **FROM THE GROUND** This composite shows the Martian and terrestrial moons at the sizes they'd appear when seen from the surfaces of their respective planets. Hold the page at arm's length for the approximate effect.

Moon
384,400 km

SIZE COMPARISON: NASA / JPL-CALTECH / MALIN SPACE SCIENCE SYSTEMS / TEXAS A&M UNIV; MOON: NASA; ORBITS: GREGG DINDERMAN / *S&T*, SOURCE: E. ASPHAUG / *NATURE GEOSCIENCE* 2016

> **PEEKABOO MOONS**
> Because they orbit so close to Mars, Phobos and Deimos aren't visible from all parts of the planet's surface. An observer poleward of about 80° latitude couldn't see either of them. Deimos would be visible equatorward of that, but you'd have to be lower than 70° north or south before you'd see Phobos. If that were true on Earth, people in the northern half of Greenland or nearly anywhere in Antarctica wouldn't see the Moon.

Ring, Moon, Rinse, Repeat

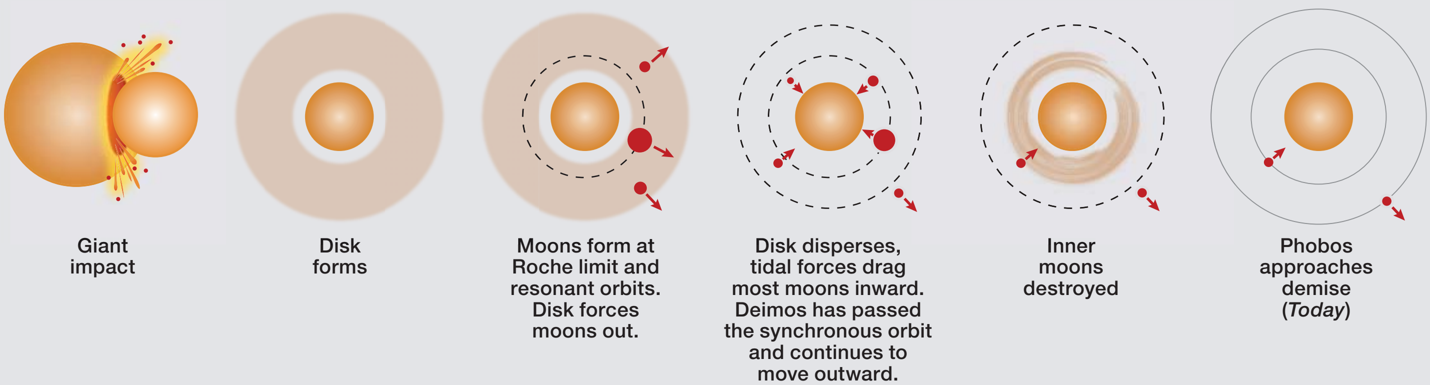
After seeing the work by Rosenblatt and Charnoz, David Minton (Purdue University) decided to look into the problem himself. He was intrigued by the fate of Phobos and how it could survive for billions of years after its siblings disappeared. "If Phobos is very ancient and really originated in this giant impact early in the solar system's history, we're really lucky to be seeing it near the end of its life," Minton says. Then, he wondered: Could Mars have had more than one of these Phobos-like moons?

Minton found a clue in a 2015 study that, after gauging the structural strength of Phobos, predicted that the moon will collapse in 20 to 40 million years. When that happens, the study found, Phobos will turn into rubble and form a ring around Mars, not unlike Saturn's rings. This led Minton to think that maybe the moons that form below the synchronous orbit of Mars are cyclically destroyed and turned into rings, only to have smaller moons accrete from their remains.

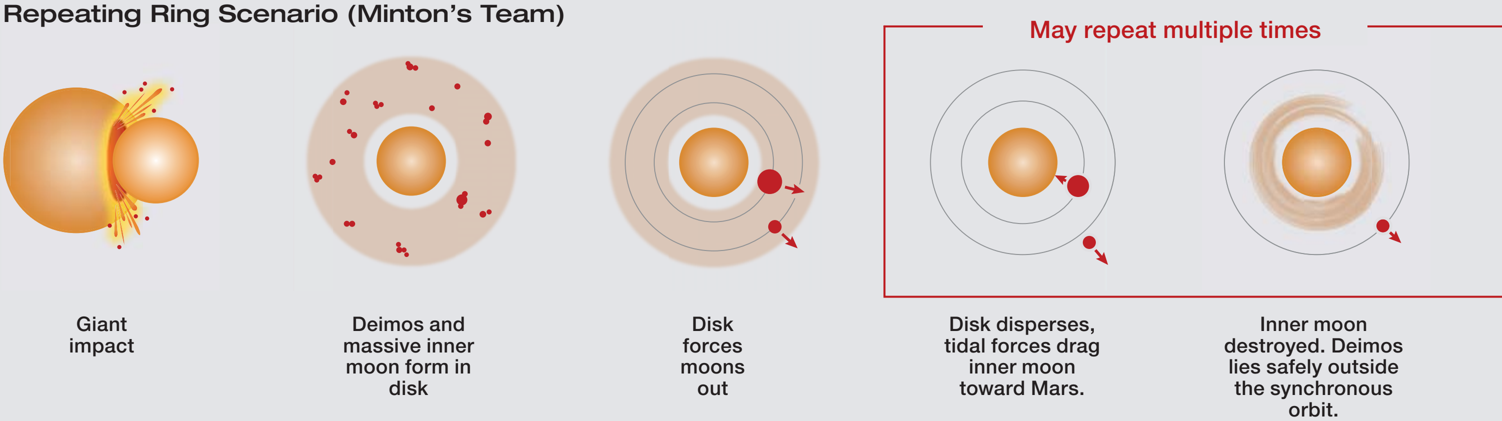
Along with Andrew Hesselbrock, his graduate student at the time, he created new simulations in which a large impactor produces a heavy disk where Deimos and an inner moon 1,000 times more massive than Phobos form. The large moon migrates outwards while the disk is present, but then falls back into the planet until it's torn apart by tidal forces. The shredded moon forms a ring of debris around Mars, which again spreads outwards to form new moons above the Roche

ROSENBLATT'S SCENARIO: GREGG DINDERMAN / S&T; MINTON'S RING-AND-REPEAT SCENARIO: GREGG DINDERMAN / S&T, SOURCE: E. TASKER / JAXA

Single-ring Scenario (Rosenblatt's Team)



Repeating Ring Scenario (Minton's Team)



limit. "Then you rinse and repeat," Minton says.

With every cycle, about one-fifth of the mass in the ring clumps together to form new moons, while the rest falls into Mars, resulting in smaller moons with every generation. Phobos might have been destroyed and rebuilt six or seven times, depending on how massive the post-impact disk was.

If Minton is right, Deimos ought to be billions of years old and Phobos just a few hundred million — just as old as the last ring-moon cycle. This is something that a robotic mission to the moons could elucidate.

In the meantime, the ring-moon theory has found some backing in an often-overlooked characteristic of the Martian system. The orbit of Deimos is off by two degrees from the equatorial plane of Mars. "Two degrees doesn't sound like much if you're driving, but actually it's quite a bit for the very precise orbits of inner moons," says Ćuk, who has partnered with Minton to test these ideas.

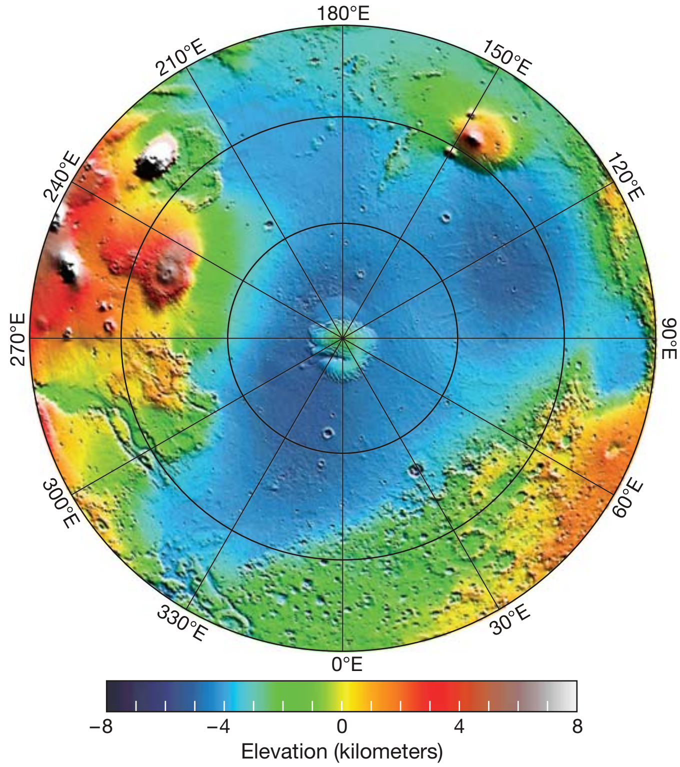
Ćuk found that an inner moon migrating outwards and caught in a 3:1 resonance with Deimos — orbiting Mars three times for each loop by the tiny moon — could have tilted its orbit while keeping it circular.

This kind of resonance works like a swing: A small push at the right time boosts the orbit of the outer body. Ćuk thinks that the resonance shoved Deimos to a slightly larger orbit at the cost of the orbit becoming tilted. "There's no free lunch: Something, somewhere, has to be compensated for this increase of the size of the orbit," Ćuk says. "The fact that its orbit is round but out of plane tells you that it wasn't a random process."

He also rules out impacts or close encounters with other bodies. "If you had just kept giving it random kicks the orbit would stop being circular as it goes out of the plane."

Once Deimos broke free from the resonance, the tilting stopped, revealing the mass of the lost moon like the fossilized footprint of a long-extinct creature. Ćuk's calculations show that the mass matches Minton's predictions for Phobos's "grandparent," a moon 20 times more massive than Phobos that existed 3 billion years ago.

NASA / JPL / GSFC

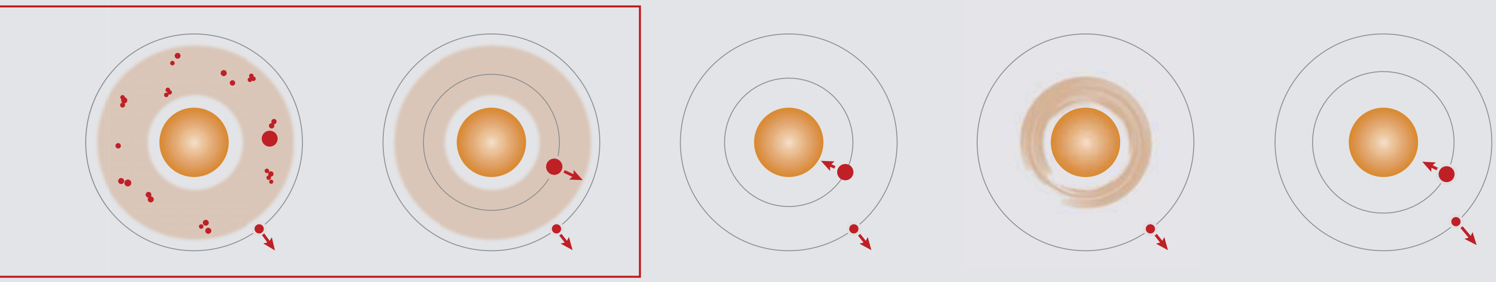


▲ **IMPACT SCAR?** Geologists suspect that the vast lowlands in Mars's northern hemisphere (blue) are the vestiges of an ancient impact. Subsequent events obfuscated the basin, and today the stark topographic dichotomy is the only surface manifestation. This map is an equal-area projection of pole-to-equator topography.

"We're looking for ways of testing this hypothesis and, like any good scientists, I'd be happy to see it challenged and whether or not it all hangs together," Minton says. "But I'm more excited to see what we'll learn when we actually study these objects really up close."

Fly Me to the Moons

To solve the riddle, scientists worldwide are looking forward



New, smaller inner moon forms.

Disk pushes inner moon out. During one of these cycles, the inner moon catches Deimos in a 3:1 resonance and changes Deimos's orbital inclination.

Disk disperses, tidal forces drag inner moon toward Mars. Deimos continues to move outward with new orbital inclination.

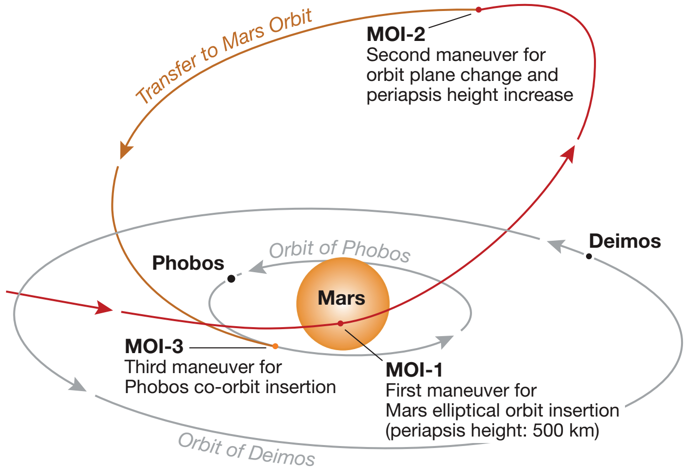
Inner moon destroyed.

Phobos forms from disk, now approaches demise. (*Today*) to Japan's Martian Moons Exploration (MMX) mission. Expected to launch in 2024, it will send a spacecraft to study both moons from orbit for about three years. It will also deliver a microwave-sized rover that will explore Phobos from the surface. Finally, the spacecraft itself will land on Phobos to retrieve samples and bring them to Earth.

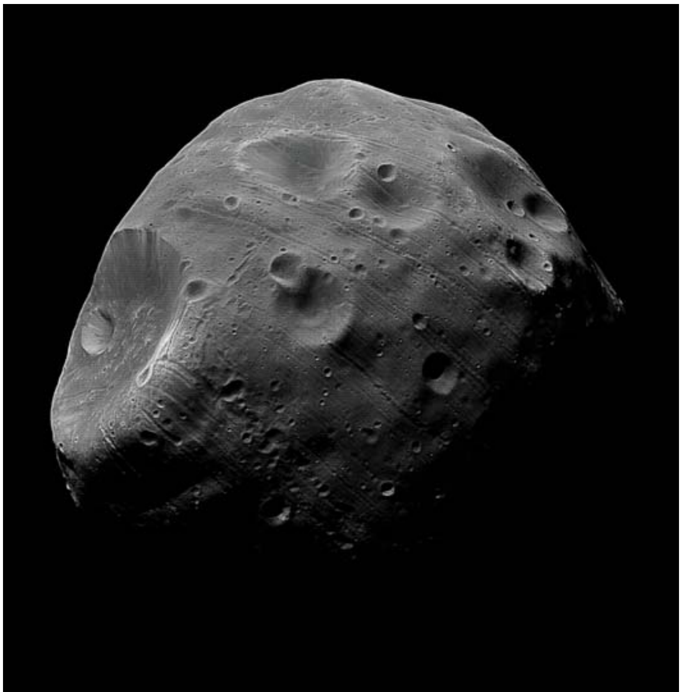
MMX aims to unravel the origin of the Martian moons and to investigate the evolution of the Martian system. "With these samples," Rosenblatt says, "we will be able to have a very reliable measurement of the age of Phobos, and we will see if David Minton is right or if I am right."

Or, the captured-asteroid scenario might still win out. Whatever the mission finds, MMX will provide invaluable insight into the evolution of Mars, our own planet, and the early solar system. If the impact scenario is correct, the moons should contain minerals from Mars from a time when it might have been habitable. "Comparing this satellite time capsule with present-day Mars would provide insight into how a habitable environment developed and then died," says Tomohiro Usui (JAXA), project scientist on the MMX team. Conversely, if the moons are captured asteroids, it means they originated elsewhere in the solar system. "This would make the moons examples of celestial delivery packages that were scattered between the outer and inner solar system, potentially delivering water and even primitive organics to the terrestrial worlds."

The highlight of the mission is the sample return. JAXA is building on its experience with the Hayabusa 1 and 2 spacecraft. While riddled with technical problems, the former managed to return some grains of material from near-Earth asteroid 25143 Itokawa. The follow-up mission, Hayabusa 2, had a smoother ride, successfully retrieving samples from asteroid Ryugu that safely dropped to Earth in December 2020 (see page 11).



▲ **PLANNED TRAJECTORY** Once Japan's MMX spacecraft enters the Mars system, it will execute a series of maneuvers to insert itself into a *quasistationary orbit* (QSO) around Phobos. A QSO is similar to a geostationary orbit, except that, instead of hovering over the same patch of surface, the satellite moves in a figure eight.



POCKMARKED The crater Stickney is the largest scar on Phobos, seen here from a distance of less than 200 km by the European Mars Express orbiter. Linear fractures also mar the moon.

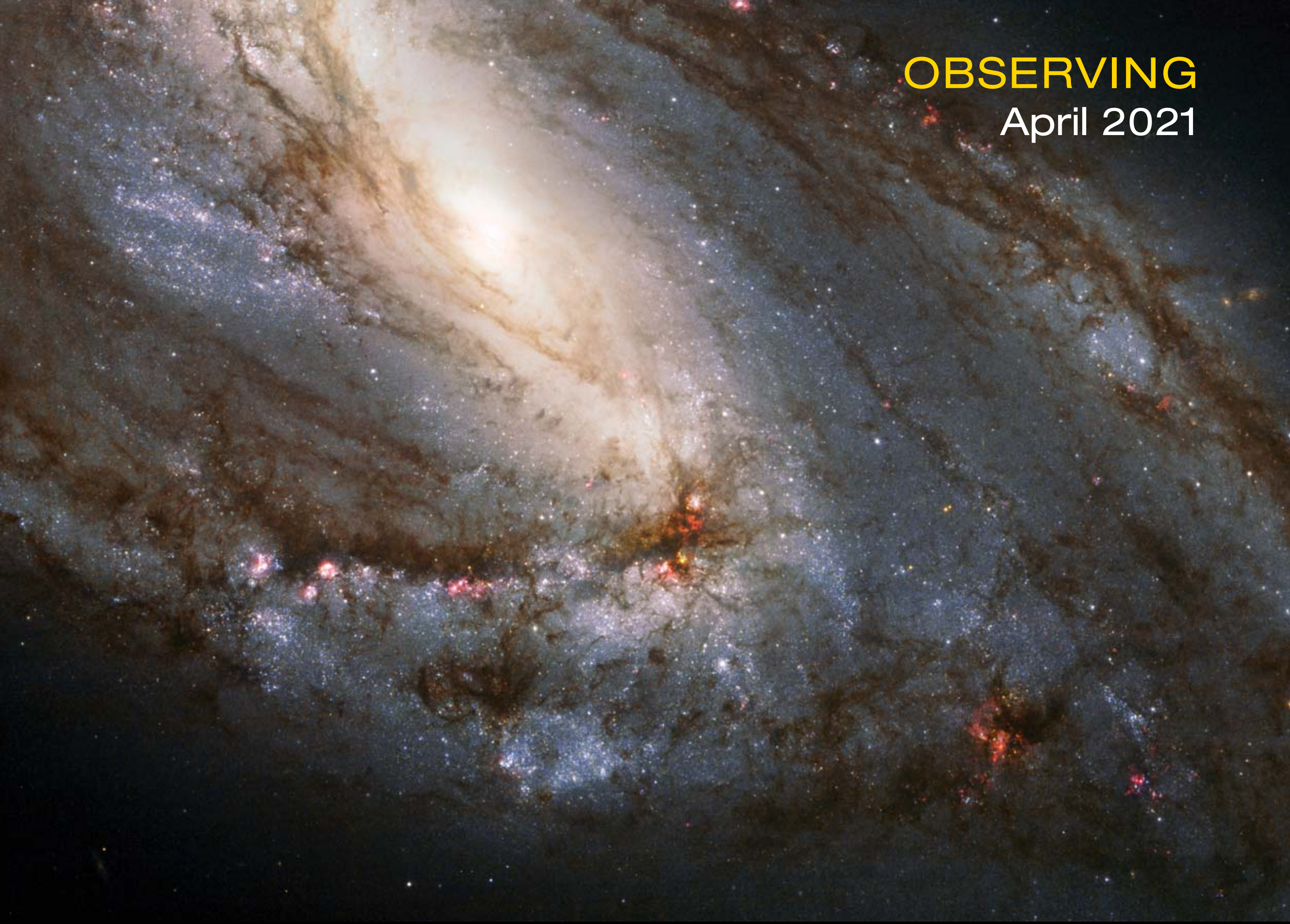
Those who investigate the moons hope that MMX will deliver as much information about the Martian system as the Apollo program did for Earth and its Moon.

"Phobos and Deimos were kind of ignored for a long time, but they're the only other moons in the inner solar system," Minton says. "We've learned a lot about how our solar system formed by understanding how our Moon formed and what history it went through. So I think the existence of these two little moons of Mars is telling us something about the early solar system and how planets form."

The results will also enhance our understanding of a process that might occur time and again across the universe — and might be key to the evolution of life. "It's very important to understand if moons around terrestrial planets are commonplace, because our moon has played and still continues to play a very important role for the apparition and the maintaining of life," Rosenblatt says. "It has an impact on our future understanding and the exploration of the extraterrestrial planets."

But first and foremost, MMX will help solve a riddle that has puzzled astronomers for decades. "We're all really looking forward to the Japanese mission and keeping our fingers crossed," Rivkin says.

■ **JAVIER BARBUZANO** is a freelance science writer based in Spain. While researching and writing this feature, he welcomed his second daughter, Clara, into the world. He proposed several astronomy-related names for her, but his wife wouldn't budge.



OBSERVING
April 2021

5 **DAWN:** The waning crescent Moon, Saturn, and Jupiter are gracefully lined up above the southeastern horizon. Catch this sight before the Sun washes it away.

6 **DAWN:** The Moon is now positioned about 4½° below Saturn, with Jupiter to their left completing a pretty triangle.

7 **DAWN:** Exchanging one gas giant for the other, the slender lunar crescent is now around 5° below Jupiter. Saturn, to their upper right, adds to this pleasing predawn tableau.

15 **DUSK:** The waxing crescent Moon is high in the western sky in Taurus, the Bull, and some 5° right of Aldebaran.

16 **DUSK:** The Moon is positioned between the horns of the Bull, with Mars hovering some 5° above.

17 **DUSK:** Continuing its climb along the ecliptic, the Moon has skipped over Mars and is now some 5° above the Red Planet.

19 **DUSK:** After sunset, look high in the west-southwestern sky to see the Moon, Pollux, and Castor emerge from the gloaming in a neat line.

20 **DUSK:** The first-quarter Moon visits the Beehive (M44). Find the open cluster less than 4° from the Moon.

22 **MORNING:** The Lyrids are predicted to peak in the predawn hours, but the waxing gibbous Moon may interfere somewhat with viewing before it sets at around 4 a.m.

26 **DAWN:** Some 5° separate the full Moon from Spica, Virgo's lucida. Look toward the west to catch this brilliant pair before they set.

29 **DAWN:** The waning gibbous Moon visits another bright star — this time it's Antares, in Scorpius. The pair shine less than 4° apart above the southern horizon.

— DIANA HANNIKAINEN

▲ Leo, the Lion, is up all night during April. This composite Hubble Space Telescope image depicts M66, the largest of the three galaxies that make up the Leo Triplet (north is to the upper left). You'll need binoculars or a telescope to spot this interesting spiral (see page 18 for more).
NASA / ESA / HUBBLE HERITAGE / STSCI / AURA / ESA-HUBBLE COLLABORATION / DAVIDE DE MARTIN / ROBERT GENDLER

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	

LAST QUARTER
April 4
10:02 UT

NEW MOON
April 12
02:31 UT

FIRST QUARTER
April 20
06:59 UT

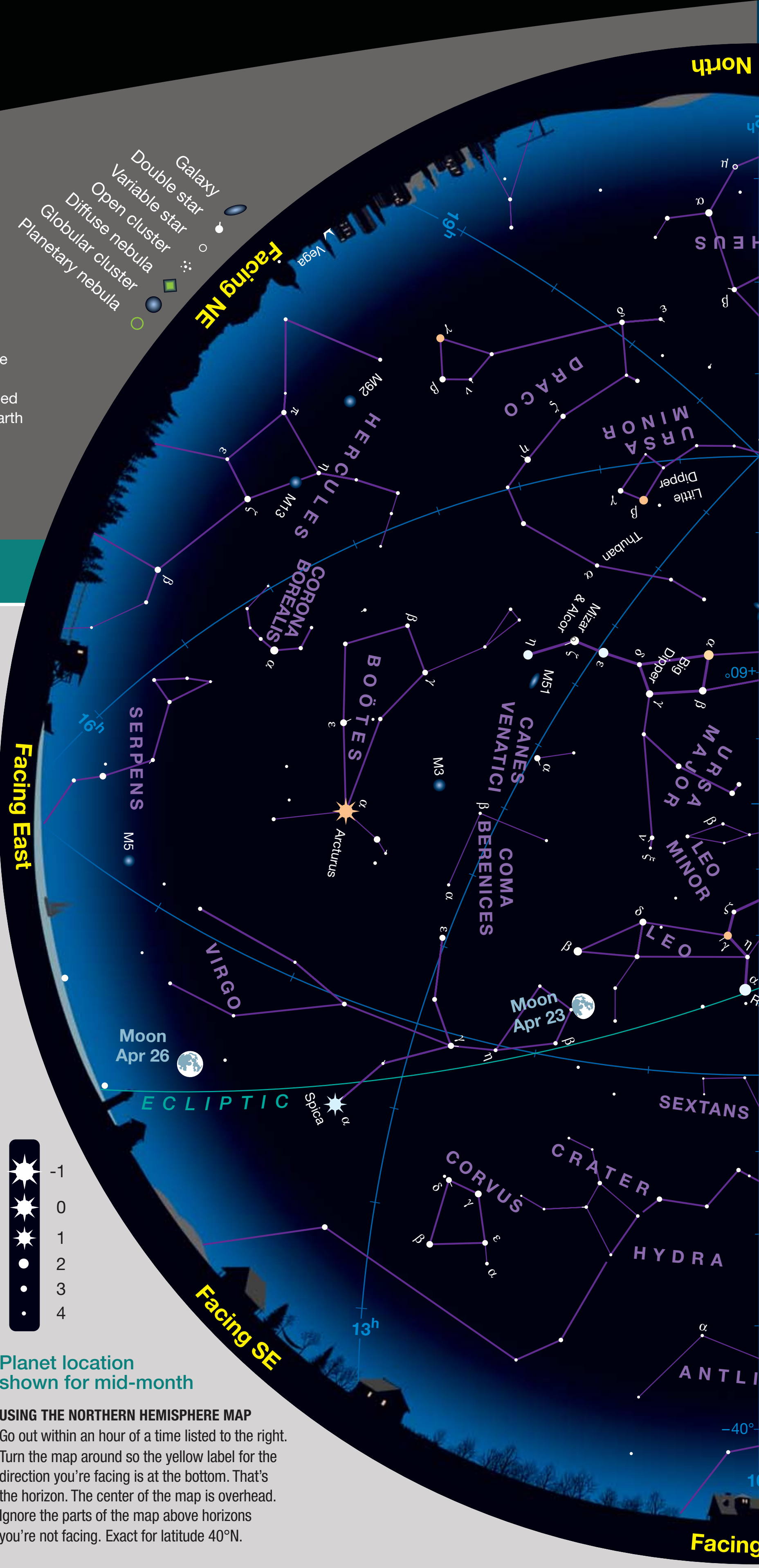
FULL MOON
April 27
03:32 UT

DISTANCES

Apogee	April 14, 18^{h} UT
406,118 km	Diameter 29′ 25″
Perigee	April 27, 15^{h} UT
357,381 km	Diameter 33′ 26″

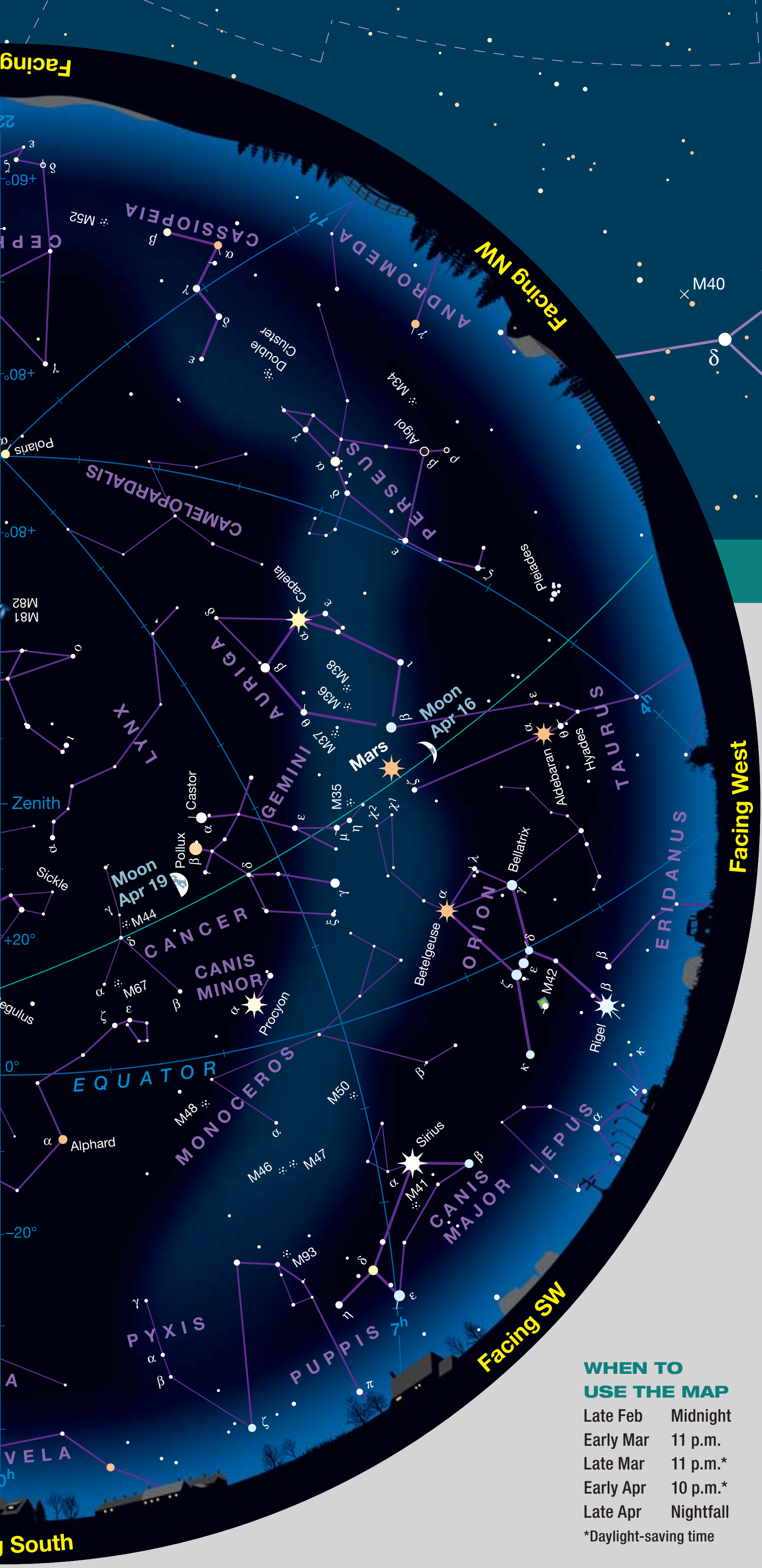
FAVORABLE LIBRATIONS

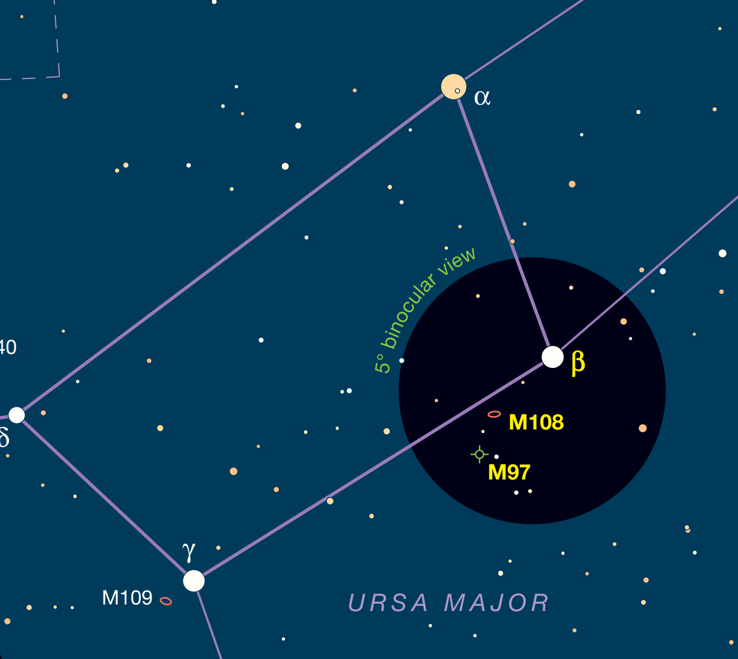
• Pingré Crater	April 26
• Bailly Crater	April 27
• Boguslawsky Crater	April 28



Planet location shown for mid-month

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





Binocular Highlight by Mathew Wedel

Flash in the Pan

Our subject this month is the **Ursa Major Moving Group**, a set of stars traveling together through space that were probably born from the same nebula. The Group includes all the stars of the Big Dipper except the ones at the asterism's eastern and western extremes — Alpha (α) and Eta (η) Ursae Majoris (Dubhe and Alkaid, respectively). Its center is about 80 light-years away, making it the nearest grouping of stars to our Sun. The closest open cluster, the Hyades, is almost twice as far away.

The bowl of the Dipper contains my favorite cosmic odd couple: **M97**, a nearby planetary nebula, and **M108**, one of the more distant Messier galaxies. M97 is about 30 times farther from us than nearby Beta (β) Ursae Majoris (Merak) — but at 47 million light-years, M108 is roughly 20,000 times more distant than M97.

The Dipper doesn't include every member of the Group, which is actually a stream of stars, spread out across roughly half the sky. Other group members above the horizon at this time of year include Gamma (γ) Leporis and Beta Aurigae in the west, and Alpha Coronae Borealis and Beta Serpentis, both rising in the east. Try to pick them all out in quick succession, and you may feel that a cascade of stars is racing past, like a formation of jets at an airshow. Which, in astronomical terms, is pretty much what's happening. In the small compass of human history, these stars appear fixed in our skies, but on a galactic scale they're just passing through.

I like to think of the cosmos as an ocean, and Earthlings as tourists on a submersible. The stars, nebulae, and galaxies flash by like shoals of fish, and we press our eyes to the glass in wonder.

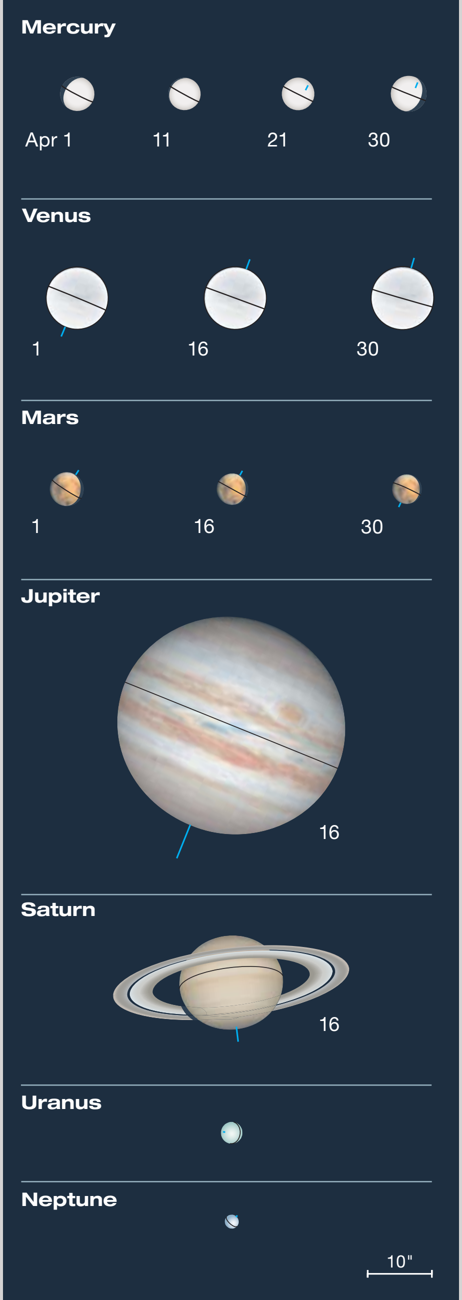
■ **MATT WEDEL** likes to imagine that the night sky is below him, not above him, and that he's at risk of falling in. That hasn't happened. Yet.

WHEN TO USE THE MAP

Late Feb	Midnight
Early Mar	11 p.m.
Late Mar	11 p.m.*
Early Apr	10 p.m.*
Late Apr	Nightfall

*Daylight-saving time

PLANET VISIBILITY (40°N, naked-eye, approximate) **Mercury** is visible at dusk after the 25th • **Venus** emerges at dusk after the 18th • **Mars** is visible at dusk and sets after midnight • **Jupiter** and **Saturn** are visible at dawn and rise less than 4 hours before the Sun mid-month.



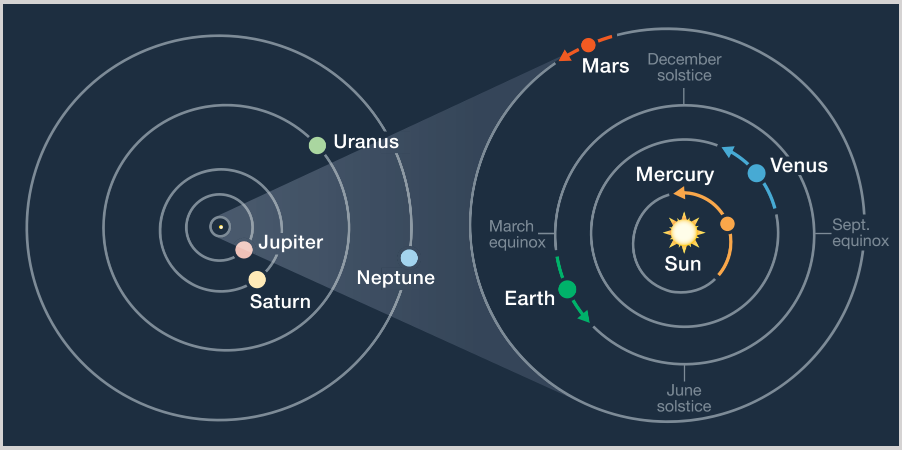
▲ **PLANET DISKS** have south up, to match the view in many telescopes. Blue ticks indicate the pole currently tilted toward Earth.

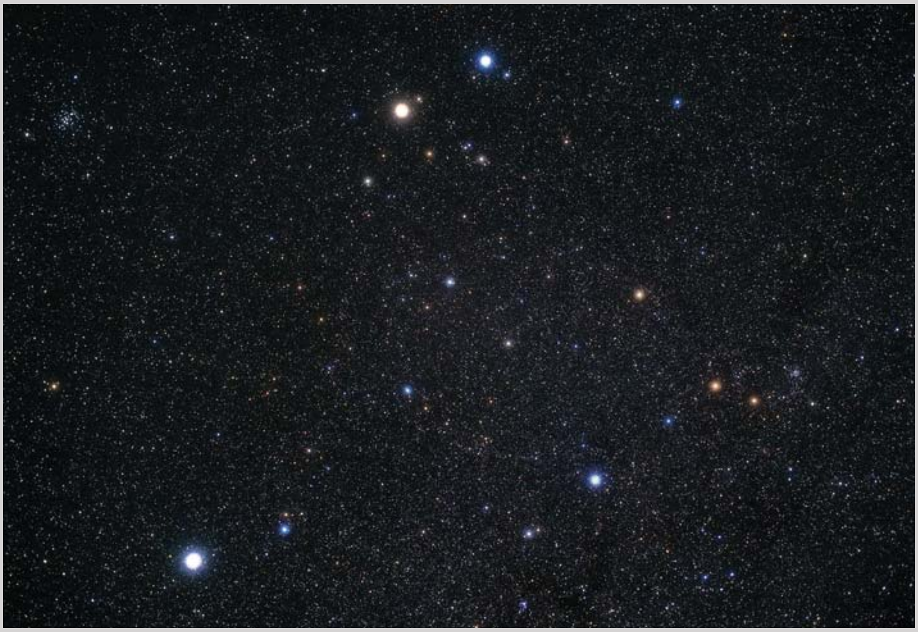
April Sun & Planets

	Date	Right Ascension	Declination	Elongation	Magnitude	Diameter	Illumination	Distance
Sun	1	0^h 41.2^m	+4° 26′	—	–26.8	32′ 01″	—	0.999
	30	2^h 28.7^m	+14° 41′	—	–26.8	31′ 46″	—	1.007
Mercury	1	23^h 42.4^m	–4° 26′	17° Mo	–0.5	5.3″	86%	1.259
	11	0^h 48.6^m	+3° 23′	9° Mo	–1.2	5.1″	96%	1.328
	21	2^h 03.6^m	+12° 17′	2° Ev	–2.2	5.1″	100%	1.320
	30	3^h 16.4^m	+19° 31′	12° Ev	–1.2	5.6″	86%	1.207
Venus	1	0^h 48.5^m	+3° 50′	2° Ev	–4.0	9.7″	100%	1.723
	11	1^h 34.4^m	+8° 44′	4° Ev	–3.9	9.7″	100%	1.720
	21	2^h 21.2^m	+13° 19′	7° Ev	–3.9	9.7″	99%	1.712
	30	3^h 04.7^m	+16° 58′	9° Ev	–3.9	9.8″	99%	1.699
Mars	1	4^h 59.2^m	+24° 11′	65° Ev	+1.3	5.3″	91%	1.761
	16	5^h 38.7^m	+24° 49′	59° Ev	+1.4	4.9″	92%	1.895
	30	6^h 16.1^m	+24° 50′	54° Ev	+1.5	4.7″	93%	2.013
Jupiter	1	21^h 42.0^m	–14° 29′	48° Mo	–2.1	34.7″	99%	5.676
	30	22^h 01.4^m	–12° 54′	72° Mo	–2.2	37.3″	99%	5.283
Saturn	1	20^h 54.8^m	–17° 57′	60° Mo	+0.8	15.9″	100%	10.432
	30	21^h 01.7^m	–17° 32′	87° Mo	+0.7	16.7″	100%	9.972
Uranus	16	2^h 29.1^m	+14° 17′	14° Ev	+5.9	3.4″	100%	20.732
Neptune	16	23^h 31.0^m	–4° 18′	34° Mo	+7.9	2.2″	100%	30.749

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

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





◀ **O GEMINI!** The celestial twins, Castor and Pollux, are prominent in the upper portion of this image of the constellation Gemini.

AKIRA FUJII

Pollux and Castor's April Prominence

The most famous two-star pattern in the heavens deserves a second look.

Last month I discussed the visual basics and physical nature of the Gemini twins, Pollux and Castor. There is, however, a lot more to say as they adorn the April evening sky.

Twins at the top of spring's arch. When Gemini rises on December evenings, the constellation lies on its side to the left of the even more spectacular constellation Orion. But in April, Pollux and Castor assume a marvelously prominent position as they descend in the hours after nightfall. As our star map on page 42 shows, the two stand at the top of a giant arch of bright stars that includes Sirius in the southwest, along with Procyon and Capella in the northwest. At the end of April (or during nightfall later in spring), Sirius, Orion, and Taurus have disappeared, leaving only the arc of Procyon, Pollux, Castor, and Capella. *Sky & Telescope* Senior Editor Alan MacRobert popularized the name Arch of Spring for this striking figure.

Three bright pairings. Pollux ranks as the 17th brightest star in the night sky and Castor is 23rd. But in the far-south constellations of Centaurus and Crux, there are two similarly close pairs of even brighter stars. Alpha and Beta Centauri are the 3rd and 11th brightest stars, while Alpha and Beta Crucis rank 13th and 19th. (Unfortunately, these stars are too far south to be seen at mid-northern latitudes.) The amazing thing is that the separations of all three pairs is so similar. Alpha and Beta Crucis are 4.2° apart, Alpha and Beta Centauri 4.4°, and Pollux and Castor 4.5°. Remarkably, Alpha Centauri's great *proper motion* (its detectable motion in the night sky) will bring it closer to Beta Centauri than Alpha and Beta Crucis are to each other. You might expect that such a shift would take millennia, yet it will occur in just 150 years.

The brightest zodiacal pair. Pollux and Castor are near the ecliptic, which means they're often visited by the Moon and planets. However, the list of 1st-magnitude stars that the Moon can occult presently only includes Aldebaran, Regulus, Spica, and Antares. But there was a time when Pollux was on that list, too. Remarkably, the last time the Moon occulted Pollux was not tens of thousands of years ago, but as recently as 117 BC. Thanks to the combined effects of Earth's precession and Pollux's own motion in space, the star no longer lies in the Moon's path.

Pollux, Castor, and St. Elmo's fire. Castor and Pollux are named for the famed twins of Greek mythology, though Pollux is actually the Roman name for the Greek "Polydeuces." (For Guy Ottewell's outstanding discussion of the myths of the twins, visit **universalworkshop.com/the-shining-twins**.)

According to certain versions of the story, immortal Pollux and mortal Castor hatched from eggs, and the fair Helen of Troy was their sister. Pollux and Castor were on the ship Argo with Jason and the Argonauts when the ship was beset by a terrible storm. Fortunately, the turbulence was tamed by Orpheus playing a lyre (Lyra, bejeweled by the brilliant star Vega, rises in the northeast on April evenings). As the seas calmed, everyone aboard was awed by the mysterious light that appeared around the heads of Castor and Pollux, who therefore received some of the credit for saving the ship.

This is how Castor and Pollux became the figures Roman sailors prayed to for safety in storms. Their cry of "O Gemini" eventually became "by Jiminy" in modern times. And what were the mysterious glows above the heads of the twins? Perhaps it was St. Elmo's fire, a kind of slow electrical discharge that can appear above pointed objects in the waning stages of a storm.

■ **FRED SCHAAF** is the author of 13 books, including *The Brightest Stars: Discovering the Universe through the Sky's Most Brilliant Stars*.

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

Venus Returns

The brilliant Evening Star pops up at dusk after a long absence.

TUESDAY, APRIL 6

Each month the **Moon** serves as a helpful tour guide highlighting the brightest planets strung out along the ecliptic. And April is no exception. During the month, Earth's companion pairs up with a trio of planets, beginning this morning with **Saturn**. The ringed planet is currently a +0.8-magnitude spark in the zodiacal constellation Capricornus. Saturn rises at roughly 4 a.m. local daylight-saving time, followed 20 minutes later by the waning lunar crescent. The Moon is about 4½° below Saturn as morning twilight begins to brighten the sky. Telescope users should be able to get reasonable views of Saturn as the planet attains an altitude of 20° half an hour before sunrise in early April. The planet's famous rings are presently tilted open at an angle slightly greater than 17°.

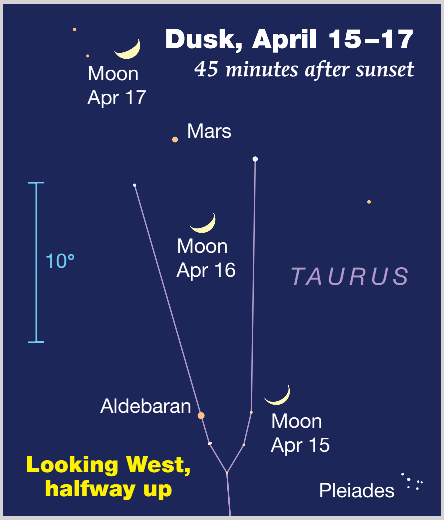
WEDNESDAY, APRIL 7

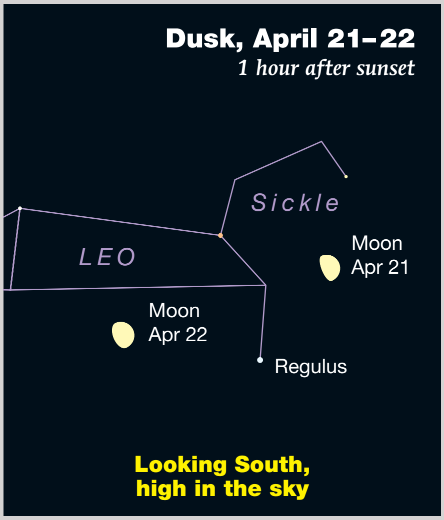
The **Moon** visits **Jupiter**, and this time the separation between planet and Moon is slightly wider — nearly 5°. However, given Jupiter's greater brightness (magnitude –2.1 on this date), this pairing will be more striking than that with Saturn for naked-eye observers. Like Saturn, Jupiter is gradually becoming a more impressive telescopic sight, as it now rises nearly two hours before the Sun and climbs to an altitude of 15° half an hour before sunrise. Jupiter is a rewarding world to inspect with your scope, not least because of all the comings and goings of its four brightest satellites. Turn to page 51 to identify which moon is which, and to see a listing of events — including several *mutual events* in which the moons eclipse and occult one another. The planet's array of pastel belts and its Great Red Spot are also endlessly fascinating, even in modest instruments.

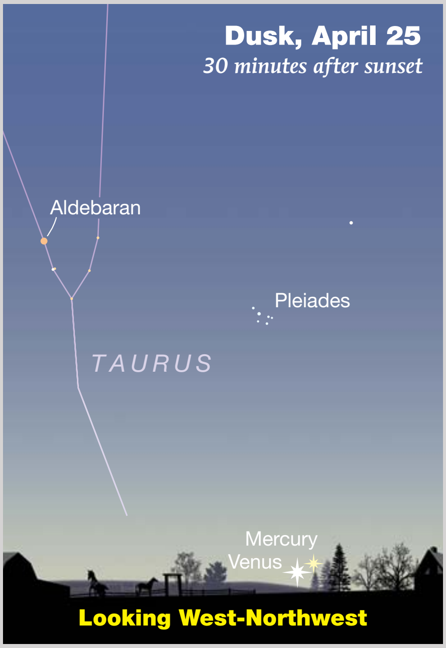
FRIDAY, APRIL 16

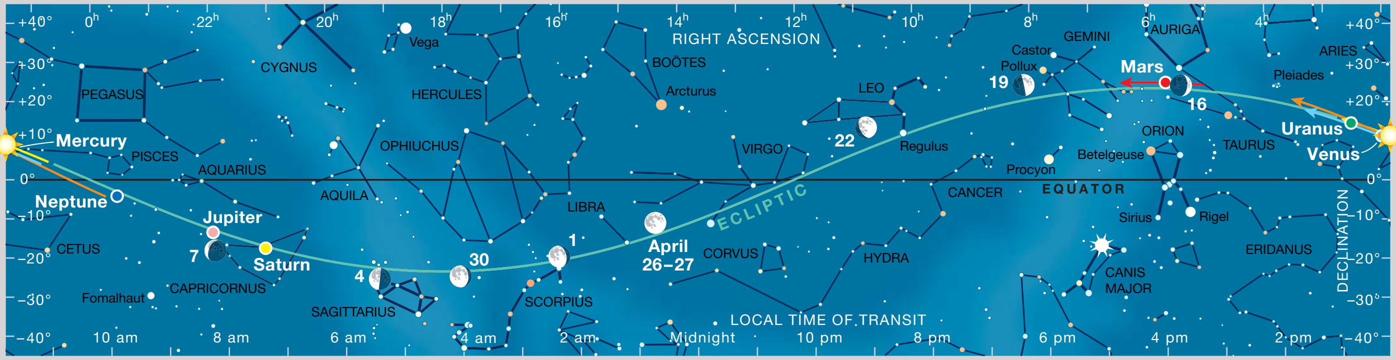
Having slipped out of view after its dawn encounters with Jupiter and Saturn, the **Moon** reappears in the evening sky as a waxing crescent. On the 16th its journey along the ecliptic brings it near the third and final planet of our April tour: **Mars**. On this night, the Moon sits roughly 5° below the 1.4-magnitude Red Planet. Both objects are positioned within the confines of the Winter Hexagon — a large asterism comprising the bright stars Aldebaran, Rigel, Sirius, Procyon, Pollux, and Capella. With the temporary addition of the Moon and Mars, this is a splendid naked-eye vista high in the west during fading evening twilight. If the weather doesn't cooperate, try again the follow-

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









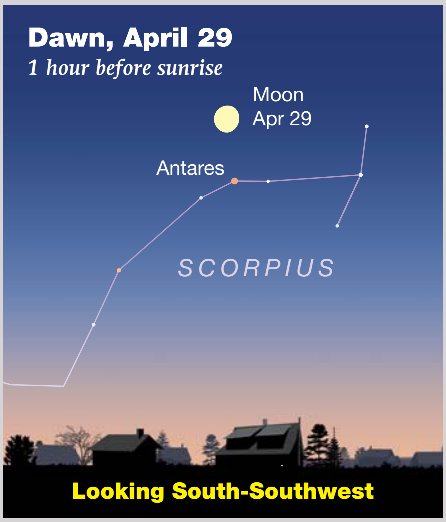
▲ The Sun and planets are positioned for mid-April; the colored arrows show the motion of each during the month. The Moon is plotted for evening dates in the Americas when it's waxing (right side illuminated) or full, and for morning dates when it's waning (left side illuminated). "Local time of transit"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

ing evening when the Moon is nearly as close to Mars, but positioned above left. (Observers mainly in India and southeast Asia actually get to see the Moon occult the planet on the 17th.) For telescope users, however, Mars is now a shadow of its glorious opposition self. It now spans a meager 4.9″ — a far cry from the 22.6″ maximum diameter it attained last October.

SUNDAY, APRIL 18

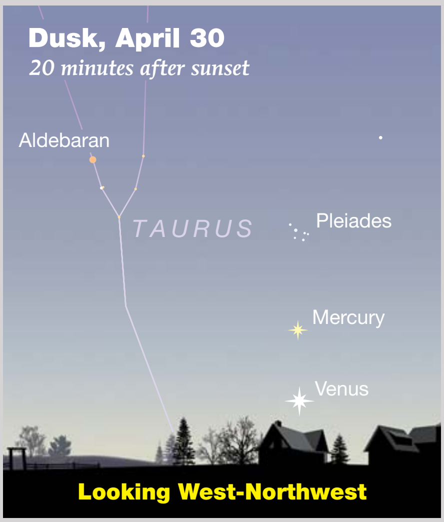
Shortly after sunset today, look to the west to get your first glimpse of **Venus** as it ascends to its position as the reigning Evening Star. Although there's more than a small degree of arbitrariness involved in assigning a specific date to an event such as this, there's a good chance you'll now be able to spot the brilliant planet, provided you have an unobstructed horizon. If at first you don't succeed, trying using binoculars. Even though Venus gleams at magnitude –3.9, it's only roughly 4° above the horizon at sunset.

Venus will be with us throughout 2021. Indeed, its dusk apparition doesn't wrap up until January 2022. Venus slowly climbs higher throughout the spring and summer and finally reaches its greatest elongation from the Sun on October 29th. However, it's not until the beginning of December that the planet attains its highest position above the horizon for observers at mid-northern latitudes.



SUNDAY, APRIL 25

And speaking of planets returning to the evening sky, speedy **Mercury** pulls up alongside lumbering **Venus** today. Mercury was in conjunction with the Sun just a week earlier (on the 18th) and is now ascending toward its greatest elongation on May 17th. Mercury's brief apparition includes two Venus encounters — today's and another in May when it plunges sunward and slips by Venus again. But early this evening you'll find Mercury shining at magnitude –1.6, about 1.2° upper right of Venus. (You can try to spot the pair on the 24th when they're similarly close, but with Mercury slightly closer to the horizon.) Both planets are very low in the west, so this is another occasion in which binoculars may prove helpful.



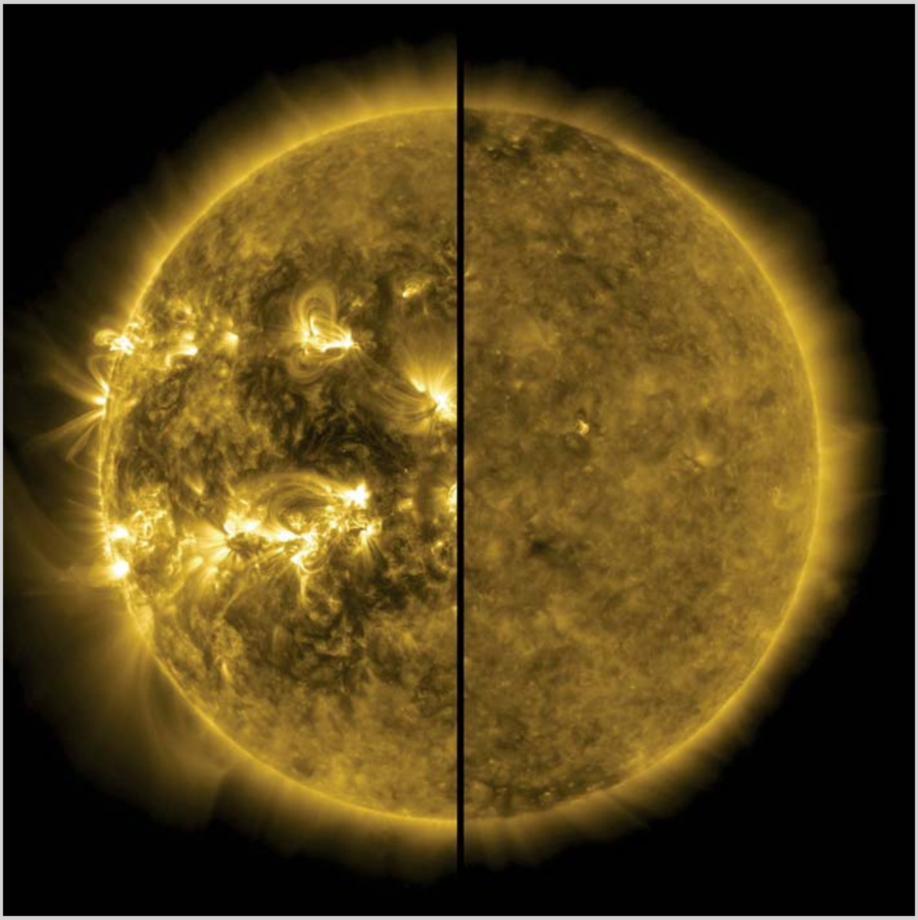
THURSDAY, APRIL 29

As the **Moon** makes its way along the ecliptic, it doesn't only encounter planets — sometimes a bright star gets to enjoy some lunar companionship, too. First it was Regulus (at dusk on the 21st and 22nd), then in the predawn hours of the 29th, the Moon meets up with Antares, the leading light in the zodiacal constellation Scorpius. At magnitude 1.1, Antares is the third-brightest zodiacal star — only slightly fainter than Aldebaran and Spica (which the Moon visits on the morning of the 26th). Just 3½° separate the Moon and Antares when they're at their closest at around 4:47 a.m. EDT. Both objects will comfortably fit in the field of view of standard binoculars, not that you need them to enjoy this conjunction.

■ Consulting Editor **GARY SERONIK** began exploring the night sky as a child many, many moons ago.

Solar Cycle 25: Full Speed Ahead

Sunspots are beginning to appear on the solar disk after a prolonged lull.



NASA / SDO

This split image, taken in ultraviolet light by NASA's Solar Dynamics Observatory, highlights the difference in activity between solar maximum (left, photographed in April 2014), and at minimum in December 2019.

It started quietly in December 2019. Solar Cycle 24 whispered to a finish as the first tiny sunspot groups sporting reversed polarities emerged, heralding the arrival of Cycle 25.

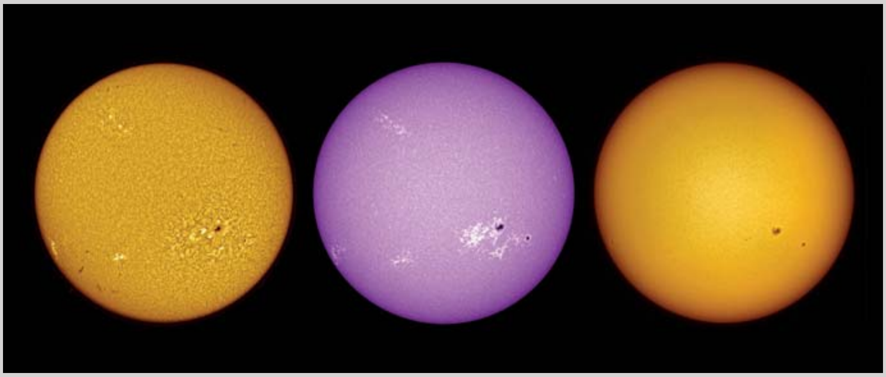
Sunspots are manifestations of powerful magnetic fields that bob to the surface when differential rotation winds up and concentrates the Sun's magnetic field. And like a bar magnet, the lead spot in a group has one polarity (positive or negative) and the spots trailing it the opposite. During Cycle 24, spots in the Sun's southern hemisphere displayed a negative/positive pattern, while those in the northern hemisphere were positive/negative. The new cycle started when polarities flipped to positive/negative in the south and negative/positive in the north.

The number of sunspots and the storms they spawn varies in an approximately 11-year cycle (or 22 years, if you count a complete set of magnetic reversals). Solar Cycle 24 reached its maximum in April 2014 with a monthly total of 116 spots. That figure is underwhelming when compared with other recent cycles, but similar to the weak cycles observed from 1878 to 1923.

The current Cycle 25 could be unusually energetic or just "meh," depending on which forecast you consult. The official NOAA/NASA Prediction Panel expects another weak-to-average cycle peaking in July 2025 (give or take 8 months) with a sunspot number of 115. However, a team of scientists led by Scott McIntosh of the National Center for Atmospheric Research believes Cycle 25 could be among the strongest ever observed, with sunspot numbers exceeding 180 at maximum.

McIntosh bases his forecast on the timing of the *termination* of the 22-year magnetic solar cycle. A termination occurs when opposite bands of magnetic polarity meet at the solar equator, nullifying each other and setting the stage for the next cycle. Supporting evidence comes from observations of early Cycle 25 sunspots, which appeared at higher-than-normal latitudes (greater than around 40°) — something typical of active cycles. (You can read about their research at **arxiv.org/pdf/2006.15263.pdf**.)

In November 2020, the Sun stirred from its slumbers and cooked up two spectacular sunspot groups, designated AR 2781 and AR 2786. Both grew in magnetic complexity and released several modest solar flares. AR 2786's biggest spot was large enough to be visible



▲ **SOLAR TRIPTYCH** Martin Wise used an 80-mm refractor on Dec. 1, 2020 to make this set of images of sunspot region 2786 at three different wavelengths. *From left:* Hydrogen alpha (656.3 nm), which reveals the Sun's upper chromosphere; calcium K (393.4 nm), the lower chromosphere; and visible light (540 nm), the photosphere that underlies the chromosphere.

through eclipse glasses. Solar observers were elated, but only time will tell if we're off to a strong start.

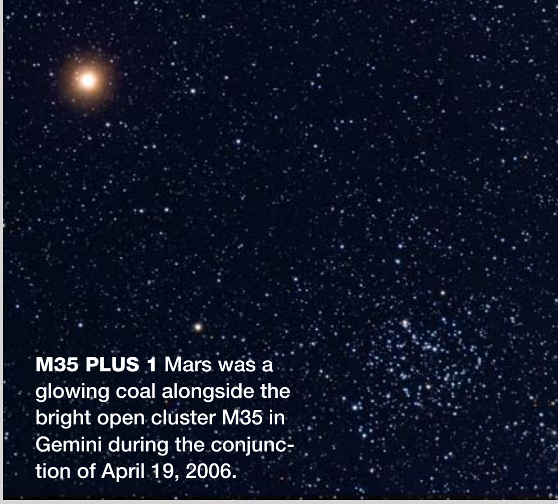
While it's difficult to predict how speckled the Sun will be this spring, now is a good time to think about investing in safe solar filters for both naked-eye and telescopic observations. I regularly view the Sun with an 80-mm refractor fitted with a full-aperture filter. Even at 26×, I readily see filamentary details in sunspot penumbrae; *faculae* (magnetic regions similar to sunspots but concentrated in small patches that appear bright against the solar limb); and the sand-grain texture of convective cells called *granulation* carpeting the solar photosphere. To view the largest sunspots, a pair of solar eclipse glasses or #14 welder's glass does the trick.

Sunspots are key to solar activity since the magnetic energy concentrated within them can spawn flares that provoke spectacular aurorae. As Cycle 25 ramps up to maximum, it'll be interesting to see which path the Sun takes: ho-hum, spectacular, or something else altogether. In the meantime, enjoy the show.

Jupiter Occults 44 Cap

As noted on page 46, Jupiter has become a prominent dawn sight this month — and just in time. On April 2nd the planet occults 5.9-magnitude star 44 Capricorni. While the disappearance will only be visible from western and central South America, observers in eastern North America can witness the star's reappearance on Jupiter's western limb in twilight, at around 6 a.m. EDT. With the planet quite low at that time, you'll need to find a spot with an unobstructed view of the southeastern horizon.

Observers farther west will miss the occultation but instead get a nice consolation prize: They can watch as Io passes just 0.5″ south of the star, which will look like an extra Jovian moon (depicted in the illustration on page 50 of the January issue). At moderate magnifications, the two objects will appear to briefly merge then separate over the span of 10 minutes or so. Io is nearest the star around 5:21 a.m. CDT, which favors those in the middle of North America. Luckiest of all will be observers in some locations in Central America and northwestern South America who get to see Io occult 44 Cap. From San José, Costa Rica, Io covers the star from 4:18 a.m. to just before 4:20 a.m. CST. The moon and star have an altitude of 22° at this time.



M35 PLUS 1 Mars was a glowing coal alongside the bright open cluster M35 in Gemini during the conjunction of April 19, 2006.

Mars Marches Past M35

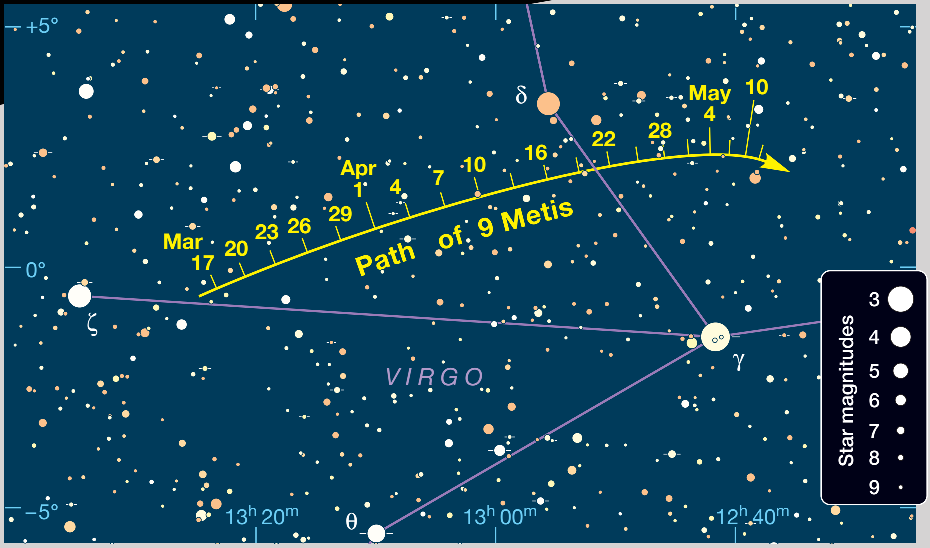
NOW SIX MONTHS PAST opposition, Mars still has drawing power. From April 25th to 27th, the Red Planet slides by the bright (magnitude 5.1) open cluster M35 in Gemini. On these dates, Mars is just 4.7″ across and shines at magnitude 1.5. On the evening of the 26th, it will be roughly ½° north-northwest of the cluster's center. The planet's rusty hue will contrast nicely with M35's diamond glitters, whether you're using a low-power telescope or binoculars. Viewed from mid-northern latitudes, Mars and the cluster stand 30° above the western horizon at the end of astronomical twilight.

Minima of Algol

Mar.	UT	Apr.	UT
2	4:21	2	17:23
5	1:10	5	14:12
7	21:59	8	11:01
10	18:49	11	7:50
13	15:38	14	4:39
16	12:27	17	1:29
19	9:16	19	22:18
22	6:06	22	19:07
25	2:55	25	15:56
27	23:44	28	12:45
30	20:33		

These geocentric predictions are from the recent heliocentric elements Min. = JD 2445641.5540 + 2.86732400*E*, where *E* is any integer. For a comparison-star chart and more info, see **skyandtelescope.org/algol**.

MARS AND M35: ALAN DYER



Metis: A Minor Planet for Small Telescopes

REACHING OPPOSITION ON April 4th, asteroid 9 Metis provides an opportunity for amateurs to explore beyond the "big four" (Ceres, Pallas, Juno, and Vesta) and observe a lesser-known but still bright asteroid. Metis reaches magnitude 9.5 in Virgo and sits about 6° northwest of the tight double star Gamma (γ) Virginis (Porrima). The asteroid travels westward in retrograde motion this month and is well placed for observing as soon as the sky gets dark. Meanwhile, 6.5-magnitude Vesta is next door in Leo. (Turn to page 48 of the March issue for a Vesta finder chart.)

Metis is a moderately large object about 235 kilometers (146 miles) across with an irregular, elongated shape. It's related compositionally to 113 Amalthea, and both are believed to be the surviving fragments of a much larger Vesta-sized asteroid that broke up about a billion years ago.

Irish astronomer Andrew Graham discovered Metis in April 1848, and for 160 years it remained the only minor planet discovered from Irish soil. The drought ended in October 2008, when amateur astronomer Dave McDonald found 19th-magnitude 2008 TM9 from his home in County Kildare, west of Dublin.

Selected Jupiter Mutual Satellite Events

Date	Time (UT)	Event	Mag change
April 1	13:17 – 13:23	Ganymede occults Io	0.6
April 6	11:46 – 11:51	Europa eclipses Io	0.3
April 11	10:01 – 10:11	Io eclipses Callisto	0.4
April 12	11:51 – 12:13	Io eclipses Callisto	0.5
April 15	10:08 – 10:16	Ganymede eclipses Europa	0.5
April 18	9:52 – 9:58	Io eclipses Europa	0.6
April 25	12:06 – 12:11	Io eclipses Europa	0.6
April 29	12:13 – 12:27	Ganymede eclipses Callisto	0.4

Action at Jupiter

BY MID-APRIL Jupiter rises around 5 a.m. local daylight-saving time and has an altitude of nearly 20° by the time morning twilight extinguishes all but the very brightest stars. On the 15th, the planet displays a disk 36″ across and beams at magnitude –2.1 from easternmost Capricornus.

Any telescope will reveal the four Galilean moons, and binoculars usually show at least two or three. Use the diagram on the facing page to identify them by their relative positions on any given date and time.

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

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

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

April 1: 9:47, 19:42; **2**: 5:38, 15:34; **3**: 1:30, 11:25, 21:21; **4**: 7:17, 17:13; **5**: 3:08, 13:04, 22:59; **6**: 8:56, 18:51; **7**: 4:47, 14:43; **8**: 0:39, 10:34, 20:30; **9**: 6:26, 16:22; **10**: 2:18, 12:13, 22:09; **11**: 8:05, 18:00; **12**: 3:56, 13:52, 23:48; **13**: 9:43, 19:39; **14**: 5:35, 15:31; **15**: 1:27, 11:22, 21:18; **16**: 7:14, 17:09; **17**: 3:05, 13:01, 22:57; **18**: 8:52, 18:48; **19**: 4:44, 14:40; **20**: 0:35, 10:31, 20:27; **21**: 6:23, 16:18; **22**: 2:14, 12:10, 22:05; **23**: 8:01, 17:57; **24**: 3:53, 13:48, 23:44; **25**: 9:40, 19:36; **26**: 5:31, 15:27; **27**: 1:23, 11:19, 21:14; **28**: 7:10, 17:06; **29**: 3:01, 12:57, 22:53; **30**: 8:49, 18:44

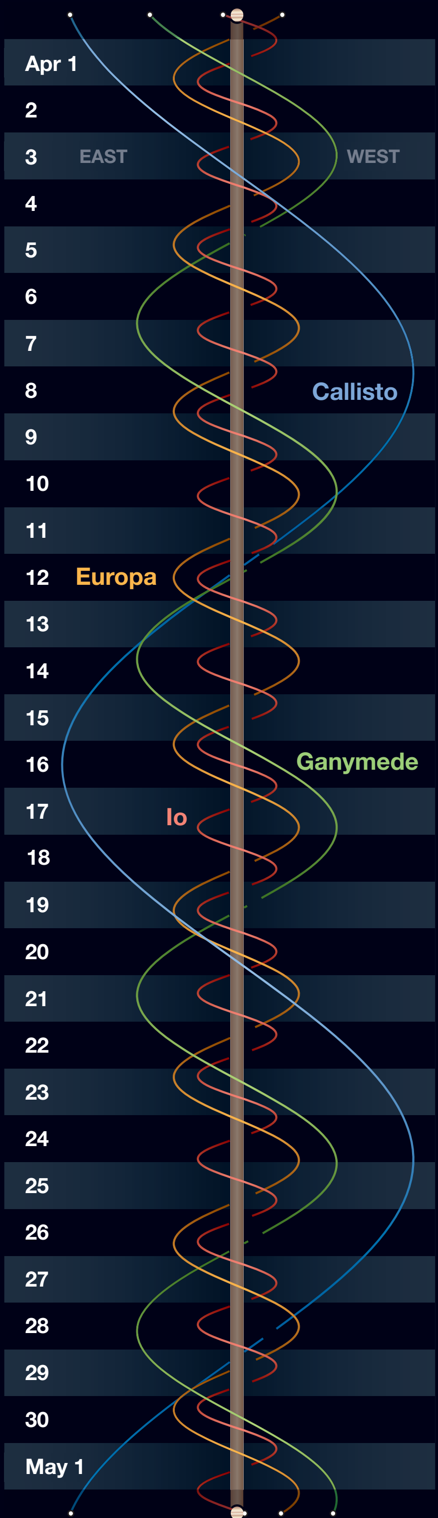
These times assume that the spot will be centered at System II longitude 356° on April 1st. If it has moved elsewhere, it will transit 1⅔ minutes earlier for each degree less than 356° and 1⅔ minutes later for each degree more than 356°.

Phenomena of Jupiter's Moons, April 2021

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

Every day, interesting events happen between Jupiter's satellites and the planet's disk or shadow. The first columns give the date and mid-time of the event, in Universal Time (which is 4 hours ahead of Eastern Daylight Time). Next is the satellite involved: **I** for Io, **II** Europa, **III** Ganymede, or **IV** Callisto. Next is the type of event: **Oc** for an occultation of the satellite behind Jupiter's limb, **Ec** for an eclipse by Jupiter's shadow, **Tr** for a transit across the planet's face, or **Sh** for the satellite casting its own shadow onto Jupiter. An occultation or eclipse begins when the satellite disappears **(D)** and ends when it reappears **(R)**. A transit or shadow passage begins at ingress **(I)** and ends at egress **(E)**. Each event is gradual, taking up to several minutes. Predictions courtesy IMCCE / Paris Observatory.

Jupiter's Moons



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

Lunar Skating Rinks

Why are some craters filled with smooth lavas and others aren't?

Tycho and Copernicus are frequently presented as archetypal lunar craters, and they are indeed beautiful and fresh. But most lunar craters aren't fresh. Many are much older and have been modified by subsequent events, including shaking from moonquakes and showers of ejecta from the creation of younger craters and basins. Additionally, mare lavas partially fill several craters, creating smooth floors, which, with their bright rims, remind me of skating rinks. **Plato** and **Archimedes** are the best examples, with **Endymion**, **Hercules**, **Condorcet**, **Goddard**, and **Lyot** being less well known.

These "skating-rink craters" are located on or near maria but don't have broken rims. That means the lavas on their floors didn't flow into the craters from outside; instead, the lava must have erupted onto the floors through basin fracture zones and the impact-pulverized crust beneath the craters. Subsequent eruptions of mare lavas probably buried many craters excavated near the centers of basins. Most surviving lava-flooded craters formed between 3.5 and 2.5 billion years ago, when mare volcanism was very active. And most skating-rink craters are large, with diameters greater than 40 kilometers (25 miles). Presumably, fractures from these larger impacts were able to penetrate deeply enough to connect to magma-filled basin fractures, creating the conduits for surface eruptions.

Skating-rink craters formed as normal complex impact craters, which are characterized by a deep floor, central peak, and terraced wall, like 40-km-wide **Aristarchus**. Aristarchus appeared about 280 million years ago, long after the final mare lava eruptions, and so there was no magma available under nearby **Oceanus Procellarum** to flood the crater's floor. But I transformed Aristarchus into the skating-rink crater seen on the facing page by measuring the depth (1.1 km) of nearby, 36-km-wide skating-rink crater **Herodotus**. I determined that if 3-km-deep Aristarchus had originated 3 billion years ago (as Herodotus probably did), it

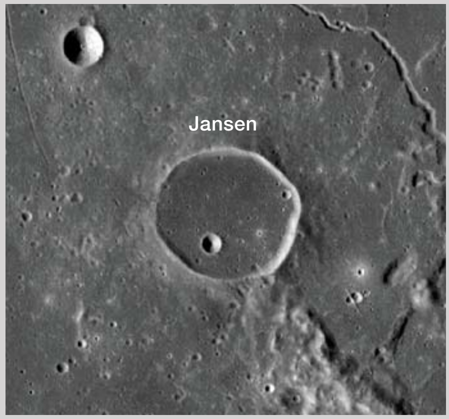
▲ Mare lavas flooded craters Crüger and Billy, as clearly seen above. Fractures feeding southern Oceanus Procellarum supplied the magma within Billy. Crüger's lavas likely arose from an unseen basin discovered in gravity data from NASA's Clementine mission.

NASA / GSFC / ARIZONA STATE UNIVERSITY

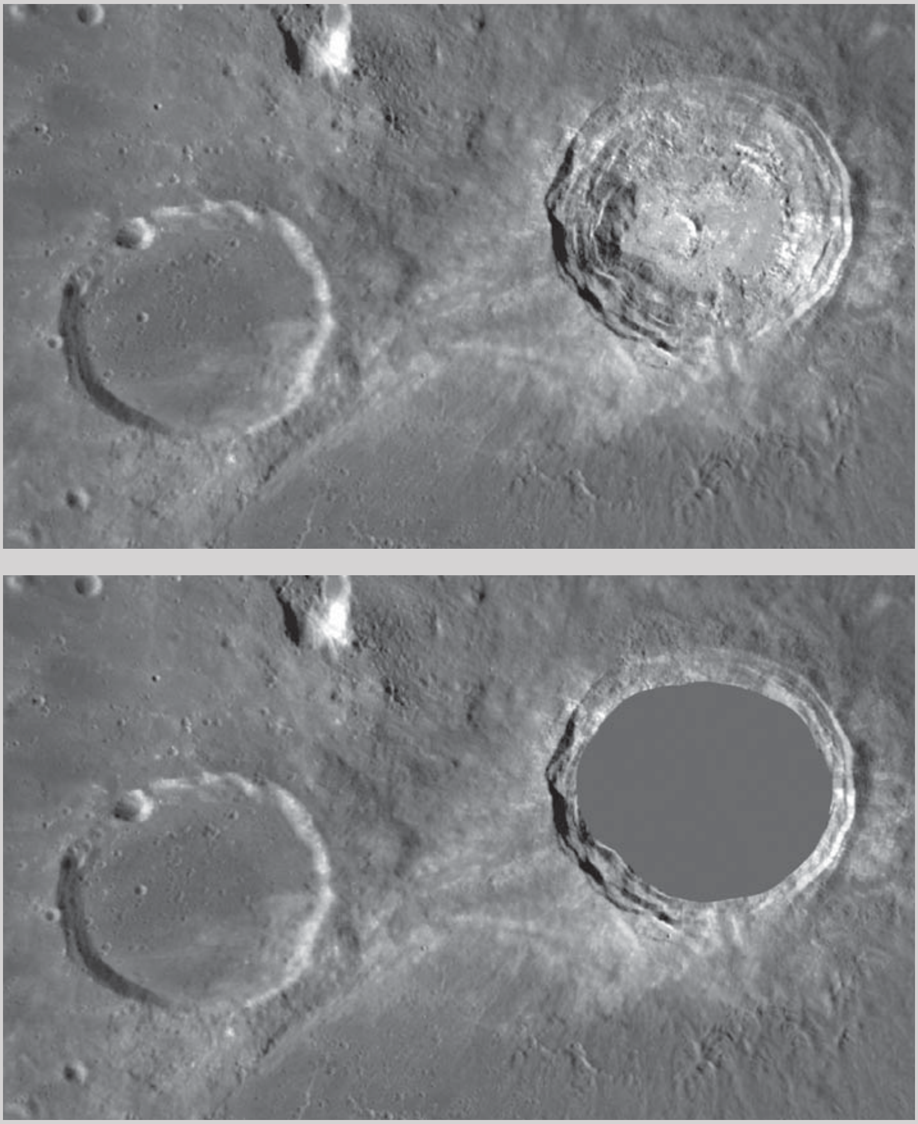
too could have been filled with about 2 km thickness of lava. Only the top 1.2 km of Aristarchus's rim would be visible, and its 300-meter-high central peak would be deeply buried beneath a smooth lava surface. This is what happened at Plato and with other skating-rink craters — they were inundated by so much rising magma that their original floors, lower walls, and central peaks were submerged.

Not all craters are filled so deeply with lava. Hercules, at the east end of **Mare Frigoris,** has a smooth floor with one significant disruption — the 14-km-wide crater **Hercules G**. At 68 km wide and 3.5 km deep, Hercules has a shallow lava pool that didn't even cover its small peaks rising 300-400 meters above its existing floor. Because of its great depth, and peaklets, I wouldn't call Hercules a skating rink. Similarly, smooth-floored Neper (130 km) wouldn't qualify. It's 3.9 km deep and has a central peak that rises 2.2 km above the lava-covered floor. You'll have to take your skates elsewhere.

Two of the more remarkable lunar skating rinks are **Crüger** and **Billy**. These 46-km-wide craters formed with depths of roughly 3 km but now contain thick lava — 2.3 km in Crüger and 1.9 km in Billy — burying their peaks and most of their walls. Billy is at the southernmost range of Oceanus Procellarum, but Crüger seems to be far from a source of mare lava. Yet looks can be deceiving. Gravity data derived from NASA's Clementine mission revealed an otherwise totally undetectable impact basin as large as the **Grimaldi Basin** immediately to the north. Crüger and other nearby small patches of mare lava lie inside this Crüger-Sirsalis Basin.



▲ Unlike the other skating-rink craters, Jansen appears to be a completely volcanic formation and not the result of an impact.



▲ *Top:* Craters Herodotus (left) and Aristarchus (right) are nearly the same size, though Aristarchus formed long after the final mare eruptions. *Above:* Had Aristarchus formed 3 billion years earlier, it likely would appear much as it does in this simulation.

HERODOTUS AND ARISTARCHUS: NASA / GSFC / ARIZONA STATE UNIVERSITY / CHARLES WOOD (2); JANSEN: NASA / GSFC / ARIZONA STATE UNIVERSITY

All the skating-rink craters discussed so far are volcanically modified impact craters. However, **Jansen** (24 km) is a skating rink that may be a completely volcanic structure. It resides on a slightly elevated ridge that's about 800 meters above other nearby lava plains to the north. The ridge is cut by a sinuous rille and peppered with rimless pits — all of which are volcanic features. Jansen, like Crüger, is on the edge of a positive gravity anomaly, hinting that a small basin may be buried nearby.

If there's one feature we can consider a "mega-skating rink," it's **Mare Crisium**. It's 400 km wide and lies 4 to 5.5 km lower than the Crisium Basin rim. The mare has no central mountains — just a few small craters and low ridges to slow your skating.

■ After 20 years, Contributing Editor **CHUCK WOOD** continues to piece together fascinating lunar stories to share with *S&T* readers.

▲The reward for your imaging efforts can be a treasure like this superbly detailed portrait of the Andromeda Galaxy, M31. Shifting from multiple targets per night to multiple nights per target will allow you to go deeper and produce more interesting images.

ALL IMAGES COURTESY OF THE AUTHOR

I Wish I'd Known Then What I Know Now

Learn from an experienced astrophotographer's early mistakes.

Many years ago, I played a game called *Gold of the Desert Kings* as part of a team-building day at work. The goal was simple: Bring back as much gold from the desert as possible. Each team had the option to trade a turn for a chance to "ask the Old Man" for advice before setting out on a quest. My team didn't stop to talk to the Old Man and, predictably, soon died of thirst, penniless, in the desert. Had we asked him for advice, the Old Man would have revealed the location of the oasis that could have kept us alive.

Fast-forward 20 years, and now I'm the Old Man. While there's no substitute for experience, it doesn't always have to be *firsthand* experience. I'm hoping that some of my hard-learned lessons can help you scale the astrophotography learning curve a little more quickly, and without acquiring as many bruises as I did!

Most of what I learned applies whether you're shooting the sky with a DSLR and kit lens or using a dedicated astro camera fitted to a telescope.

Hardware Considerations

All your gear needs to work well together to yield good imaging results, but the foundation of every great imaging setup is the mount. In addition to carrying the *payload* (the camera plus lens and/or telescope and associated accessories), the mount must aim accurately at your target, then track precisely for long periods. I've changed optics and cameras many times, but I've stuck with one mount for the last eight years.

Make sure the rated capacity of your mount is significantly greater than what you need to easily carry your current payload, balance it correctly, and polar align precisely. This strategy allows you to effectively "future proof" your mount, at least for a few years. Buying a good mount to begin with is always going to be more economical than purchasing a cheap model now and then getting a good one later.

▲ *Left:* At the heart of any imaging setup is a sturdy, accurate mount, such as the Paramount MX shown here. The author's advice is to choose a mount with future needs in mind to avoid the expense of having to buy a better mount in future. *Right:* The author's current imaging rig includes a Sky-Watcher Esprit 150 f/7 refractor with a QHY16200A CCD camera. The smaller scope on top is a Takahashi FSQ-106 f/5 refractor with a QHY367C Pro one-shot color CMOS camera. Using paired setups simultaneously allows him to double the image data he can acquire in a single night.

I wish I'd known from the get-go that it's best to consider an optic and camera together as a single imaging system. Select a combination that gives a field big enough (or small enough) to frame objects of interest, along with enough resolution to reveal as much detail as your sky and targets will allow. In other words, if you typically want to shoot large objects like the Andromeda Galaxy (M31), a modest lens (with a focal length of roughly 100 mm) and a DSLR can get you there. Capturing fine details in small galaxies and planetary nebulae really requires bigger scopes with longer focal lengths. And those bigger telescopes need beefier support, which takes us back to the importance of an adequately sized mount. Savvy astrophotographers also know the Law of Unintended Consequences: The cost of upgrading from an 3-inch refractor to an 8-inch astrograph might also include the expense of a new mount to carry the heavier payload.

Critically, resist the urge to change a setup that's producing reliable results night after night. Equipment upgrades can be fun — especially when some wondrous new camera or astrograph appears on the market — but be careful what you wish for. A new piece of hardware can really reduce your productivity if everything doesn't work as expected, or if you discover you need an extra piece (like a custom adapter) that's not readily available. I only alter my imaging equipment if I need to overcome some significant limitation.

This advice extends to your computer, too — a piece of equipment that has become an integral part of the modern imaging chain. If you're thinking of updating your computer, operating system, imaging software, or drivers, make sure to back up everything first. I wish I had followed that advice when I was getting started. More than once.

Something else I learned the hard way: If there's a threat of thunderstorms, always unplug the power to your equipment and disconnect all other cables to prevent damage that can occur even when the power is switched off.

Image Processing

No matter what celestial objects you decide to photograph, you'll likely have to perform some image enhancement. Even photos of the Moon benefit from processing. The specific software you'll need depends on what you image and how deep you want to dive into astrophotography. The basic software that probably came with your camera may be sufficient for nightscapes or lunar photos. But if you want to shoot more difficult astronomical subjects, you'll need something with additional capabilities. I've settled on *PixInsight* (**pixinsight.com**) for my deep-sky image processing needs, having also dabbled in several other suites. But as my teaching partner, Warren Keller, says, "It's not the plane, it's the pilot." *Photoshop*, *Astro Pixel Processor*, *MaxIm DL*, *Prism*,

▶ The Heart Nebula (upper right) and Soul Nebula (lower left) grace the northern constellation of Cassiopeia. Long exposures (in this case more than 20 hours accumulated over 8 nights) help reveal plenty of rich details.

and *ImagesPlus* are just some of the other software packages that, in the right hands, can produce spectacular deep-sky images. Luckily, a good set of image data never goes bad. You can return to it time and again as your processing skills improve. I've gone back to older images and have been pleasantly surprised at how my results have improved with practice. The main thing is to do your homework, pick one piece of software, and stick with it so that you master its capabilities.

Digital imaging unavoidably generates a lot of data. Don't underestimate how much storage space your new hobby will consume. With so many image files, it's very helpful to develop a consistent format for naming and organizing your data folders. A little effort up front will make it easier years from now to retrieve and work with your collection of older images.

With my setup, the archive for a single final image can consume up to 50 GB of disk space. That's why I have a hard drive dedicated to astrophotography only. I give each imaging project a folder named with the format: Object-Filters-Month-Year (e.g. M57-HaRGB-Sept-2020). Within that folder I make subfolders for the different types of image data, be it "light" frames or "calibration" images. I also include a text file containing basic information about the equipment I used, exposure times, and date(s) of acquisition.

▲ Sometimes it's a treat to indulge in some imaging "fast food." You can often capture open clusters and dark nebulae in just a single night. This image of Barnard's E (B142 and B143) required just a few hours of exposure time.

Strategic Thinking

They say patience is a virtue, but as a new astrophotographer I wanted to shoot *everything*, and right away! I would photograph up to five different objects in a single night. Now I'm more interested in quality over quantity. Give me one great shot of the Heart and Soul Nebula (IC 1805 and 1848) over a set of mediocre images of a half-dozen different deep-sky objects. I tend to spend several nights on each target, and I choose objects that transit near local midnight, when they're highest and least affected by atmospheric conditions. On long winter nights when it's dark from about 6 p.m. to 6 a.m., I might shoot two targets: one that transits around 9 p.m., and another that's highest around 3 a.m. On short summer nights, I typically have to spend multiple nights on a single target.

Great nights when everything goes right can feel like a rare prize. That's why you don't want to be adjusting your equipment while the stars shine invitingly overhead. I prefer to use hazy or moonlit nights for those inevitable maintenance tasks. You can also make productive use of sub-par nights to test out your equipment. For example, it's useful to know how long an unguided exposure you can take and still obtain round stars, or figure out the size of your setup's properly corrected image circle. It's also handy to know how often you need to refocus as the temperature drops during the night. Knowing these things can help you make the most of your time when a really good night comes along.

Astrophotography requires a lot of different skills and a daunting number of things have to go right at the same time to achieve the finest results. Luckily, there are lots of Old Men like me willing to share our experiences. Maybe with the benefit of this hindsight, you'll bring back more astrophotography gold than I did when I started!

■ **RON BRECHER** has been imaging the sky for more than 20 years and is *still* learning about astrophotography.

Outstanding in the Field

THE LAST STARGAZERS: *The Enduring Story of Astronomy's Vanishing Explorers*

Emily Levesque
Sourcebooks, 2020
336 pages, ISBN 9781492681076
$25.99, hardcover.

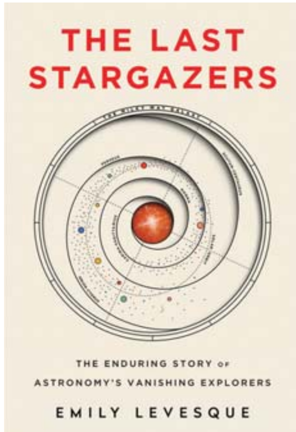
FOR COLLEAGUES HEADING out to Kitt Peak for their next observing run, astronomer Emily Levesque has a tip: Watch out for the scorpions. The dry Arizona air is great for observing starlight, but as this University of Washington associate professor notes, it's also ideal for unexpectedly meeting up with an unwelcome guest in the bathroom.

That scorpion encounter is just one of the colorful vignettes Levesque shares in *The Last Stargazers*. The book is a celebration of modern-day professional astronomy and the characters who populate it, wrapped in a profound meditation on the rapidly changing profession. Today's astronomers still struggle with sleep deprivation, unexpected cloud cover, and the occasional hurricane while observing at the lonely edges of our planet, where they find the clearest skies and strongest electromagnetic

> Levesque shares her front-row seat at the vanguard of modern astronomy with generosity and a true sense of wonder.

signals. But they're just as apt to use computers to control those telescopes from home or office as they search for the literal secrets of the universe.

The Last Stargazers begins with all of the gee-whiz amazement of Levesque's youth as a kid astronomer, from witnessing Halley's Comet in 1986 to announcing her intention to join the profession — at age seven. In middle school, Levesque balances ninth-grade math classes and "seventh-grade everything else" before ultimately pursuing a physics degree at MIT and a PhD at the University of Hawai'i. From her first stint at Kitt Peak (and that scorpion) to an observing run in SOFIA, the tricked-out 747 that collects infrared data



from high in the stratosphere, Levesque shares her front-row seat at the vanguard of modern astronomy with generosity and a true sense of wonder.

The book's title is a bit of a head fake. Stargazing as a profession or a hobby isn't going anywhere, of course, but the field of astronomy, like the universe itself, is expanding with greater velocity than ever before. Levesque highlights the technologies that, for one thing, enable today's astronomers to analyze terabytes of data. As Levesque shows in her entertaining prose, it's a long way from her family's Celestron C8 to the 200-inch reflector at Palomar.

It's tempting to characterize this book as a straightforward memoir of a young astronomer on her way up the academic ladder, weaved into a history of the scientific development of the profession, but *The Last Stargazers* digs deeper. Between stories of scientists trapped in prime focus cages, accidentally smashing data-rich glass photographic plates, or licking those plates to identify the silver halide-coated side that captures photons arriving from distant stars, Levesque reminds us of just how far the profession has come, particularly for women. Legendary astronomer Margaret Burbidge (who died in April 2020 at age 100), denied a Mount Wilson fellowship in 1955, posed as her husband's assistant to obtain precious observing time. Another giant of the field, Vera Rubin, after decades as an astronomer, experienced her first-ever night with an all-female observer team (at Las Campanas) only in 1984 — the year Levesque was born.

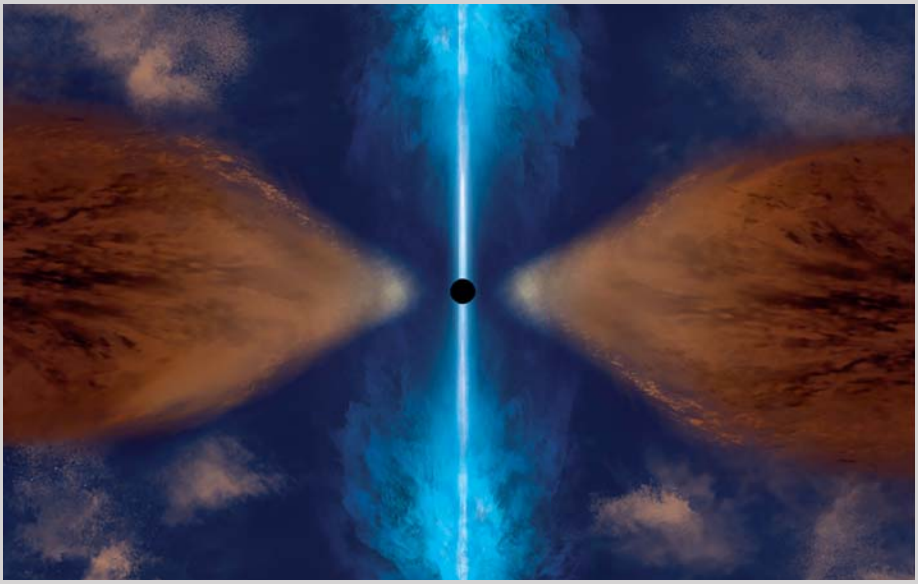
It's fitting that *The Last Stargazers* concludes with Levesque's journey to the construction site at Cerro Pachón, where the formerly named Large Synoptic Survey Telescope is slated to achieve first light in 2021 on its way to mapping the Southern Hemisphere sky continuously for a decade. The telescope is better known by its new official name: the Vera C. Rubin Observatory.

The Last Stargazers is a book for any serious astronomy aficionado, and especially for students considering a career in the field. Levesque is a compelling investigator and a deft writer of popular science. She highlights the professionals who make exciting discoveries while retaining the curiosity and capacity for awe that led them to astronomy in the first place. This is a book celebrating science and stargazers, of which no doubt Levesque will be anything but the "last" of her book's title.

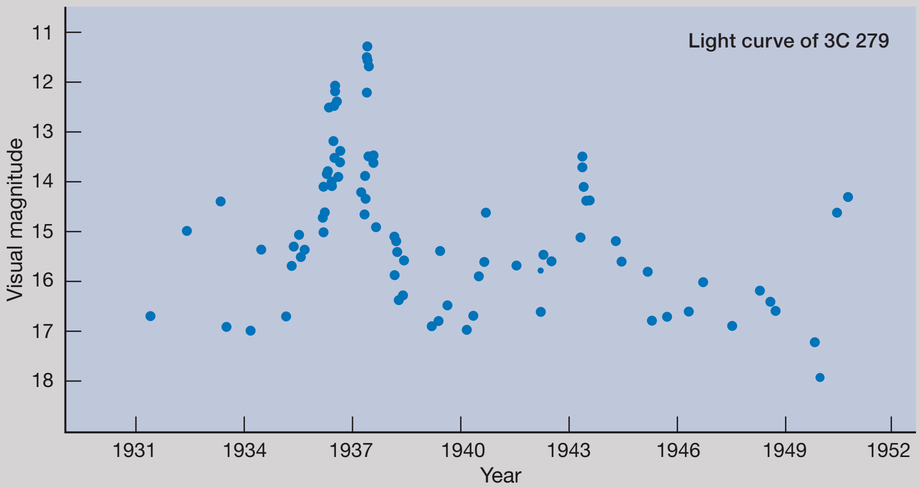
■ **NICOLE NAZZARO** is a writer based in Edmonds, Washington. See her article on a classic telescope's restoration on page 24 of this issue.

Variable Galaxies

With a big enough telescope and the right tools, you can contribute to the study of variations in the visible-light output of AGNs.



◀ **DEEP INSIDE A GALAXY** Although the origin of variability in the visible-light output of galaxies such as BLOs, quasars, and Seyferts is not fully understood, a large body of research suggests the cause is instabilities in the accretion disk, or the interaction between the accretion disk and the base of the jets. The diagram at left zooms into the very core of these types of galaxies, where a supermassive black hole feeds off its host. Below left is the light curve of the quasar 3C 279, showing regular brightenings at seven-year intervals.

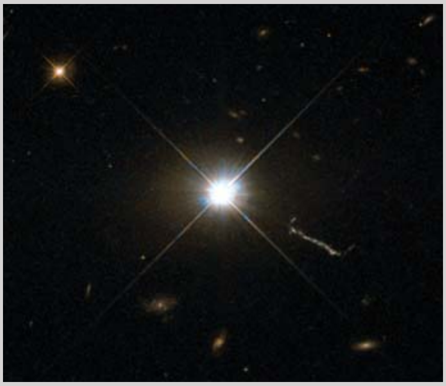


Twinkle, twinkle, quasi-star,
Biggest puzzle from afar.
How unlike the other ones,
Brighter than a trillion Suns.
Twinkle, twinkle, quasi-star,
How I wonder what you are!
—George Gamow (1964)

Active galactic nuclei (AGNs) are the cores of some galaxies that outshine their hosts. True powerhouses, they spew out radiation covering the entire electromagnetic spectrum, from gamma rays to the radio. Jets of matter flow away from them at relativistic speeds. When the jets are pointed along our line of sight, we know these sources as BL Lac Objects (BLOs) or blazars. Quasars, by contrast, have their relativistic jets pointed away from our line of sight. As a result, we can get amazing views of these structures that can extend for hundreds of thousands or even millions of light-years from the host galaxy. Professional astronomers have monitored the fluctuating radiation output of AGNs for decades. Amateurs can join in the fun by capturing changes in the visible-light output, all while appreciating some of the characteristics of AGNs, including their vast distances.

In the days before astronomers understood that the visible-light output of galaxies could vary, they classified objects that exhibited brightness variations as variable stars due to their pointlike appearance on photographic plates. In fact, when German astronomer Cuno Hoffmeister discovered the prototype of the BLOs in 1929, he assumed it was a variable star and designated it BL Lacertae, using the standard nomenclature. The name stuck even after astronomers identified is as a blazar.

LEAH TISCIONE / *S&T* (2); LIGHT CURVE SOURCE: L. J. EACHUS / W. LILLER / *ASTROPHYSICAL JOURNAL* 1975



▲ **QUASARS, BLACK HOLES, AND JETS** The word quasar is derived from *quasi-stellar radio source* — indeed, they were first identified as strong radio emitters. These objects appeared pointlike on photographic plates, i.e., they looked like stars (hence their moniker). We now know quasars and their kin are galaxies at vast astronomical distances that are powered by supermassive black holes in their cores. Jets of relativistic matter, such as the one captured by the Hubble Space Telescope in this image of 3C 273, are often observed in quasars.

Swiss astronomer Fritz Zwicky discovered the first variable galaxy, IV Zw 29 (later classified a *Seyfert galaxy*, an object akin to a quasar but with a more easily detectable host galaxy), on photographic plates in 1965. In reexamining his own Palomar Observatory plates dating back some 30 years, Zwicky revealed that the galaxy's magnitude varied irregularly during that timespan. In another series of studies, researchers documented the galaxy's changing brightness from 1958 to 1993, showing that it fluctuated between 17th and 18th magnitude, punctuated by an occasional rise to magnitude 16.7 followed by a gradual decline. Zwicky's observations marked the beginning of what would become a new field unto itself: variable galaxies, which include BLOs, quasars, and Seyferts.

Amateur astronomers will find detailed descriptions of specific variable galaxies in German astronomer and author Wolfgang Steinicke's article "Extragalactic Objects Discovered as Variable Stars" (**https://is.gd/steinicke_agn**). In it, he lists pertinent data and characteristics of 21 variable galaxies, including finder charts and some interesting historical facts. For example, W Comae (yet another variable star designation), is a BLO that exhibited a peak magnitude of 11.5 in 1916 and has one of the largest brightness ranges, varying by up to 6 magnitudes. In neatly encapsulated descriptions, we learn that some sources vary over the course of days, while others change over months, years, or even decades — usually with no discernible periodicity.

Describing the Variability

The exact origin of the variability is still a much-studied subject, and many theories abound. Various scenarios invoke an *accretion disk* — matter captured from the host galaxy and swirling around its central supermassive black hole — or even the jets themselves.

Astronomers use *light curves* to decipher the variability of celestial objects: By plotting the magnitude of the object against time, patterns may emerge. The nature of the variability depends on its underlying causes. For example, Lola Eachus and William Liller (both at the Center for Astrophysics at Harvard College Observatory at the time) published a study in 1975 on the long-term light curve of 3C 279, a quasar in Virgo. They plotted the object's magnitude (derived from the blue-sensitive refractor plates) from 1929 to 1952 and found that the source brightened from around magnitude 16–17 to around 12–14 at regular intervals of seven years (see the plot on page 58). Some researchers propose that this behavior arises from alternating accretion-disk-dominated or jet-dominated emission from the quasar.

Want to Observe Variable Galaxies?

The American Association of Variable Star Observers (**aavso.org**) welcomes your data on a number of objects, including variable galaxies. You can find a handy table that lists variable galaxies (among other high-energy targets) that should be within reach of amateurs with larger telescopes at **https://is.gd/aavso_vargal**. Specifically, the AAVSO is looking for estimates of magnitudes, along with the exact dates and times of the observations. They provide finder charts that indicate field stars and their magnitudes, which you can use to estimate the magnitudes of your target. See also the article "Measuring the Stars" by Richard Berry on page 60 of the December 2020 issue of *Sky & Telescope* — you can use the same technique described therein for galaxies.

INSTRUMENTATION

The following setup was used to obtain the images of three of the targets presented here (Mrk 876, Mrk 507, 3C 351):

System description: Starizona Hyperion Telescope, aperture 12.5 inches (318 mm), FL 2520 mm

Exposure: 60 seconds, unguided

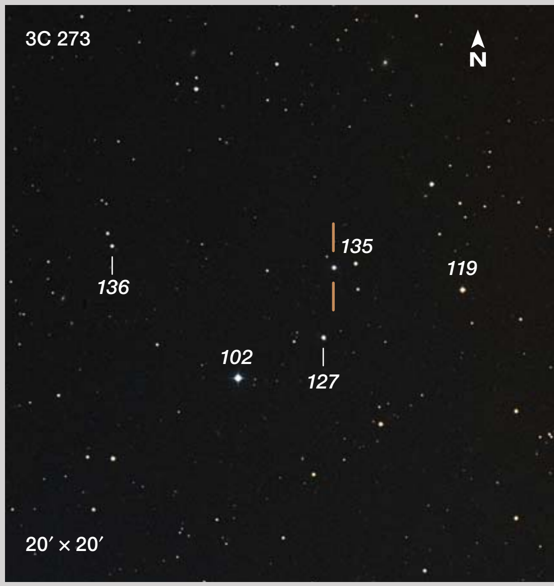
Camera: Apogee (Andor) U8300, unbinned, –20°C, pixel size 5.4u

Filter: Luminance filter to limit exposure to visible wavelengths

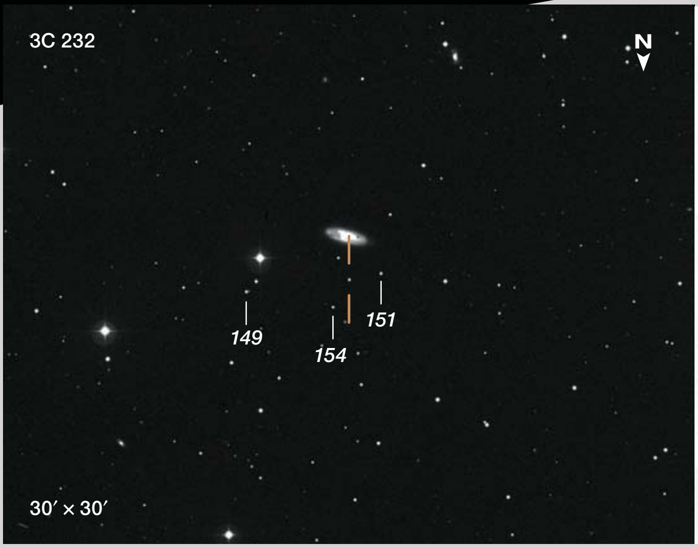
Mount: Software Bisque Paramount ME

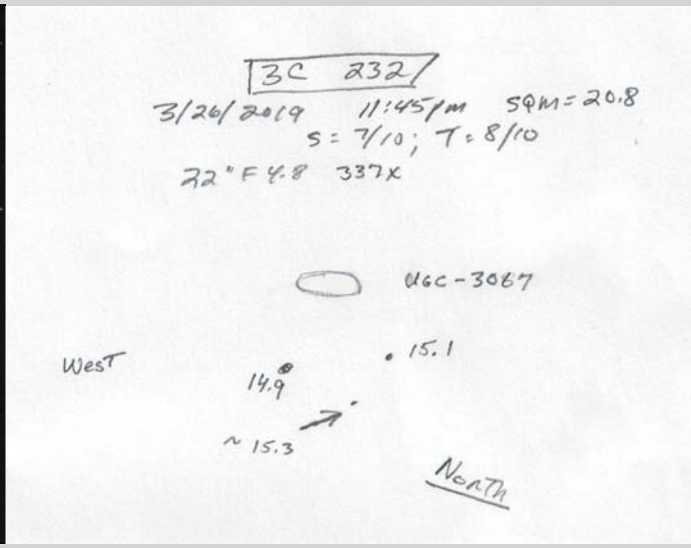
Our Sample

3C 273 The first quasar to be identified as such (in 1963) is a good place to start. Found in Virgo, it's about 1⅓° almost due west of the 10.6-magnitude galaxy NGC 4536. I (Lamperti) first observed the quasar in 1991 with a 13-inch reflector at 130× and saw it as a faint



3C 273: ESA / HUBBLE / NASA; FINDER: POSS-II / STSCI / CALTECH / PALOMAR OBSERVATORY





point of light. At a distance of around 2.3 billion light-years (Gl-y), it's one of the closest quasars to Earth. At the time, however, it was the most distant object I'd observed, and that experience remains quite indelible in my mind.

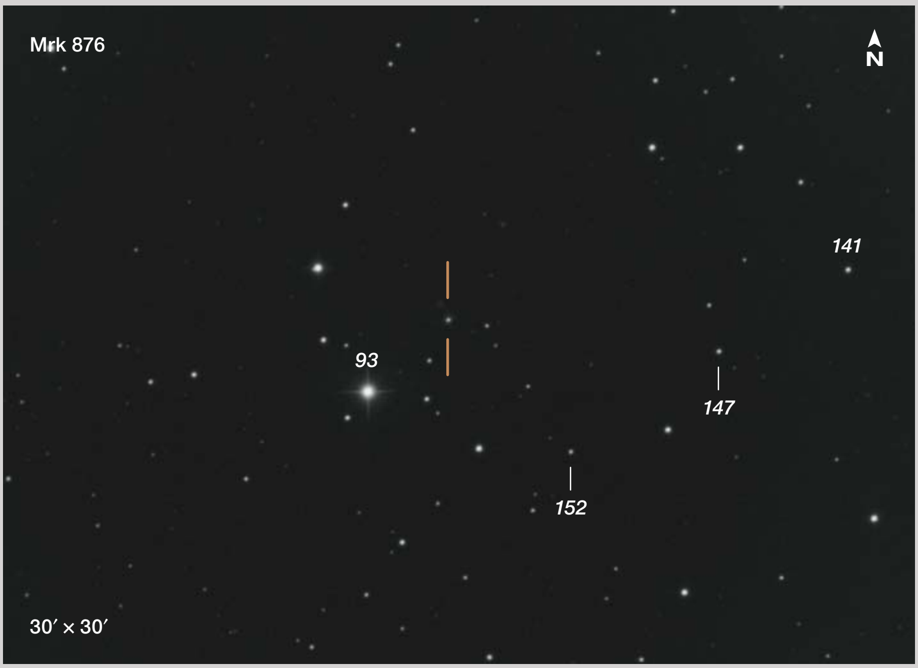
I revisited the object in May and June of 2020 with a 22-inch reflector at 337×. I used the finder chart provided by the AAVSO and guided by the reference stars labeled "135" and "127" (representing magnitudes 13.5 and 12.7, omitting the decimals so they don't get confused with stars; the AAVSO numbers are reproduced in the images here) prepared to estimate the quasar's magnitude. Once I located the field of 3C 273, I oriented the chart to match the eyepiece view and compared the quasar with the two reference stars. Taking a few minutes to compare the brightness of the three, I pegged 3C 273 at magnitude 12.5, slightly brighter than the magnitude-12.7 reference star. This puts it at the brighter end of its range, as listed in the table on page 61.

3C 232 in Leo occupies the same high-magnification field as NGC 3067, a 12.1-magnitude galaxy some 2.5′ × 0.9′ in size. I estimated the quasar's magnitude at 15.3 when I observed it at 207× in 2019. Granted, it appears as just another starlike dot, but the fact that its photons had traveled for the past 7.7 billion years still fills me with wonder — one of the pleasant benefits of observing any AGN (as I highlighted on page 57 in the March 2018 issue of *S&T*).

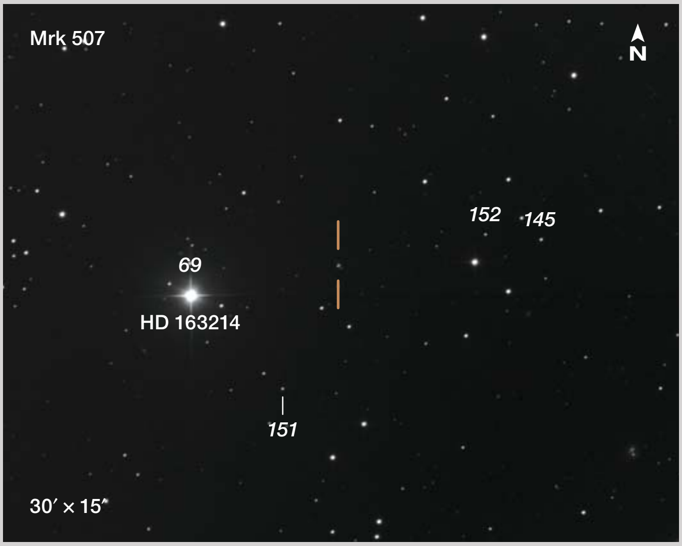
Markarian 876 This AGN in Draco is 0.8° northeast of the magnitude-11.3 barred spiral galaxy NGC 6140 (6.3′ × 4.6′ in size). Over the past seven years, Mrk 876's magnitude has varied slightly between 13.7 and 14.7. When I observed it in 2019 at 337×, I estimated it to be magnitude 14.1, as it appeared identical to the magnitude-14.1 reference star on the AAVSO finder chart.

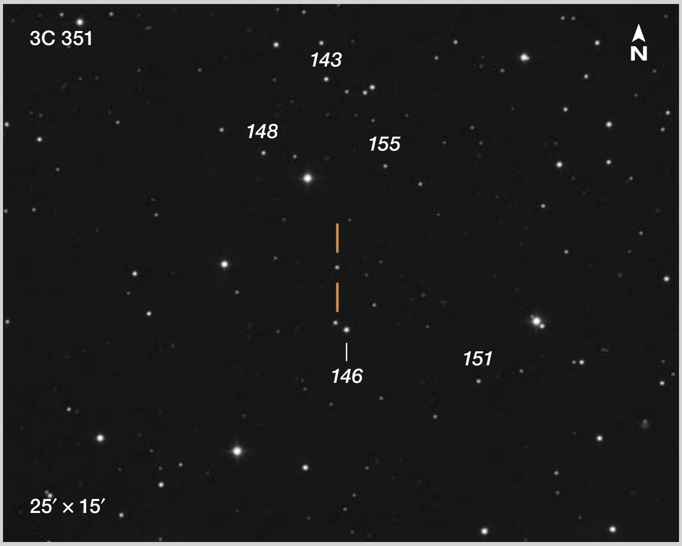
Mrk 507 Staying in Draco, we find this Seyfert galaxy a smidgen more than 2¼° northwest of NGC 6543, the Cat's Eye Nebula. A 6.9-magnitude star (HD 163214) sits just off the galaxy's eastern side. I observed Mrk 507 on the same night as Mrk 876 using the same setup and estimated it to be around 15th magnitude, noticeably dimmer than the 14.5-magnitude reference star.

3C 351 Still in Draco, this quasar is almost halfway below a line connecting 6.1- and 6.7-magnitude stars (HD 154391 and HD 155513, respectively), and about ⅓° due west of a pair of galaxies comprising 12.9-magnitude NGC 6307 and 13.7-magnitude NGC 3606. I also observed this source on the same night and with the same



3C 232: POSS-II / STSCI / CALTECH / PALOMAR OBSERVATORY; SKETCH: AL LAMPERTI; MRK 876: FRANK COLOSIMO

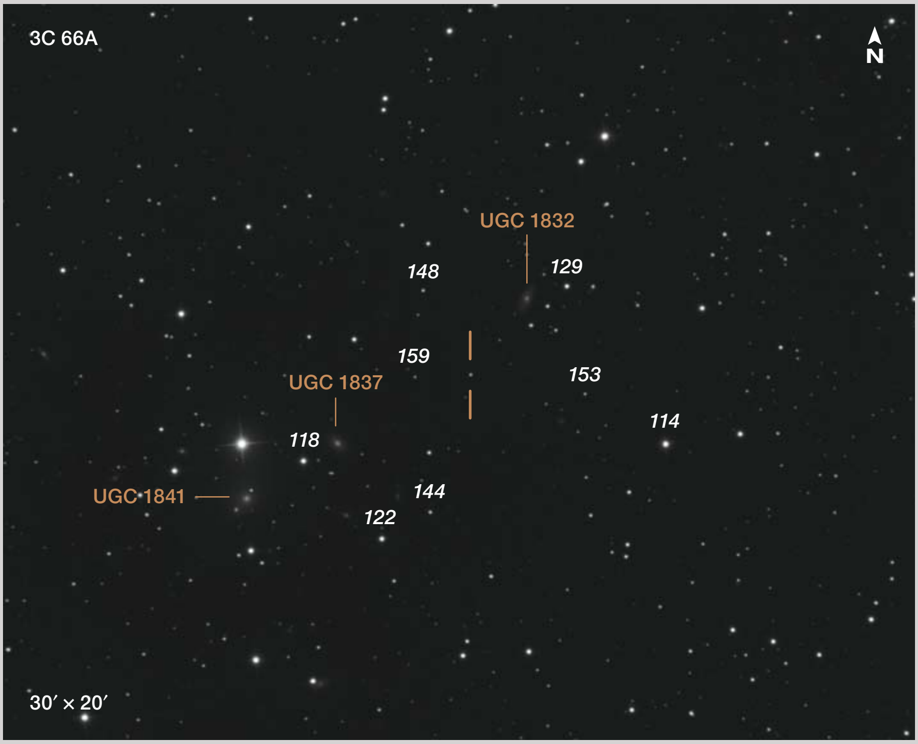




setup as Mrk 876 and Mrk 507, and estimated its magnitude at 15.1.

3C 66A Moving over to Andromeda, I first observed this BLO in 2007 with my 20-inch at 272×. The object is 0.7° almost due north of the splendid edge-on, 10th-magnitude galaxy NGC 891. My observing notes indicate that the BLO almost forms a right triangle with a field star and UGC 1841. At that time, I didn't make any magnitude estimates, so I reobserved it in September 2020 and found it to be around magnitude 15.1, at the dimmer end of its range.

The time scales on which AGN exhibit variability — and whether this variability is periodic or not — are largely unknown. If you submit your observations to the AAVSO website, professional astronomers will combine your data with theirs to help unravel the mysteries of variable galaxies. Your observations might even help them identify the mechanisms that contribute to the heartbeats of these puzzling objects. Observing variable galaxies allows you to push your envelope, contribute to a worthy cause and, at the same time, stand in awe of the universe.



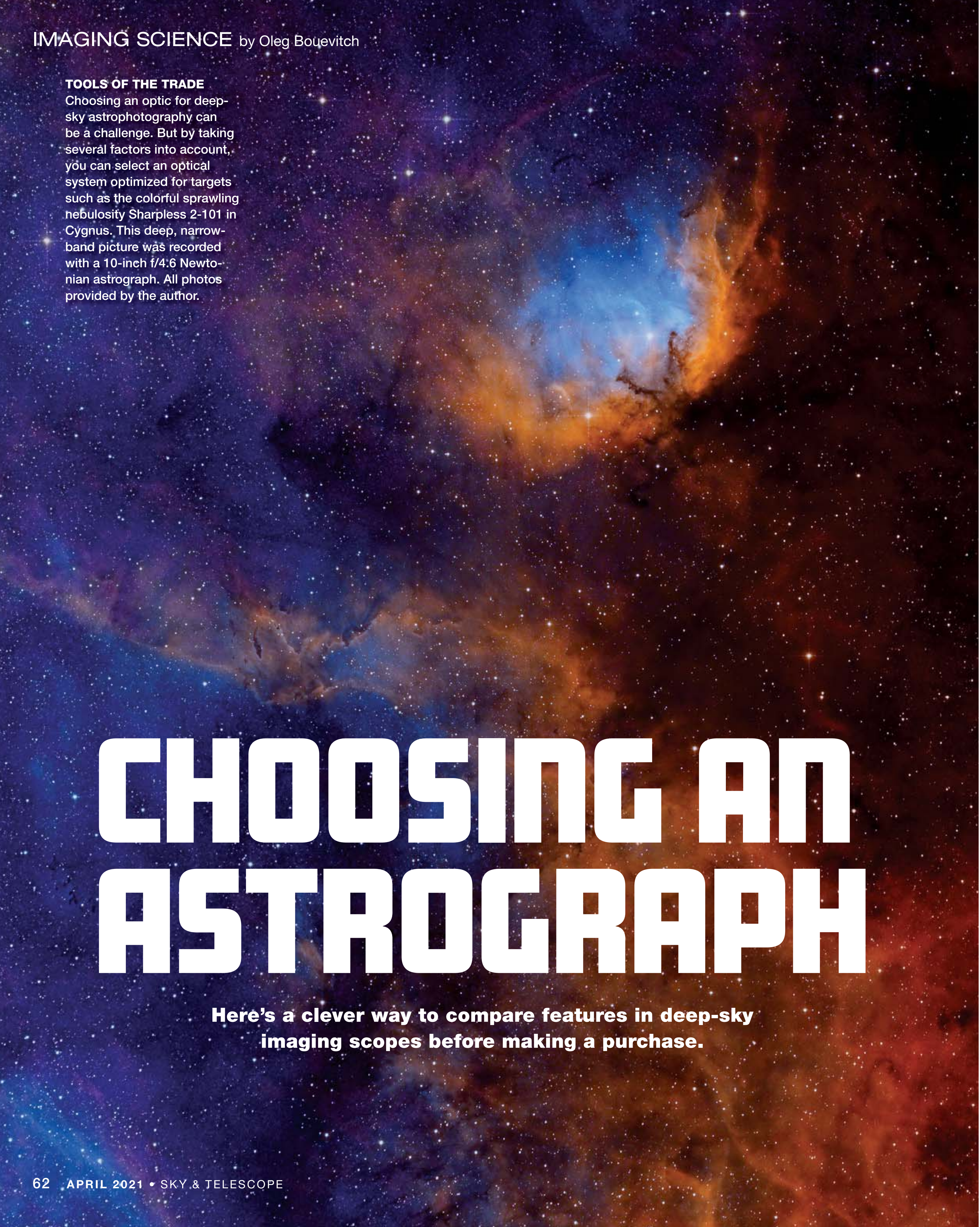
FRANK COLOSIMO (3)

Variable Galaxies

Object	Type	Const.	Mag(v)	Dist. (Gl-y)	RA	Dec.
3C 273	Quasar	Virgo	12.2 – 13.6	2.3	12^h 29.1^m	+02° 03′
3C 232	Quasar	Leo	15.3 – 15.9	7.7	09^h 58.3^m	+32° 24′
Mrk 876	Seyfert	Draco	13.7 – 14.7	1.9	16^h 14.0^m	+65° 43′
Mrk 507	Seyfert	Draco	15.0 – 15.2	0.8	17^h 48.6^m	+68° 42′
3C 351	Quasar	Draco	15.0 – 15.7	5.4	17^h 04.7^m	+60° 45′
3C 66A	BLO	Andromeda	13.7 – 15.7	6.4	02^h 22.7^m	+43° 02′

Right ascension and declination are for equinox 2000.0.

■ **AL LAMPERTI** and **FRANK COLOSIMO**, whose passion for amateur astronomy is invariable, are members of the Delaware Valley Amateur Astronomers in Pennsylvania. Most observations were done at Blue Mountain Vista Observatory and its adjacent field.



TOOLS OF THE TRADE Choosing an optic for deep-sky astrophotography can be a challenge. But by taking several factors into account, you can select an optical system optimized for targets such as the colorful sprawling nebulosity Sharpless 2-101 in Cygnus. This deep, narrow-band picture was recorded with a 10-inch f/4.6 Newtonian astrograph. All photos provided by the author.

CHOOSING AN ASTROGRAPH

Here's a clever way to compare features in deep-sky imaging scopes before making a purchase.

Which telescope should you choose for deep-sky astrophotography? The abundance of choices in today's market can be overwhelming, even for a technologically savvy person. Telescopes come in a great variety of optical designs, sizes, and prices. A reasonable approach is to first decide what your goals are for your astrophotography. Are you intending to hunt for asteroids, comets, supernovae, or otherwise contribute to science? Or is your goal to express your fascination with the universe by taking eye-catching astro-images?

Assuming the latter, that is, to photograph nebulae, galaxies, and other deep-sky objects (rather than the Sun, Moon, and planets), your goal is thus to obtain the clearest and most detailed images of these objects.

In deep-sky astrophotography under dark skies, we are limited by the amount of light we can collect on clear nights. That light is many orders of magnitude fainter than what's available to a typical daytime photographer, and it potentially leads to a loss of fine detail and images that appear grainy. To overcome this problem, we need to dramatically increase the amount of light collected.

This translates into two things when considering a telescope for the job at hand. The first is to maximize the *irradiance* (amount of light per unit area) on the pixels of a sensor at a focal plane of the telescope. This is needed to maximize signal-to-noise ratio in an exposure, which reduces the noise in the image. The second is to make sure that the telescope can illuminate as many pixels as possible without optical aberrations, such as field curvature, coma, and other distortions that detract from the aesthetics of the final image. This is important particularly when using large detectors, especially when our goal is to record expansive star fields and nebulae in the Milky Way.

Pixel Irradiance and the Image Circle

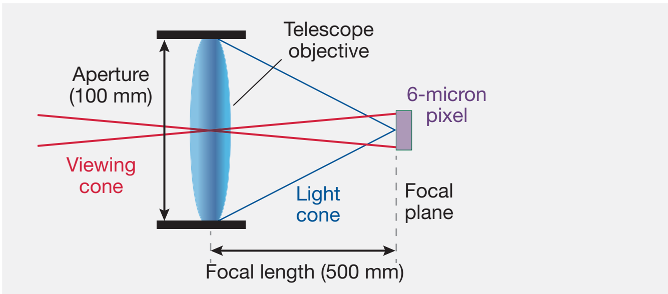
You can think of an astrograph as a big camera lens, and one rule of optics is that the pixel irradiance is inversely proportional to the square of a lens's *focal ratio*, or f/number. The f/number is the ratio of the telescope's focal length to the diameter of its light-collecting aperture. For example, a 200-mm (8-inch) telescope having a 1,000-mm focal length has a focal ratio of 5, typically written as f/5. A camera lens having a focal length of 100 mm and its aperture stopped down to 20 mm is also f/5. To maximize the pixel irradiance, we should select a telescope with a low f/ratio (smaller f/ratios are photographically "faster" than higher ratios).

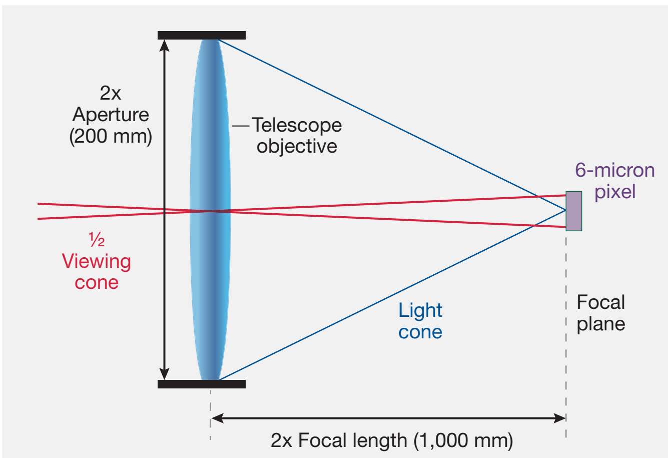
The area of a telescope's or camera lens's focal plane that can fully illuminate a detector is called the *image circle*. The diameter of the image circle is twice the distance from the telescope's optical axis to the edge of a flat area where the telescope can form an image of good quality. This area produces distortion-free star images, without too much illumination dropping off away from the center (known as *vignetting*, which can mostly be compensated for during image calibration). The number of properly illuminated pixels is proportional to the square of the image circle diameter. The image circle is the limiting factor in how large a detector will be useful with the chosen optic. For example, if you're considering a telescope that has a 20-mm-diameter usable image circle, it doesn't make much sense to pair it with a detector that's 24 × 36 mm — the outer portion of the image will display distorted stars that will only detract from the final result.

The table on page 64 compares the light-collecting power of several different optics. I've listed important features of four optical tube assemblies (OTAs) I currently own or have owned in the past, including their f/ratios, image-circle diameters, dimensions, and weights. For convenience, I've come up with a "figure of merit" (FOM), representing the light-collecting power of each OTA in question. I calculate the FOM by multiplying the image-circle diameter in millimeters by the inverse of the f/number, squaring the result to make the FOM proportional to the total light collectable by each OTA, and reducing the resulting number by the percentage blocked by the central obscuration, if any.

The numbers in the table are approximate, especially in relation to the image circle diameter, which is somewhat subjective as it depends on what constitutes an acceptable spot

▼ **SCALING UP** A telescope with a focal ratio of f/5 produces the same image brightness regardless of its aperture. For example, a 4-inch f/5 telescope will produce the same brightness of an extended object at its focal plane as an 8-inch f/5 optic. The difference will be the image scale — a given pixel at the focus of the 8-inch f/5 scope will see ¼ the field that the 4-inch optic does (in a viewing cone ½ as large) and provide higher spatial resolution when using the same camera in both instruments.





LEAH TISCIONE / S&T

size variation across the image circle and level of vignetting.

The Petzval refractor has the largest FOM, mostly due to its relatively large 88-mm image circle. A close second is an f/2 135-mm camera lens stopped down to f/4, which would easily have been the first if opened to its full aperture of f/2, where it collects 4 times more light. At f/2 the image circle is 43 mm, and its FOM totals 462 mm^2, which is the same FOM of any full-frame camera equipped with an f/2 lens. The lens is compared at f/4 because fast camera lenses nearly always fail to produce good star images at the very edges of the image circle when used wide open.

The table below illustrates that small refractors and camera lenses not only have excellent light-gathering capability as compared with larger reflectors and catadioptric telescopes, but they're also lighter and more compact. So why do many imagers use large, bulky reflectors and catadioptrics?

Resolving Power

The answer is image scale, or resolution. There just aren't many bright objects large enough to cover the field of view of a small astrograph. After a few years, you'll run out of interesting targets, at least those big enough and bright enough to take advantage of an expansive field of view with a moderate image scale. Fainter objects are more numerous but generally are too dim to image with the desired clarity and dynamic range, particularly if you're imaging under even moderately light-polluted skies. As far as camera lenses go, the range of suitable deep-sky objects is even narrower, being mostly limited to Milky Way vistas and a few large galaxies. As the resolution of an imaging setup increases, so does the number of viable targets. Not only will you be able to photograph many more small objects, but the larger ones can be shot at higher resolution and assembled into mosaics to produce very detailed panoramas.

So, how far should you go in your quest for resolution? Not as far as you might think. Atmospheric turbulence provides an upper limit on resolution. Even on the best nights, the "seeing" will limit the angular resolution to about 1 arcsecond, which is $^{1}/_{1,800}$th of the angular diameter of the Moon. No matter how good your telescope is, the smallest angular diameter of a star image it produces will be about 1 arcsecond. Typically, imperfect seeing, guiding errors, and optical aberrations may increase the size of star images to 2 to 3 arcseconds on a good night. In this context, a reasonable resolution goal is about 1 arcsecond per pixel, which leaves us with a circle of around 4 to 9 pixels per star image on most nights, which are still nice, small, round stars.

This brings us to another important consideration in deep-sky imaging — the pixel size of your detector. While this can be somewhat subjective, I prefer larger pixels of 5 to 6 microns to match the spot size of a telescope across a reasonable image circle. Different pixel sizes may of course be used, depending on your typical seeing conditions and the focal length of your optics.

The table at the top of the facing page lists the image scale of the OTAs using a detector with 6-micron pixels. Both tables reveal the major compromises inherent in small refractors and camera lenses compared to telescopes with larger

Optical Comparisons

Telescope / Lens	f/ratio	Image Circle Diameter	Central Obstruction	Figure of Merit	Size	Weight
f/2 135-mm lens at f/4	f/4	43	0%	116	3.5″ × 5″	2 lbs.
Petzval Refractor	f/5	88	0%	310	5″ × 17″	15 lbs.
10″ Newtonian with 3″ coma corrector	f/4.6	43	31%	79	12″ × 47″	29 lbs.
11″ Schmidt-Cassegrain	f/10	36	34%	11	12″ × 24″	29 lbs.
11″ Schmidt-Cassegrain with 0.7× reducer	f/7	36	34%	23	12″ × 28″	32 lbs.

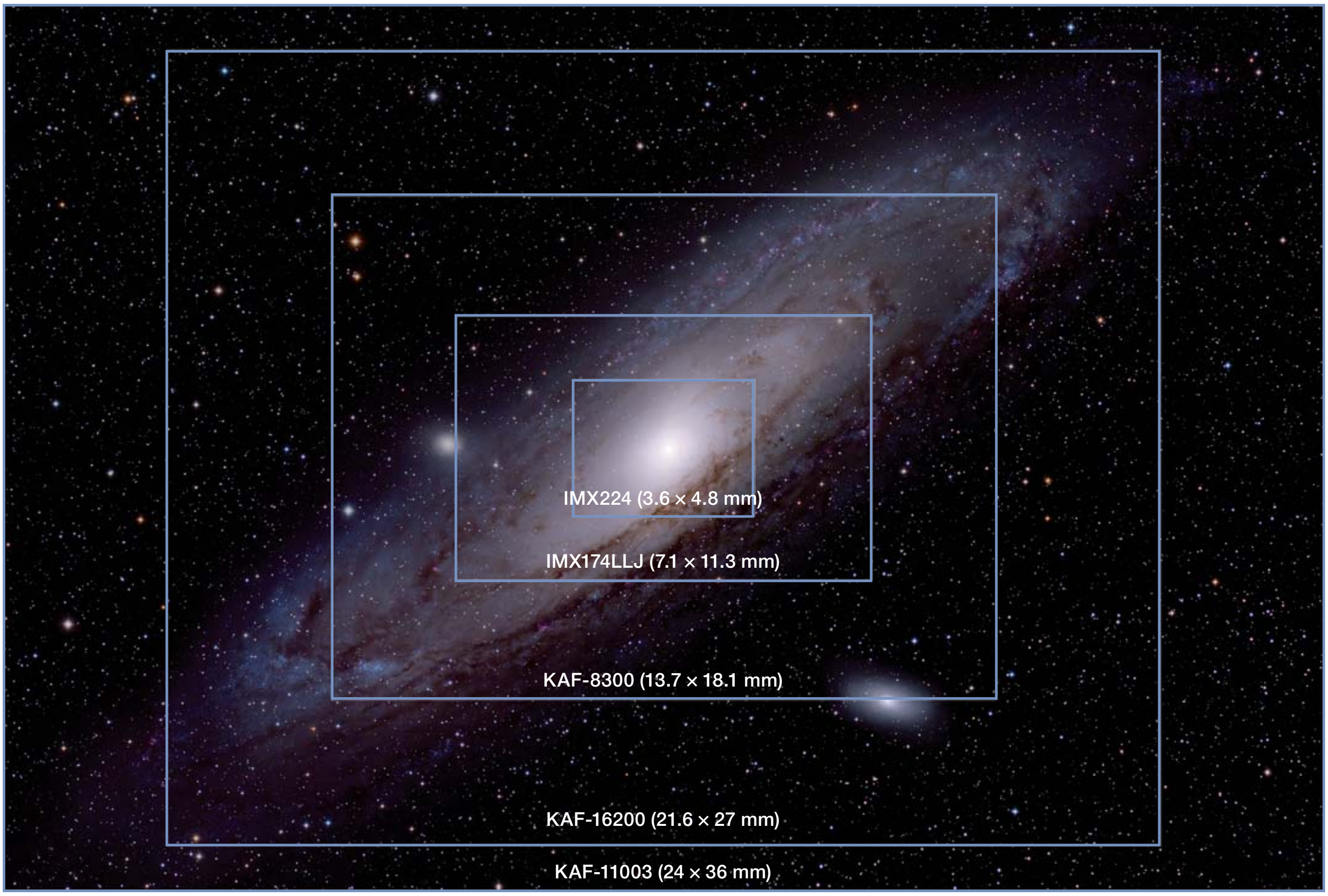
◀ **TOOLS OF THE TRADE** The author compared several optics, including, beginning at far left, a Rokinon 135mm f/2 camera lens, a Takahashi FSQ-106EDXIII refractor, a Teleskop Service 10-inch f/4.6 Newtonian, and a Celestron EdgeHD 11-inch Schmidt-Cassegrain with a focal reducer.

Optical Resolution with 6-micron Pixels

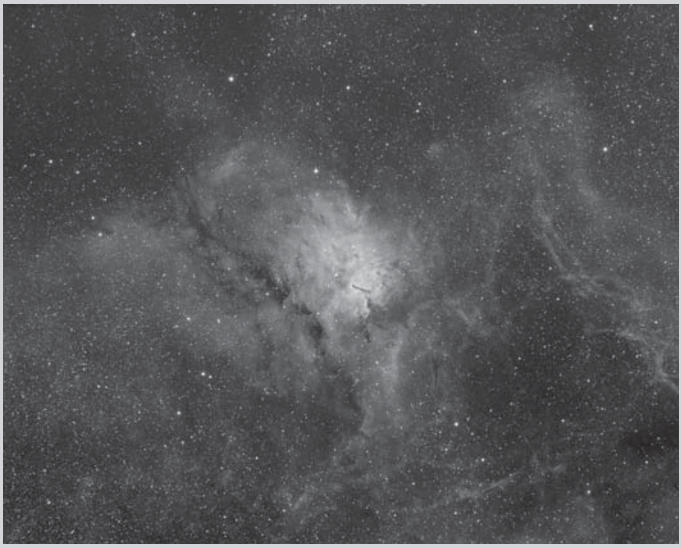
Telescope / Lens	f/ratio	Focal length (millimeters)	Arcseconds per pixel
f/2 135-mm lens at f/4	f/4	135	9.17
Petzval Refractor	f/5	530	2.34
10″ Newtonian with 3″ coma corrector	f/4.6	1,180	1.05
11″ Schmidt-Cassegrain	f/10	2,800	0.44
11″ Schmidt-Cassegrain with 0.7× focal reducer	f/7	1,960	0.63

apertures — one sacrifices resolution for improved light-gathering capacity and small size and weight.

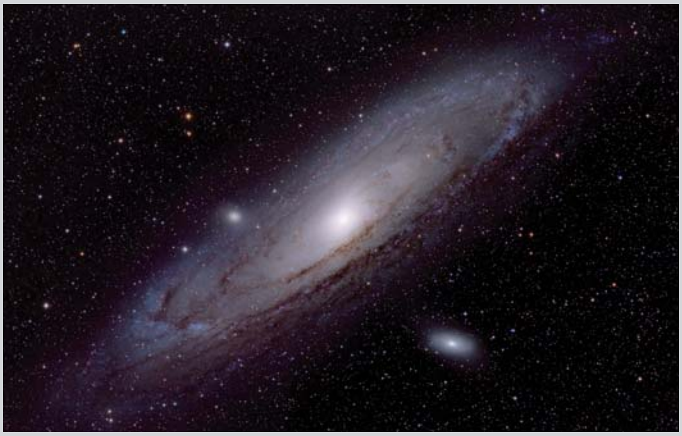
For example, by assuming 1-arcsecond resolution in a perfect scope under perfect weather conditions, a 135-mm camera lens sacrifices 9× the resolution because it has the image scale of 9 arcseconds per pixel, while the Petzval refractor sacrifices about 2× the resolution. Interestingly, the 10-inch f/4.6 Newtonian hits the target of 1 arcsecond per pixel while retaining decent light-gathering capability, albeit at a cost of having the longest optical tube of the bunch. On the other hand, the 11-inch SCT, even with its 0.7× focal reducer, has a light-gathering capacity several times less than



▲ **DETECTOR SIZES** Although it's best to match a detector to a telescope, if you're starting with a camera having a relatively small detector, it's a good strategy to purchase an astrograph with a large image circle. This gives you room to "grow" with the instrument by upgrading your camera at a later date, rather than having to replace both your camera and telescope simultaneously. This image of M31 in Andromeda recorded at 850 mm illustrates the field of view with several common image sensors.



▲ **SMALLER FIELDS** Both of these hydrogen-alpha images of NGC 6823 were captured with the same FLI ML16200M CCD camera, with the image at left recorded with the 106-mm f/5 refractor, while the image at right was captured using the 10-inch f/4.6 Newtonian. Although the Newtonian records about ¼ of the field of the refractor, it resolves finer details.



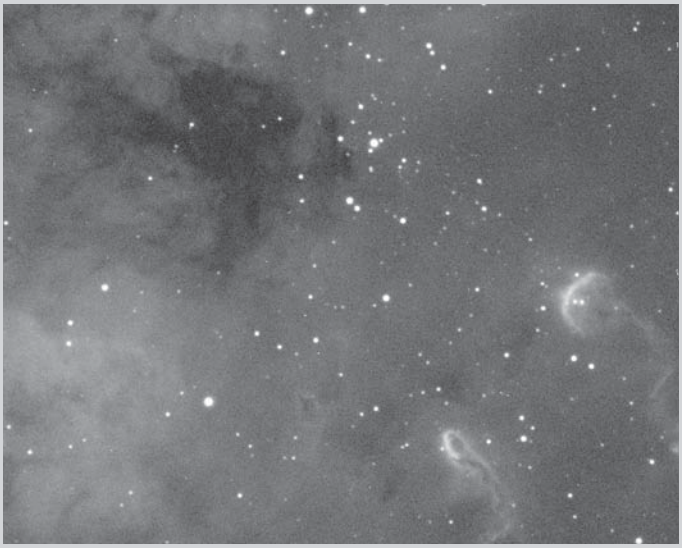
▲▶ **FOCAL LENGTH ADVANTAGE** Stepping up to a larger telescope not only permits you to shoot smaller objects to advantage, but it also allows you to revisit targets you recorded in the past and shoot them at higher resolution. Compare these images of M31 taken with an FSQ-106EDXIII at f/5 (above) and a close-up recorded with a 11-inch SCT at f/7 (right). The wide-field shot highlights the bluish outer arms of the spiral galaxy, while the high-resolution close-up focuses more on the dust lanes in the galaxy's inner regions.

that of the Newtonian's due to a narrower field of view. At the same time, it's as heavy as the Newtonian and doesn't yield a meaningful resolution gain, taking into account the atmospheric seeing limit of 1 arcsecond.

Can one reach the goal of 1 arcsecond per pixel with a small refractor by choosing a sensor with smaller pixels? While the idea looks attractive, this approach doesn't quite work. Due to the wave nature of light, in practical terms the spot size (star-image size) produced by a diffraction-limited OTA depends only on the instrument's f/ratio, and thus does not scale down as the OTA is scaled down at the same f/ratio. Too small a pixel can emphasize optical abberations in the scope. The end result is that scaling down both the telescope and the camera pixels while retaining the same focal ratio results in the inevitable loss of resolution.

Final Considerations

In short, a small, high-quality refractor is a great choice for imaging larger nebulae and a few nearby galaxies, but the number of available targets is small when compared to a

▲ **STRONGER SIGNAL** A large, fast astrograph lets you collect lots of signal in less time than a slower instrument can. These pictures of IC 410 in Auriga are both 30-minute exposures, but the image at left recorded through the 10-inch f/4.6 astrograph has noticeably less noise than the image to the right, shot with an 8-inch f/10 Schmidt-Cassegrain.

◀▲ **VARYING PERSPECTIVES** Some targets benefit greatly from several image scales. For example, the great extent of Comet NEOWISE (C/2020 F3) seen at left was best recorded with a 135-mm telephoto lens, whereas the inner regions on the coma (above) required shooting through a Celestron C8 Schmidt-Cassegrain.

larger telescope with a longer focal length. A fast telescope with a low f/ratio and a large image circle is preferable, because it collects more light in a shorter amount of time and offers the potential to upgrade to a camera with a bigger sensor — something becoming increasingly affordable.

You can start out in deep-sky astrophotography with a fast, wide-field refractor and, as you gain experience, step up to a larger, fast Newtonian telescope equipped with a coma corrector. Such a strategy enables you to begin imaging with a smaller detector or a full-frame DSLR or mirrorless camera, eventually moving up to a cooled astronomical CCD or CMOS camera. My preference is a fast Newtonian with good mechanics and a high-quality coma corrector. You can always step up to other types of telescopes, such as a corrected Dall-Kirkham (CDK) for example, which has the advantages of compactness and mechanical stability, but is usually not as fast as Newtonians.

■ **OLEG BOUEVITCH** images deep-sky objects as well as the planets from his home in suburban Ontario, Canada.

◀ PLANETARY IMAGING COMPENDIUM

Interested in studying the planets? Seven French planetary imagers have pooled their expertise in writing and presenting *Planetary Astronomy: Observing, Imaging, and Studying the Planets* (€59). The book details modern techniques for systematic observation and high-resolution imaging of the major planets in our solar system. The first chapters detail telescope designs for planetary observing and imaging, and include sections on fine-tuning your instrument and matching your camera to your telescope to produce the best results. Each major planet is discussed in its own section. Further chapters discuss software for image capture, frame stacking, and data analysis to help you produce accurate science. Available in French and English. Paperback, 8¼ × 11¾, 288 pages.

Planetary-astronomy.com

◀ ZOOM EYEPIECE

Orion introduces a new, widefield zoom to its eyepiece line. The Orion 7.2-21.6mm Zoom Telescope Eyepiece ($129.99) offers a wide range of magnification with a generous field. This 1¼-inch zoom provides a 42° apparent field of view at its low-power 21.6-mm setting, and an expansive 65° when at 7.2 mm. The eyepiece contains 7 multi-coated lens elements in 4 groups for exceptionally great eye relief (18 to 20 mm), allowing users with eyeglasses to take in the full field visible. The zoom eyepiece weighs 8 ounces (227 grams) and is threaded to accept standard 1¼-inch filters.

Orion Telescopes & Binoculars
89 Hangar Way, Watsonville, CA 95076
800-447-1001; telescope.com

◀ BIG DOBSONIAN

Meade Instruments has added to its popular LightBridge series of Newtonian reflectors with a newly updated 16-inch model. The LightBridge Plus 16″ is a f/4.5 Newtonian reflector with a 1,829-mm (72-inch) focal length. The assembled telescope weighs 144 lbs (65 kg) and features tool-free assembly throughout. Its redesigned Dobsonian base incorporates roller bearings on the azimuth axis and a hand-adjustable, variable-tension brake for smooth movements in both axes. The LightBridge Plus 16″ includes a 2-inch, dual-speed, rack-and-pinion focuser with 1¼-inch adapter. Each unit comes complete with a plastic primary mirror cover, a multi-reticle unit-power finder, and a 2-inch, 26-mm Series 4000 eyepiece.

Meade Instruments
27 Hubble St., Irvine, CA 92618
800-626-3233; meade.com

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

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SB

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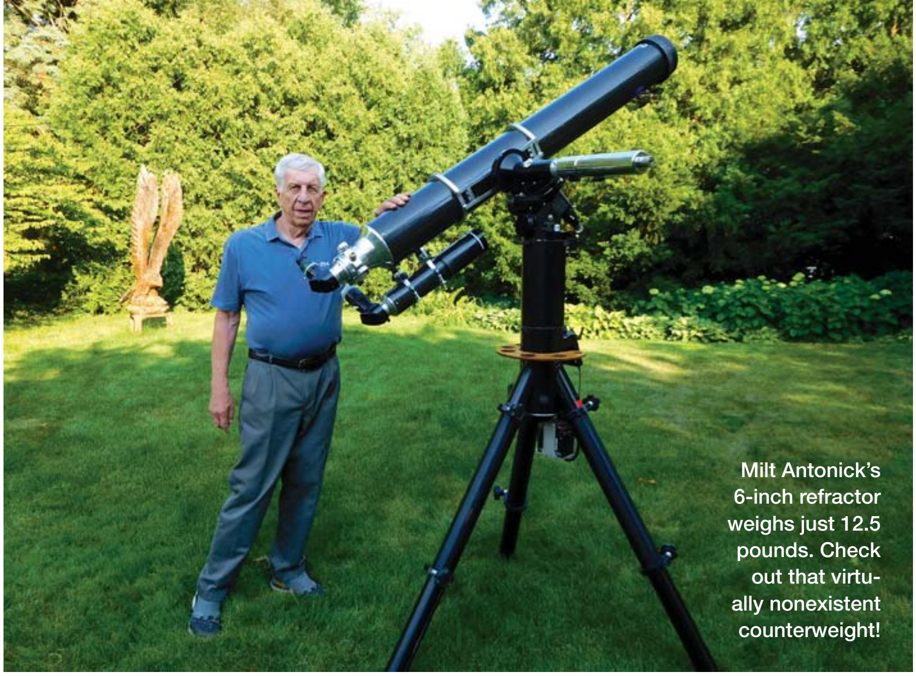
A 6-Inch Carbon-Fiber Refractor

For its size, this scope is surprisingly light and portable.



Milt Antonick's 6-inch refractor weighs just 12.5 pounds. Check out that virtually nonexistent counterweight!

MICHIGAN AMATEUR ASTRONOMER Milton Antonick got his start with a traditional 8-inch Dobsonian, then graduated to a 6-inch Maksutov-Newtonian, which he used to complete a three-year study of the Messier objects. But the latter takes up to an hour to thermally stabilize after setting it up and is difficult to collimate.

Milt wanted a scope that had minimum set-up time, minimum cool-down time, and no need to collimate it in the field. The latter requirement suggested a refractor, and after viewing through several of them he decided to build one. He wasn't quite up to grinding his own lenses, so he bought a 6″ lens set from D & G Optical (**dgoptical.com**), but the rest is all his own.

Milt sketched out the scope body using *Alias* software tools, determining the scope's dimensions, baffle placement, focuser, drawtube length, etc. He did the actual machining manually, however, using a 6″ lathe, a drill press, a mill combo, and a band saw. (Milt says he's not a machinist, but I beg to differ.)

The focuser is made of T-6 aircraft aluminum. The forward section started out as a 7″-diameter-by-3″-long billet that Milt turned on the lathe, reducing it down to ⅛″ wall thickness with a stepped section on the inner slope. He machined the rear section from a similar block to tight tolerance, then shrunk-fit together the two pieces by placing the forward section in boiling water while icing the rear section and lowering it into the expanded outer section. They're as tight as a single piece now.

The drawtube required a flat section for the drive axle (a stainless-steel rod), which Milt accomplished with his mill combo. The cavities for the bearings required some precise machining as well. Milt used six bearings, four holding the drawtube in the traditional Crayford fashion and two around the drive axle. The drawtube bearings are adjustable for collimation.

The focuser is a machining masterpiece. That required a tube to match, which meant carbon fiber. Here's where Milt ran into his first major hitch: At f/12 the tube needed to be 60″ long, but the largest carbon fiber roll is 56″. Milt used a 6″ plastic drainpipe for a mandrel, with three plywood disks stuffed inside it to make it round. That was too small a diameter for a 6″ aperture, though, so Milt wrapped the pipe with Mylar drafting sheets to achieve the required diameter of 7″.

Then he wrapped the tube with carbon fiber, using two lengths of material held together with black photo tape. He laid the carbon fiber out on a granite table and rolled the mandrel along the material, applying epoxy with a roller as he went. Incredibly, he only needed four wraps to create a rigid tube. The wall thickness is only 1 mm! (That's about

▶ The focuser is machined from solid aluminum blocks. The bearings (seen here with the housing removed) required precision machining and are adjustable for collimation.
▶▶ Like the OTA, the 80-mm finder is also made from carbon fiber.

MILTON ANTONICK (3)

JOSEPH TOCCO

▲ Milt's big refractor is a big hit at star parties.

the thickness of automobile sheet metal.)

This approach worked okay, but Milt says if he had to do it again, he would use a diagonal wrap and not use a drainpipe. Even with the plywood rings inside, the pipe was out of round enough to be difficult to remove.

The three internal light baffles were also made with carbon fiber, which allowed them to be sanded to razor-sharp edges. Milt painted the entire interior with Krylon Ultra Flat Black spray paint.

Milt also made a carbon-fiber lens cell, but he says, "I would put this operation on the 'not to do again' list, as the carbon fiber dust created while machining is difficult to contain." The lens cell is also adjustable for collimation, so together with the focuser adjustments he was able to get the optics perfectly aligned.

Milt made the finder out of carbon fiber as well, using Orion 80-mm optics, a 2″ diagonal, and a 40-mm eyepiece with his own crosshairs added. Both the finder and the telescope proper include heating elements on the lenses to prevent dew.

Thanks to its extremely thin OTA, the entire setup weighs an incredibly low 12.5 pounds. Check out the counterweights on Milt's equatorial mount. They're practically nonexistent!

Milt is extremely happy with this scope, and so are the people who look through it at the star parties he takes it to. If they're like me, they'll spend as much time looking at this beautiful work of art as they spend looking through it.

For more information contact Milt at **mantonick36@gmail.com**.

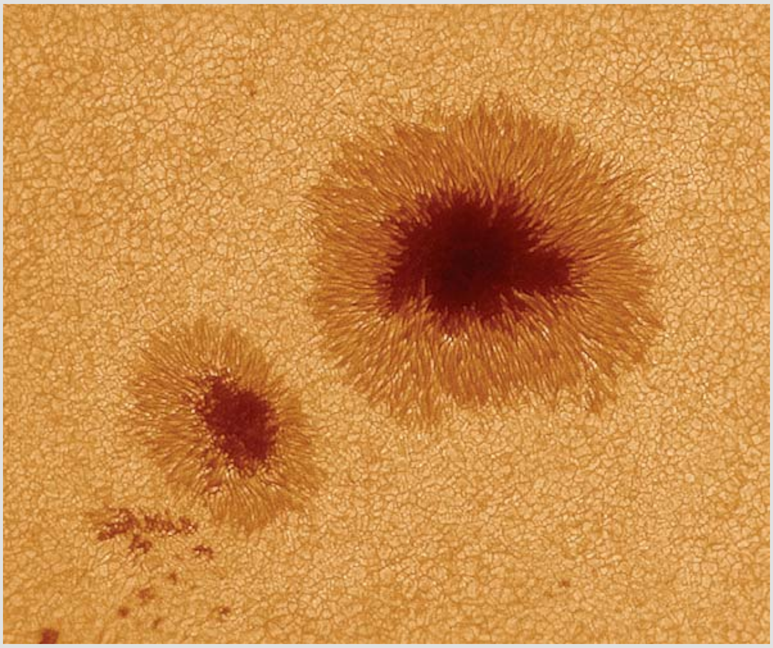
■ Contributing Editor **JERRY OLTION** thinks telescopes are a perfect form of carbon sequestration.

▷ SOLAR MANES

Leo Aerts

Penumbral filaments surrounding sunspots in group AR 12674 resemble two lions' manes in this high-resolution image recorded on September 3rd, 2017.

DETAILS: *Celestron C14 Schmidt-Cassegrain with ZWO ASI174MM video camera. Stack of multiple video frames through Baader AstroSolar Safety Film.*

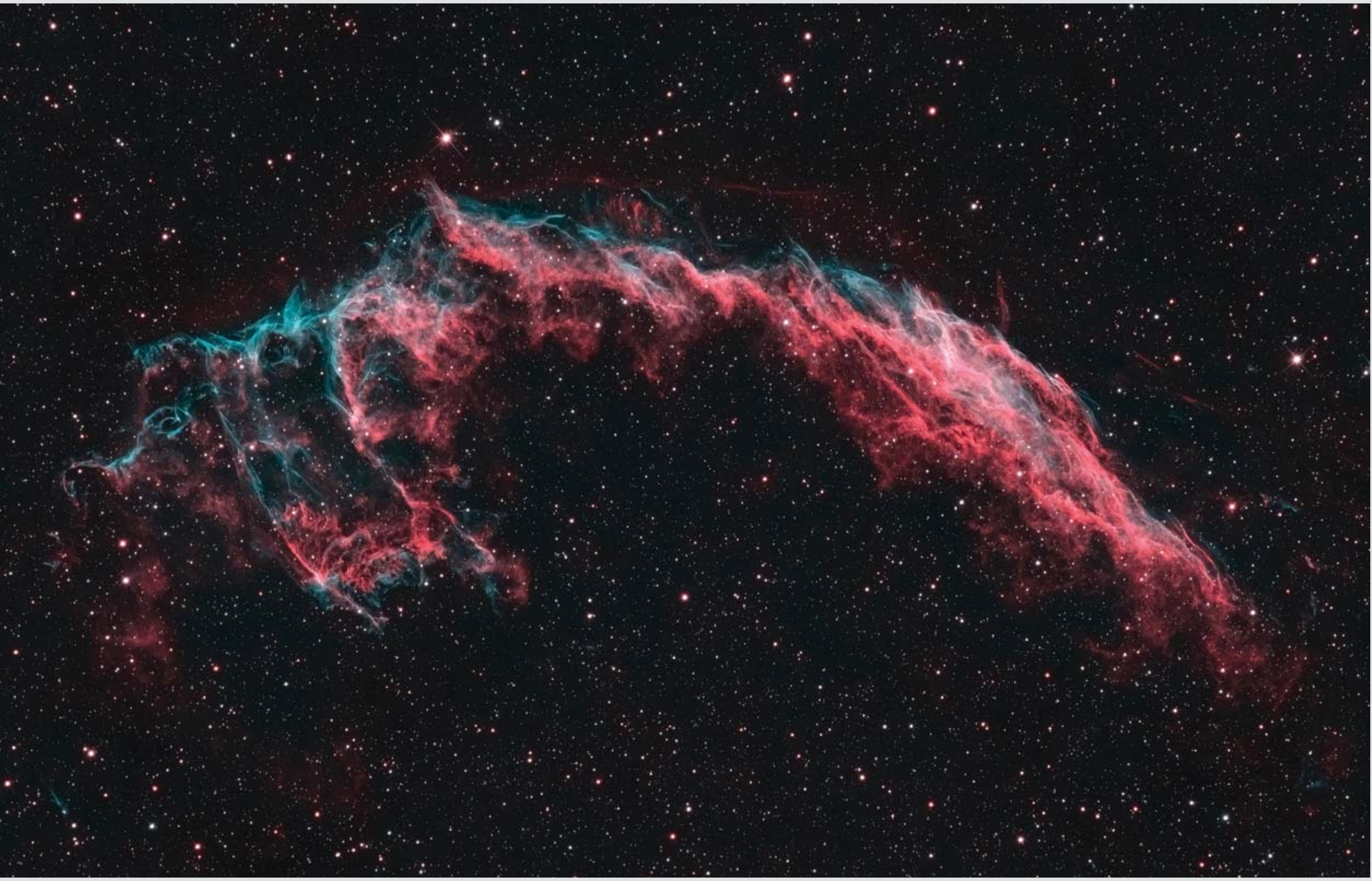


▽ THE EASTERN VEIL

Greg Polanski

NGC 6992 is the brightest portion of the Veil Nebula in Cygnus and displays teal and reddish filaments in this narrowband composite image. North is to the right.

DETAILS: *Sky-Watcher 150-mm Newtonian reflector with QHY163M CMOS camera. Total exposure: 11½ hours through Hα and O III narrowband filters.*



WINTER NEBULOSITY

Brian McVeigh

This expansive mosaic contains a cascade of large nebulae, including (from top) IC 405 and IC 410, Simeis 147, Sh 2-264 (center), and Barnard's Loop surrounding the Orion Nebula at bottom. To the right of Orion's Belt is the greenish Comet ATLAS (C/2020 M3).

DETAILS: *Nikon 50-mm f/1.8 lens with ZWO ASI1600MM Pro CMOS camera. Eight-panel mosaic, each panel consisting of approximately 4.5 hours of exposure through Hα and RGB filters.*

▷ A PETAL SET ADRIFT

Douglas J. Struble

Sharpless 2-112 is a faint emission nebula in Cygnus located roughly 1½° west-northwest of Deneb. It bears a striking resemblance to a wilting rose dropping its petals in this narrowband composite image.

DETAILS: *Explore Scientific ED165 FPL53 refractor with ZWO ASI1600MM Pro CMOS camera. Total exposure: 19 hours through narrowband filters.*

▷ MESSIER 22

Ron Brecher

At magnitude 5.1, M22 in Sagittarius is one of the brightest globular clusters visible from mid-northern latitudes. Keen-eyed observers under extremely dark skies can spot this dense cluster without optical aid by looking just above the "lid" of the teapot asterism.

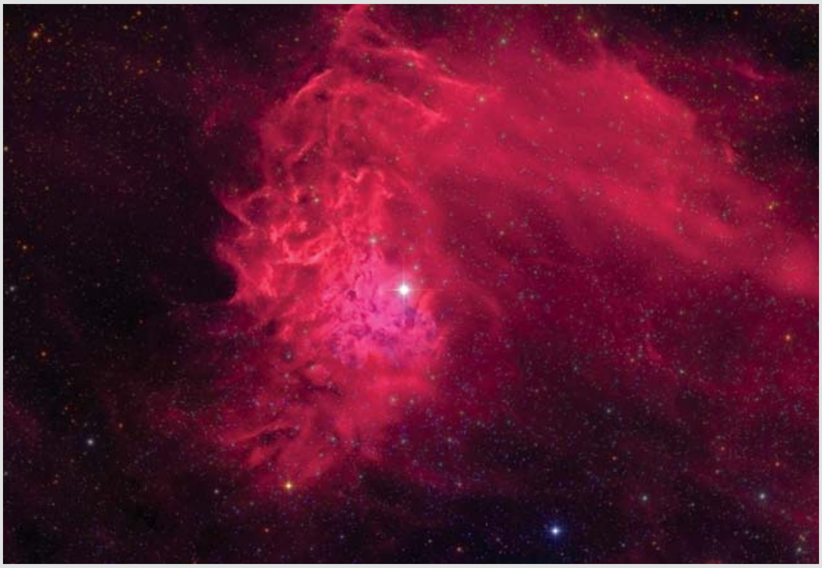
DETAILS: *ASA 10N Newtonian astrograph with SBIG STL-11000M CCD camera. Total exposure: 2⅓ hours through RGB filters.*

▷ THE FLAMING STAR

Wanda Conde

Emission nebula IC 405 in Auriga surrounds the 6th-magnitude star AE Aurigae. The dust closest to the star produces a bluish reflection nebula, which, combined with the surrounding reddish hydrogen nebulosity, led astrophotographers to dub it the Flaming Star Nebula.

DETAILS: *Orion ED80T CF refractor with ZWO ASI1600MM Pro CMOS camera. Total exposure: 9.2 hours through color and hydrogen-alpha filters.*

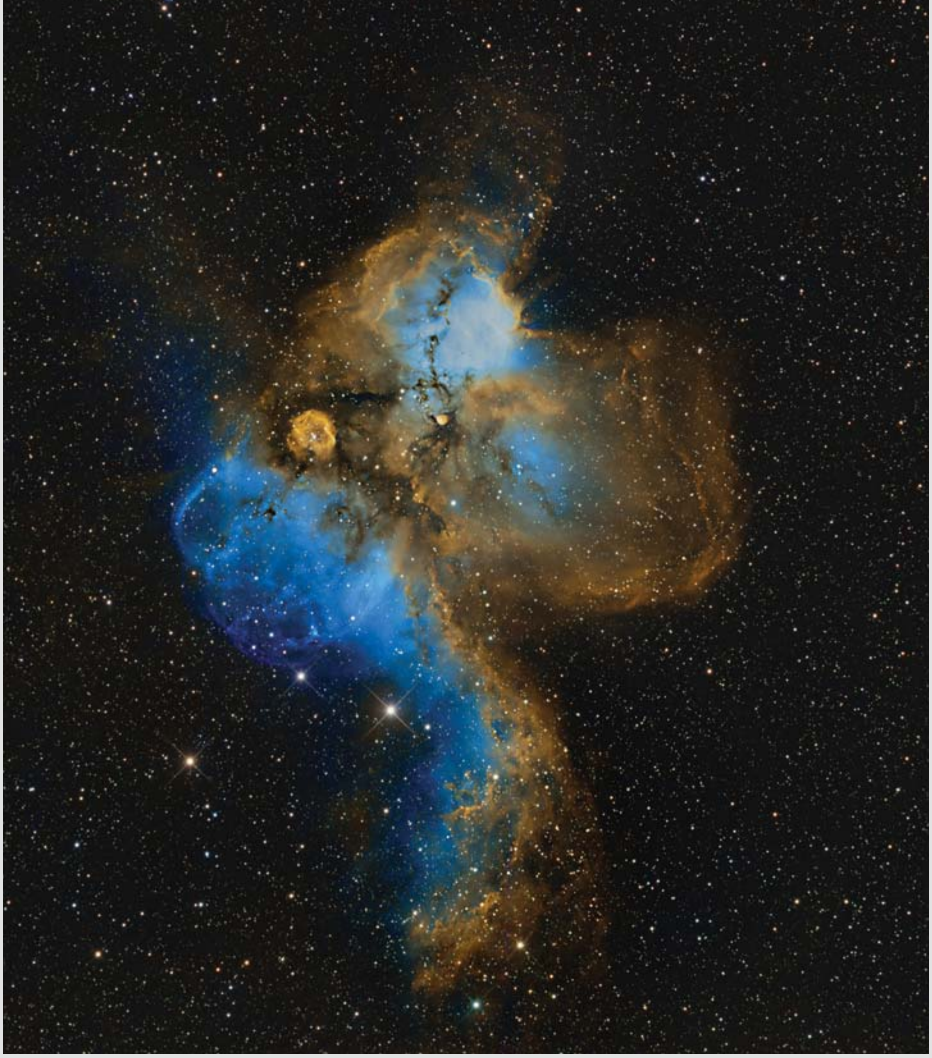


△ HOOKED ON VOLANS

Dan Crowson

The Meat Hook Galaxy, NGC 2442 and NGC 2443, is a distorted spiral in the southern constellation Volans. Other galaxies visible include PGC 21457 (center left), the faint dwarf PGC 21406 (top left), and the elliptical NGC 2434 (top right).

DETAILS: *PlaneWave CDK24 corrected Dall-Kirkham telescope with SBIG STF-8300M CCD camera. Total exposure: 6 hours through LRGB filters.*



▷ JOLLY ROGER

Michael Paling

NGC 2467 in Puppis is a highly active stellar nursery filled with gas and dust that bears a striking resemblance to the skull and crossbones often depicted on pirate flags. North is to the left.

DETAILS: *ASA 500N Newtonian astrograph with FLI PL16803 CCD camera. Total exposure: 3½ hours through color and narrowband filters.*

▽ PAS DE DEUX

Mark Killion

During the Great Conjunction of Jupiter and Saturn on December 21, 2020, observers the world over were able to see both gas giants in a single, high-power view. This stunning composite also features Jupiter's four Galilean moons and Saturn's moon Titan.

DETAILS: *Takahashi Mewlon 250CRS Dall-Kirkham telescope with Canon Ra Mirrorless camera. Stack of 16 exposures at ISO 100 and ISO 800.*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TOTALITY OVER PATAGONIA
Guillermo Abramson
The large, curved area in the solar corona at lower left is a coronal mass ejection that was visible along with several bright solar prominences during the total solar eclipse of December 14, 2020.
DETAILS: *Canon T3i DSLR with 18-to-270-mm zoom lens. Stack of 11 exposures ranging from 1/250 to 1 second.*

QUADRANTID FIREBALL
Abhijit Patil
A bright bolide streaks over a snow-laden scene in Maine on the morning of January 3rd.
DETAILS: *Nikon D750 DSLR with 14-to-24-mm zoom lens at f/2.8. Total exposure: 20 seconds at ISO 800.*

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


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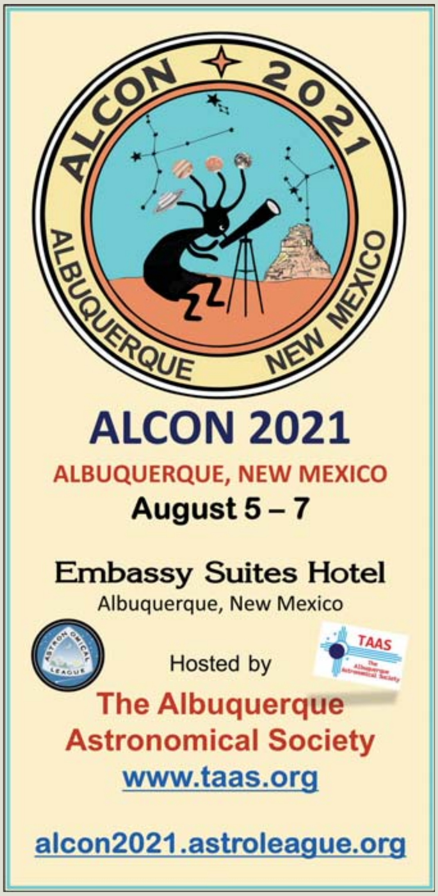

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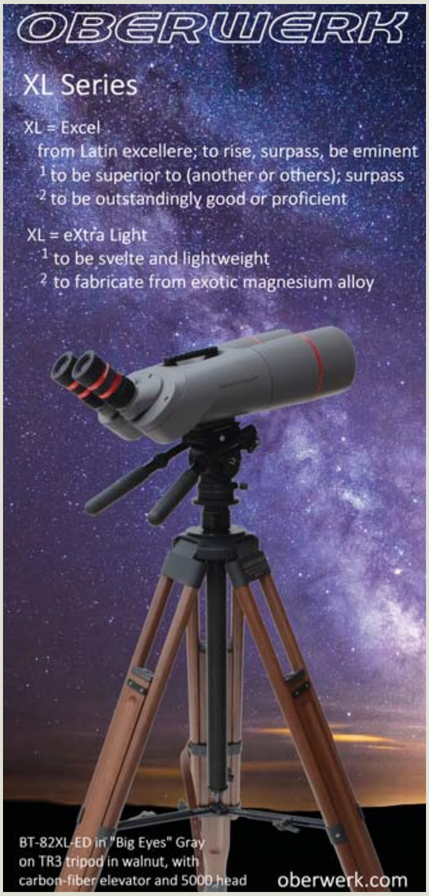

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AD INDEX

"Here, Dad, Take a Look"

I really didn't think stargazing with my son one night would bring me almost to tears.

THE SIGHT AND SOUND stopped me in my tracks. There was my 20-year-old son, lining up my Celestron CPC 925 to find Saturn in the eyepiece. When he said those five simple words above, it brought back a surprising flood of memories, both of my father and my own journey as an amateur astronomer (emphasis on amateur).

Growing up in Houston during the Apollo era, I learned to love the night sky at a very young age. Johnson Space Center's proximity made it a regular destination of school field trips.

Soon after one such excursion, I stood in our front yard and stared at the Moon *hard* during the Apollo 16 mission. My dad came out to collect me for dinner, and I told him I thought I could almost see the astronauts up there, walking around. He gently pointed out that not only could I not see them, but no telescope was powerful enough to find them. They were just too small and too far away.

I remember being struck by that sense of scale and distance, and I knew then, sharing that moment with my dad, that my adult life would definitely consist of exploring the night sky. Of course, it didn't, not in a professional sense anyway.

By the time I was 15, I'd saved enough money to buy my first telescope, an Edmund Scientific Astroscan 4½-inch reflector that I still own. A friend of mine thought a telescope could look like many things, but not a little red ball with a cylinder sticking out the side. He called it bogus and gave it the name "Bogeyscope," which made both my dad and me laugh.

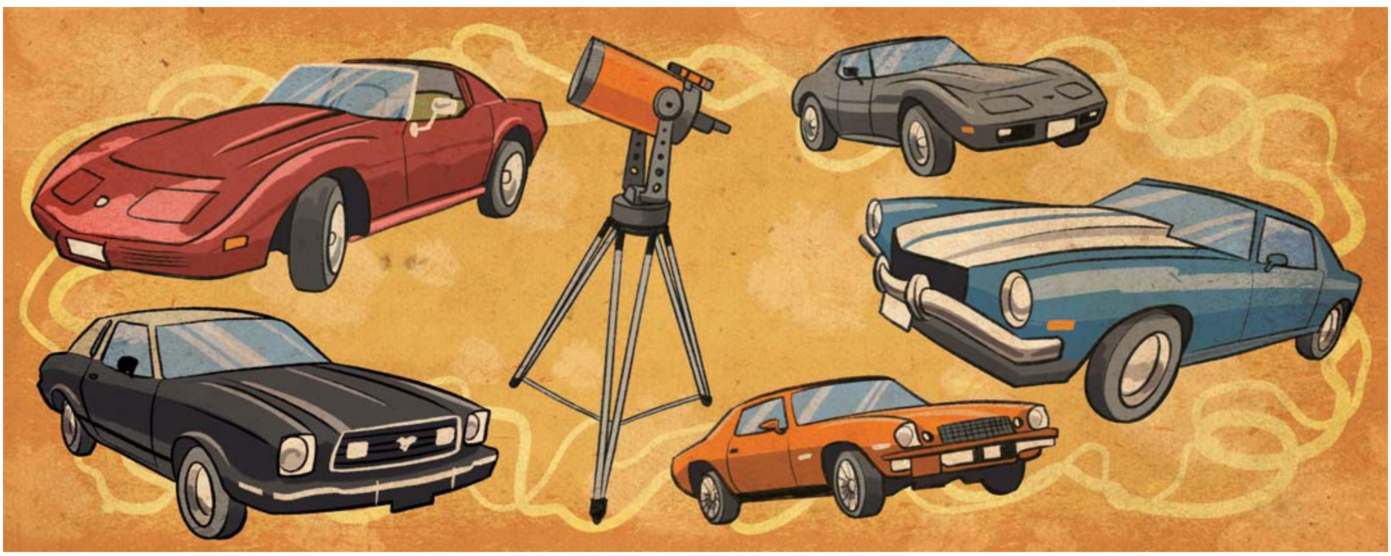
Boy, did I ever love touring the sky with that Bogeyscope. The ultimate dream, though, was a Celestron C8. Its bright orange tube filled my dreams the way Mustangs, Camaros, and Corvettes filled those of my friends. To be fair, I dreamed of those, too. When it comes to dreams, why stop at one?

The C8's price tag was well beyond my odd-job income. My parents ("A thousand dollars for a telescope?!") had doubts about how well I'd take care of it, which I admit were probably well-founded.

My father, however, loved looking in the Bogeyscope with me. One time I lined up the eyepiece on Saturn, turned, and said those same words my own son would say to me 40 years later. I can still remember my dad crying out "Whoopee!" when he saw Saturn's rings. "There they are," he said excitedly. "They're right there. I never thought you'd be able to see them with this little thing."

My recent observing session with my son brought me full circle to that long-ago night. I never did get that C8, instead "settling" on a slightly grander CPC 925. My parents are no longer with us, but I like to think they would have been happy indeed to see their grandson turn to their son and call him over with that same irresistible invitation: "Here, Dad, take a look."

■ **MARTIN HAJOVSKY** is a freelance writer, former *Houston Chronicle* editor, and author of *Humans in Space*, a space-focused reader for students of ESOL (English for Speakers of Other Languages). He lives in Houston, Texas.



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Milky Way at Stellarvue Dark Sky Star Party. Image by Tony Hallas.