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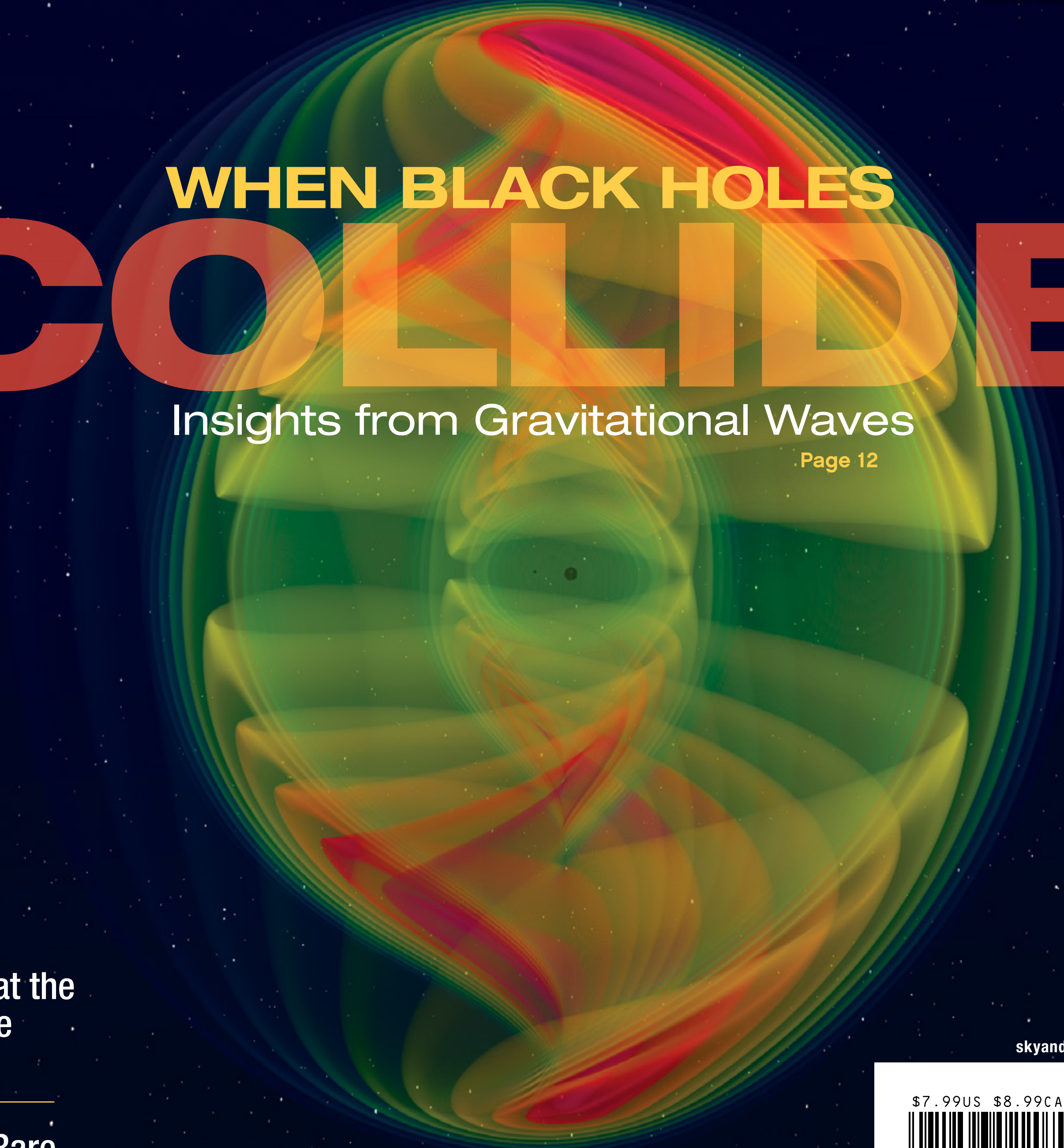
SKY & TELESCOPE

THE ESSENTIAL GUIDE TO ASTRONOMY

JUNE 2022



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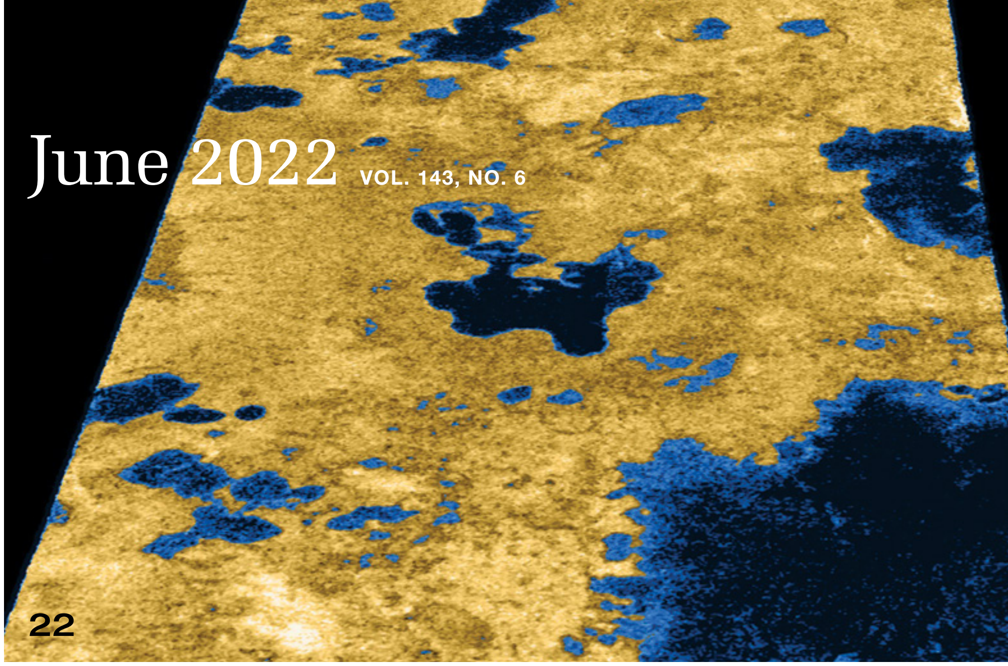
June 2022 VOL. 143, NO. 6



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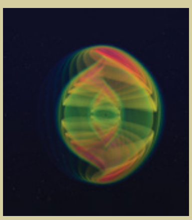

Simulation of event GW190412 just before the merger

N. FISCHER ET AL. / SXS COLLABORATION

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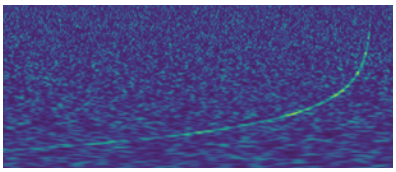
Mind the Gap

GRAVITATIONAL-WAVE ASTRONOMY, the science behind our cover story this month, has many amazing aspects: That we can actually detect these Einstein-predicted ripples in spacetime. That they arrive at our detectors from billions of light-years away. That they open a whole new window on the universe, allowing us to "hear" events that are unseeable, like the merging of two black holes.

To me, the most amazing thing of all is the almost unimaginable gap between the magnitude of the events observed and the magnitude of the gravitational-wave signal we receive at our detectors. (For details on the super-sensitive instruments, including LIGO and Virgo, that catch these waves, see *S&T:* Feb. 2018, p. 32.) The phenomena that trigger gravitational waves are some of the most energetic in the universe. Yet the notice we get of these inconceivably violent affairs makes "brief, short, and faint" sound overstated.

That's not hyperbole. The first convergence of two black holes ever detected — on September 14, 2015 — generated a signal at the LIGO detectors that lasted just two-tenths of a second. And while those two black holes each contained roughly 30 times the Sun's mass, the change in distance between the LIGO mirrors that their union caused — and that scientists measured — was equivalent to altering Earth's orbit around the Sun by the diameter of a hydrogen atom.



▲ Spectrogram of "chirp" showing gravitational waves (greenish line) rising in frequency as two neutron stars merge

LSC / ALEX NITZ

As for sound, we "hear" the echo of these wildly powerful astrophysical episodes as mere *chirps*. That's the term scientists use, because that's what the signals sound like when converted to audible frequencies we can hear. Have a listen at **https://is.gd/LIGOchirp**.

It's extraordinary enough that scientists can tease those ultra-truncated, deeply hushed signals out of the dominant "noise" at their detectors. But what they learn from that chirp is equally stupendous, as Camille Carlisle outlines in her feature article on page 12. They can gauge the event's distance and its rough location in space. They can tell what kind of merging entities spawned the event — whether two black holes, two neutron stars, or one of each. They can determine how massive the objects were before they coalesced, and how massive the resulting behemoth was.

Finally, or I should say firstly, that tiny blip tells them how much the passing gravitational waves distort spacetime. That is, how much the waves released by these colossal collisions engender tiny stretches and compressions in the coordinates describing the spacetime.

Mind the gap indeed!

Peter

Editor in Chief

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The Essential Guide to Astronomy

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▲ This Evening Venus Tour tracks the bright planet from July 2005 to January 2006. Venus followed the same path in 1997 and 2021.

Evening Venus Tour

As soon as I opened to David Grinspoon's article "Many Happy Returns" (*S&T:* Jan. 2022, p. 12), the familiarity of it struck me. Following the motion of Venus' position in the evening sky is one observing project I have always enjoyed, nearly as eagerly as Mars retrogrades. I call them "Evening Venus Tours."

My first acquaintance with an Evening Venus Tour was back in 1992, when Venus shone in the evening sky from late summer 1992 until the end of March 1993. The motion had a wide range of azimuth and altitude in the western sky, which I then tried to plot on paper using desktop planetarium software. That shape had looked familiar, too, because I remembered seeing it in an older magazine, which plotted the Evening Venus Tour of 1984-85. This 8-year repetition must be a thing, I thought at the time. I continued to plot the next few years on paper. It was nice to see how different the shapes could be.

Back in 2000, I decided to photograph the repeat of my first attempt at this from 1992-93. I frequently visited the terrace of the physics department at Middle East Technical University in Ankara, Turkey, to position my camera with a fisheye lens from September 2000 until March 2001 to photograph Venus when the Sun was 7° under the horizon. The weather in autumn and especially winter was tricky to get around. But I was really pleased with the result. It was a much better-looking version of my first plot from 8 years earlier.

My second such Evening Venus Tour project was between May 2005 and January 2006, which I photographed from the rooftop of our apartment building in Bursa, Turkey. The result was the same as the one depicted in Grinspoon's article (and my 1997-98 plot). I have also photographed the remaining three types of Evening Venus Tours.

Venus also repeats different shapes in the morning sky. Of course, observing or photographing them requires one to be an early riser or a morning person.

Tunç Tezel • Bursa, Turkey

The Comba-Windolf Telescope

I'm a longtime subscriber to *Sky & Telescope* and pretty much read every issue cover to cover. I enjoy Roger Sinnott's 75, 50 & 25 Years Ago and always try to see if I can remember any of the showcased articles. While reading this department in the January 2022 issue, the quote from the January 1997 issue, "CCD Charm," brought back many memories of my Cookbook CCD camera and the CCD revolution.

What really caught my attention, though, was the part about Paul Comba, his 18-inch (46-cm) reflector, and the asteroids he discovered with it. That 18-inch JMI NGT-18 is currently at home in the Planetary Studies Foundation's Doug Firebaugh Observatory in Freeport, Illinois. It's our largest telescope and provides beautiful images for visitors to the observatory. Planetary Studies Foundation Executive Board member Herbert Windolf, who was a friend of Paul Comba, purchased the telescope in 2010 and donated it to the Planetary Studies Foundation. We've named it the "Comba-Windolf Telescope." Explaining the history of this telescope has been part of our introductory presentations on public observing nights since 2010. When I read this article, it brought a big smile to my face just thinking about how this telescope continues to provide learning and enjoyment.

Jim Dole
Co-director, Doug Firebaugh Observatory
Freeport, Illinois

The Ambassador Grandparent

The schism between bright young minds interested in astronomy and club membership and outreach, as described by Max Corneau in "Fanning Sparks" (*S&T:* Sept. 2021, p. 84) and as discussed in the letters it inspired (*S&T:* Feb. 2022, p. 7), is not only an American phenomenon. As an expat living and conducting business in Mexico for 50 years, I believe the problem is worldwide, or at least just as relevant in Latin America as it is in the United States.

Since 2018, I have been an active member of Clavius, an astronomy club in Mexico City with an outstanding weekly program. One of my personal motives is to prepare myself to do effective outreach on STEAM-related subjects and activities with my four children and 13 grandchildren. Science is a marvelous channel of communication, which easily overcomes the enormous differences in worldview that separates three generations.

I organize star parties, Moon watches, and solar shadow sequence analyses for them and their friends to enjoy, and we also watch and discuss documentaries together. I do astrophotography, spectroscopy, and photometry on my own and show my

TUNÇ TEZEL

grandchildren. They also love stories, from the Greek mythology portrayed in the constellations to anecdotes about famous astronomers.

Coming back to Corneau's dilemma, I believe the grandparent can be an important ambassador between young people and astronomy clubs. But grandparents must understand that the objective is passing on the content and the passion, not just pursuing their own satisfaction.

In this effort, the thrust should be on hands-on discovery more than on just popular knowledge. The question and the quest are sometimes more illustrative than an answer or an established fact. This can help wake the scientist in each one of us, even when we realize that the data-gathering process and analysis may be flawed.

I hope to see more on this fascinating subject in future issues of *S&T*.

Patrick Kavanagh
Huixquilucan, Mexico

Illuminating Illustrations

While there is always so much to enjoy and admire in each issue of *Sky & Telescope*, I was particularly struck by the invaluable diagrams and graphs that accompanied Govert Schilling's article "Untangling the Cosmic Web" (*S&T:* Jan. 2022, p. 34). This very well-written article (as is all *S&T*'s content!) presented material that was new to me and that I found difficult to grasp through the text alone. But the illustrations illuminated the text beautifully, clarifying and visualizing the physics-heavy content, which is so outside my own realm of expertise. I hope you'll convey to the gifted artists that provided those invaluable illustrations — who are obviously fluent in both science *and* art — my sincere appreciation for their outstanding work.

John Neal
Greene, Maine

Highlighting Binocular Highlight

Thank you for your monthly column Binocular Highlight. After I purchased my first issue of *Sky & Telescope* for an astronomy class years ago, it's what got me to subscribe and keeps me hooked. I was worried when Gary Seronik left, but Matt Wedel has done an outstanding job. I also appreciate his more detailed pieces. In fact, I'm currently reusing his "Open Clusters Galore" article on Perseus and Auriga (*S&T:* Jan. 2018, p. 60). I enjoy my 8-inch (20-cm) Dobsonian, but my binoculars get more use.

Mark O. Rudo
Novato, California

FOR THE RECORD

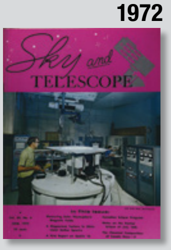
• The nebula sharing the frame with the Horsehead Nebula in the photo on page 55 of the April issue is NGC 2023.

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

1947

1972



1997

◖ June 1947

Star Photo #1 "Although the Great Refractor was in no sense a photographic instrument, it is this telescope that has the distinction of having taken [in 1850] the first picture of a star. The star was Vega in the constellation of Lyra, and a wet daguerreotype plate was used . . . In the words of the Bonds, 'we were encouraged to hope that the way is opening for further progress. If it should prove successful when applied to stars less brilliant than Alpha Lyrae, so as to give correct pictures of double and multiple stars, the advantage would be incalculable.' How little did these pioneers in astronomical photography foresee to what limits we would go in the years to come!"

Writing on the 100th anniversary of 'first light' with Harvard's 15-inch refractor, Leon Campbell paid tribute to this telescope and the observatory's first two directors, William C. and George P. Bond.

◖ June 1972

Abiogenesis? "On February 8, 1969, a great shower of stones fell in a 100-square-mile area in northern Mexico, centered on the town of Pueblito de Allende . . . Within five months more than two tons of specimens were collected, presumably from a single large meteoroid that broke up in the earth's atmosphere. . . .

"In one test, part of this material was vacuum distilled at red heat to yield a small amount of yellowish liquid. The absorption spectrum of the distillate showed that it was formaldehyde (CH_2O) . . .

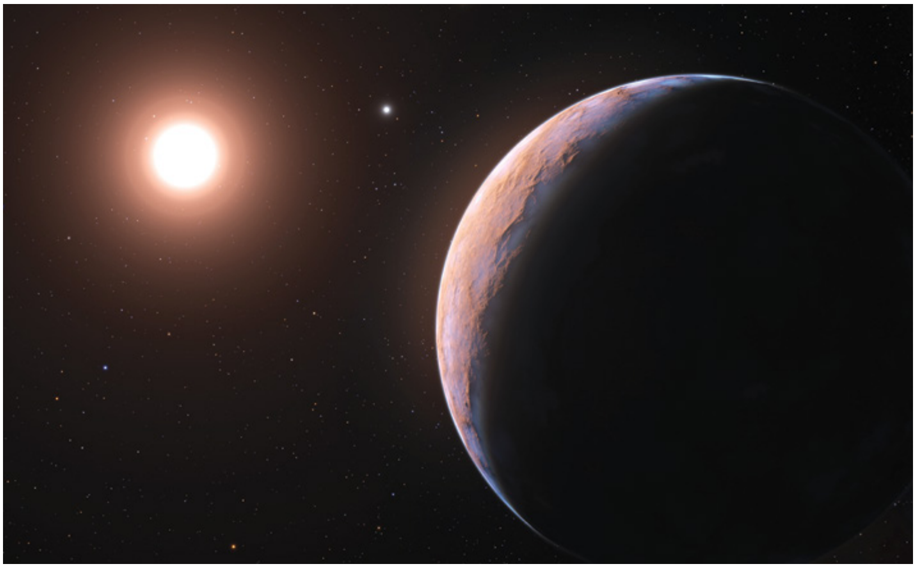
"Apparently this is the first record of formaldehyde in a meteorite. [So] it now appears that such prebiological materials as the amino acids and formaldehyde can be distributed through space by meteorites and, on landing upon a friendly body, can serve as the precursors of life . . ."

◖ June 1997

Cometary Bonanza "Not since 1957, when comets Arend-Roland and Mrkos blazed across the heavens less than four months apart, have astronomy enthusiasts enjoyed such back-to-back cometary spectacles. And those two were only 1st magnitude. Comets Hyakutake (C/1996 B2) and Hale-Bopp (C/1995 O1) gave their greatest performances exactly a year apart. Peaking at about magnitudes 0 and –1, respectively, they outshone everything in the night sky except the Moon and the brightest planets and stars. . . .

"Unlike Hyakutake's naked-eye show, which lasted only a few weeks, that of Hale-Bopp has already spanned several months and as of early May could still be going strong. [It] remained a splendid naked-eye object throughout April, conveniently placed in the northwest to west-northwest after dusk. A large fraction of the human race undoubtedly witnessed it."

As one lucky enough to have seen all four comets, I fully support Edwin L. Aguirre's synopsis.



▲ An artist's concept shows Proxima Centauri d, the third candidate planet orbiting our nearest stellar neighbor.

EXOPLANETS

Third Candidate Planet Around Proxima Centauri

A NEW INSTRUMENT on a powerful telescope has enabled astronomers to discover another planet around our nearest stellar neighbor, Proxima Centauri. The find brings the star's exoplanet tally to three candidates (one of them confirmed).

The newest of the worlds, Proxima Centauri d, would make an unpleasantly hot place to live, orbiting its faint red star every five days. But the method by which the astronomers detected the planet, by measuring the minute wobble of its host star, might well lead to the discovery of more habitable worlds.

More massive and/or closer-in planets exert greater gravitational influence on their stars, creating stronger *radial velocity* signals. Earth, on the other hand, induces a motion of only 10 cm/s on the Sun. To find other Earths, improving instrument precision is only the first step, as activity on stars' boiling surfaces can produce radial-velocity "noise" of meters per second.

João Faria (University of Porto, Portugal) and colleagues accounted for such stellar activity in order to find Proxima Cenaturi d, as announced in the February *Astronomy & Astrophysics*.

The candidate planet wobbles its star by 40 cm/s, a detection that is possible because of a new instrument: the ESPRESSO spectrograph on the Very Large Telescope (VLT) in Chile. In addition to taking incredibly high-resolution radial velocity measurements, the instrument also detects emission lines associated with stellar activity. Faria's team found that none of these indicators had the same five-day signal as the planet. However, the team still labels the discovery a candidate for now. "There is always a chance that we were fooled by the star," Faria says.

The candidate, which is at least twice the mass of Mars, orbits Proxima Centauri eight times closer than Mercury circles the Sun. Since the star radiates only 0.2% of the Sun's luminosity, the planet wouldn't be quite as scorched as Mercury is. Nevertheless, a rough estimate of the surface's equilibrium temperature is 360K (190°F), close to water's boiling point.

Guillem Anglada-Escudé (Institute of Space Sciences, Spain), who discovered the first confirmed planet around this system, Proxima Centauri b (*S&T:* Dec. 2016, p. 10), says the discovery indicates that Earth-mass planets on somewhat longer orbits (tens of days) are well within ESPRESSO's reach.

■ MONICA YOUNG

SOLAR SYSTEM

Meteorite Evidence: Earth Was Born with Its Water

ASTRONOMERS LONG THOUGHT that the terrestrial planets formed too close to the newborn Sun to harbor any water. So the inner planets must have formed dry, their water instead delivered later on by comets and/or asteroids from the outer solar system. But results over recent years have shown that the chemistry of outer solar system objects — in particular, the isotopic composition of comets — don't match that of Earth's oceans.

The difference lies in water's hydrogen atoms, some small fraction of which are deuterium, which contains an extra neutron. Lighter hydrogen is more likely to react or be stripped away by radiation, while heavier deuterium tends to stay put. The deuterium-to-hydrogen ratio (D/H) thus provides a clue to an object's chemical history.

Jérôme Aléon (National Museum of Natural History, France) and colleagues pondered this conundrum while analyzing the Efremovka meteorite found in Kazakhstan in 1962. It contains several *calcium-aluminum-rich inclusions* (CAIs), rocks that long ago trapped and preserved minerals from the hot solar nebula out of which the planets formed. Those minerals' D/H ratios, Aléon and colleagues reported February 3rd in *Nature Astronomy*, give us a glimpse of that past environment.

To their surprise, Aléon and his team found that the minerals trapped within the meteorite had two distinct D/H ratios. Some components had almost no deuterium, having interacted only with

QUASARS

Two Black Hole Behemoths Will Merge in 10,000 Years

TWO SUPERMASSIVE black holes in the heart of a distant galaxy are tightly entwined, offering unique insights into how such mergers unfold.

One of the black holes gorges on surrounding material, creating a radio jet that happens to point almost directly at Earth. Such objects, called *blazars*, are known for their volatility, typically flaring and dimming randomly. But when team member Anthony Readhead (Caltech) began observing the blazar, PKS 2131–021, in 2008, he noticed something unusual. "It was varying not just periodically, but sinusoidally," Readhead says.

To confirm that the years-long pattern was real, he and his team went trawling through older data, ultimately going back to archived data 45 years old. Upon seeing the peaks and troughs in the earlier data, "we knew something very special was going on," says Sandra O'Neill (also at Caltech), first author of the paper in the February 20th *Astrophysical Journal Letters*.

Theorist Roger Blandford (Stanford University), who took on the challenge of modeling the system, found that the simplest explanation called for a second black hole: The jet's brightness cycles with the pair's orbital period.

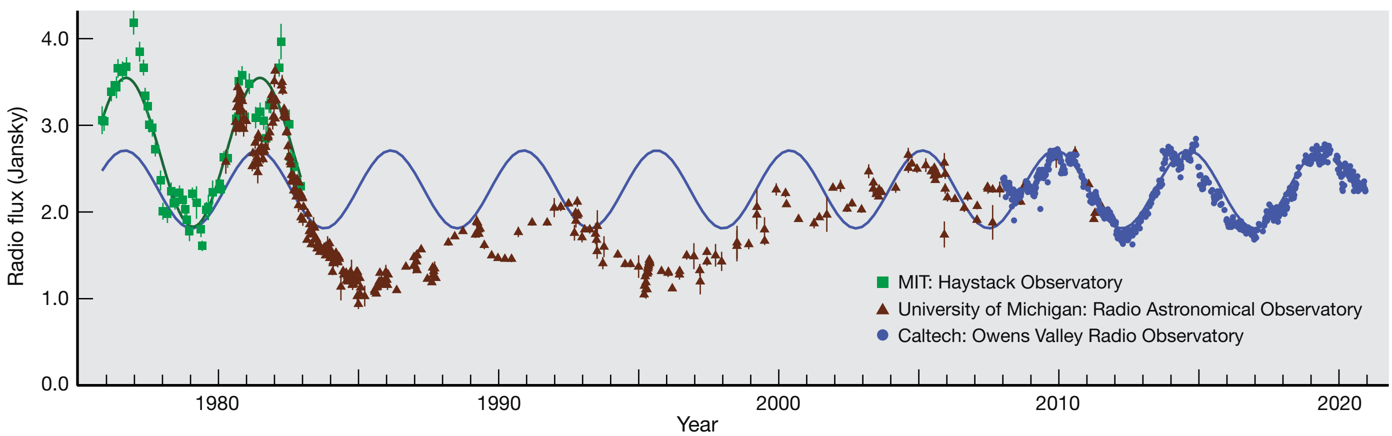
"Before Roger worked it out, nobody had figured out that a binary with a relativistic jet . . . looked like this," explains Readhead.

The variations suggest that the two supermassive black holes orbit each other every two years about 2,000 astronomical units apart, or some 50 times the average distance between Pluto and the Sun. The strongest close-binary candidate previously known to astronomers, OJ 287, takes nine years to complete an orbit.

The black holes will keep spiraling inward, ultimately colliding in around 10,000 years' time — an astronomical heartbeat away. When they do, they will unleash vast amounts of energy in the form of gravitational waves.

The discovery excites Davide Gerosa (University of Milano-Bicocca, Italy), who was not involved in the research. "It's been a long time since we've had such a strong [binary] candidate."

■ COLIN STUART



▲ Three sets of radio observations of the quasar PKS 2131-021, spanning 45 years, show the sinusoidal pattern in its brightness.

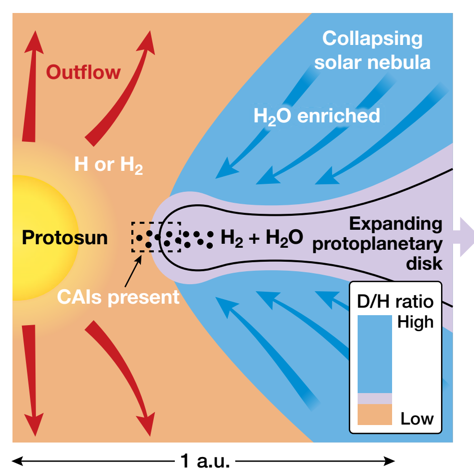
pristine hydrogen gas. Other minerals containing oxidized iron had higher D/H ratios, indicating they had encountered traces of water vapor with a chemical composition similar to Earth's oceans. In other words, our planet's water was already there in the disk as Earth was forming.

The researchers suggest that this water came from outside the solar system, dragged in as the solar nebula collapsed. Chemical reactions that had occurred long ago in the cold space between the stars had already enriched its deuterium content. The fact that some of the meteorite's minerals don't have much deuterium and the others do suggests that the influx happened within the first 200,000 years of the solar system.

"This is a coherent hypothesis," says planetary geologist Jesús Martínez-Frías (Complutense University of Madrid), "and very plausible."

■ JAVIER BARBUZANO

▶ This diagram shows a rough picture of the early solar system. As the solar nebula collapsed, a protoplanetary disk formed. An influx of water-rich (and deuterium-rich) gas from the interstellar medium fed the inner disk.



QUASAR LIGHT CURVE: TONY READHEAD / CALTECH; EARLY SOLAR SYSTEM: GREGG DINDERMAN / *S&T*, SOURCE: J. ALEÓN / *NATURE ASTRONOMY* 2022

STARS

A Star Where It Shouldn't Be

THE CREPE-LIKE DISK of our galaxy, just 1,000 light-years thick, is where almost all the Milky Way's stars form. So astronomers were baffled when, years ago, they found a massive star 3,000 light-years above the galactic plane. This star was far too young to have traveled out of the disk after its birth, but a birthplace in the halo seemed equally unlikely.

Now, Douglas Gies (Georgia State University) and colleagues have proposed a possible backstory for this stellar wanderer, HD 93521. It's currently a giant, rapidly rotating star with 17 times the Sun's mass, but perhaps it didn't start this way. They suggest this star was once a close pair of lower-mass stars that merged. The team presented this scenario in the February 1st *Astronomical Journal*.

Based on new distance and motion measurements from the European Space Agency's Gaia satellite, the team confirmed that the 5-million-year-old star would have taken 39 million years to fly up from the disk. Yet observations show no signs of birth in the halo, so the star must have come from the disk — but how?

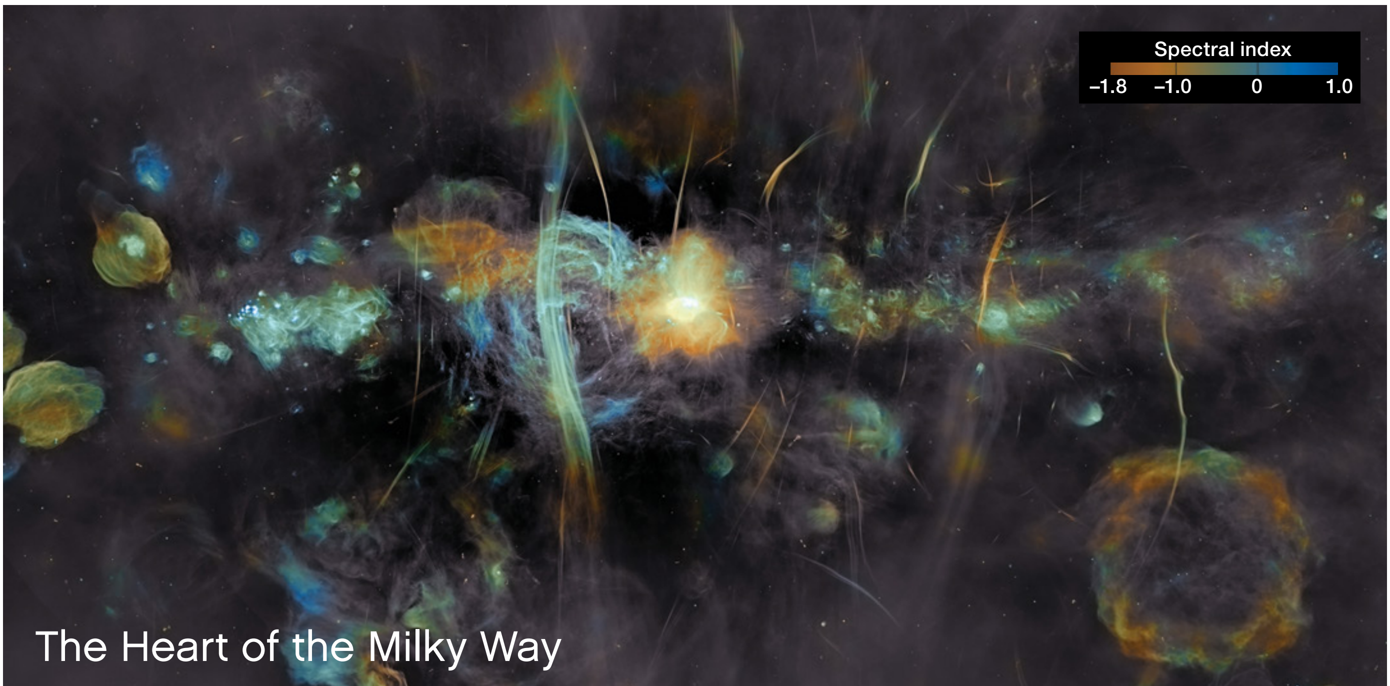
Gies's team suggests that a merger took place within an ejected star system. The collision stirred their interiors, bringing fresh hydrogen to the merged star's core and resetting the evolutionary clock. While HD 93521 appears to be 5 million years old, its "age" might mark the time of its merger, not of its birth.

◀ The *O*-type star HD 93521 is in the Milky Way's halo, far from the star-forming galactic plane.

This scenario could also explain the star's fast rotation. Although the star is 7.4 times the Sun's girth at its equator, it completes a full rotation in just 21 hours, compared to the Sun's 24.5-day equatorial period.

Ian Howarth (University College London), who first recognized the star's unique properties in 1993, says the team has resolved long-standing ambiguities surrounding this star: "They make a persuasive case."

■ **MONICA YOUNG**



The South African Radio Astronomy Observatory has released a striking series of images showing the complex and chaotic center of our galaxy, part of a study to appear in the *Astrophysical Journal*.

Unaffected by the large quantities of dust that obscure this region in visible light, radio waves reveal a scene teeming with star birth and star death as well as nearly 1,000 mysterious radio filaments. Discovered in the early 1980s, the filaments can extend up to 150 light-years and appear highly organized. Some even come in pairs or clusters. Cosmic rays streaming from our galaxy's center, perhaps from our resident supermassive black hole, might compress and illuminate the galaxy's ambient magnetic field.

Besides the filaments, our galaxy's inner 650 light-years are also home to young, massive stars, puffy remnants of supernova explosions, and shells of ionized gas surrounding massive stars. Astronomers knew of many of these objects, but the team, led by Ian Heywood (University of Oxford, UK), has already reported several new features.

■ **JURE JAPELJ**

View additional images and details at https://is.gd/GCradio.

ISOLATED STAR: ALADIN SKY ATLAS; GALACTIC CENTER: SARAO / I. HEYWOOD / J. C. MUÑOZ-MATEOS

STARS

Fast Radio Burst's Unlikely Home Puzzles Astronomers

A BABY SHOWER in a retirement home would surely raise some eyebrows. Likewise, astronomers were surprised to find a *fast radio burst* (FRB) in a globular cluster.

Strong evidence suggests these powerful, millisecond-long flashes of radio waves arise from *magnetars*, highly magnetized newborn neutron stars. But stars in globular clusters are typically billions of years old, so any supernovae should have gone off a long time ago and any magnetars produced would have long since deactivated.

"This is a really astonishing result," says magnetar expert Nanda Rea (Institute of Space Sciences, Spain). "What is a young neutron star doing in a globular cluster?"

Franz Kirsten (Onsala Space Observatory, Sweden) and team used the European Very Long Baseline Interferometry Network to study five bursts from the repeating FRB 20200120E, already known to sit in the outskirts of the nearby galaxy M81.

Using interferometry, the team pinpointed the sky position of the repeater to within a mere 1.25 milliarcseconds, placing it in one of M81's globular clusters.

Since a globular is unlikely to host young, massive stars, the researchers suggest in the February 24th *Nature* that the magnetar most likely formed some other way. Perhaps it was born when a white dwarf siphoned too much mass from a companion star or when two stellar remnants merged.

But Rea says there's no unambiguous evidence that neutron stars form through accretion-induced or merger-induced collapse. "So far, it's only theory," she says.

The nature of the bursts, published February 23rd in *Nature Astronomy*, sheds light on their origin. Kenzie Nimmo (ASTRON, The Netherlands) and colleagues found that the same FRB emits isolated, nanoseconds-long "shots" from a region just a few dozen meters across, perhaps via magnetic reconnection around the magnetar.

As team member Jason Hessels (also at ASTRON) says, "I would be surprised if FRBs stop surprising us."

■ GOVERT SCHILLING

IN BRIEF

No Signal from Cosmic Dawn

Four years after one experiment found tentative signs of the universe's first stars (*S&T:* June 2018, p. 8), another searching at the same frequency has found nothing. Both experiments were looking for a low-frequency radio signal created as the intense radiation of the first stars ionized their surroundings. To see this signal, astronomers must first remove overwhelming background noise from the Milky Way, Earth's ionosphere, human technology, and the detectors themselves. In 2018, a team working with the Experiment to Detect the Global EoR Signature (EDGES) detector in Western Australia found a tentative signal at 78 MHz, indicating that the first stars formed when the universe was 180 million years old. Oddly, the strength of the signal indicated cooler primordial gas than cosmologists had predicted, requiring nonstandard physics. But on February 28th in *Nature Astronomy*, another team announced that a floating radio antenna named SARAS 3 found no signal at that frequency. The team, led by Saurabh Singh (Raman Research Institute, India), suggests that the EDGES "signal" came from unevenly distributed ground beneath the detector. Nevertheless, a future detection remains possible, the team writes, either by beating down background noise on Earth or by positioning a detector on the farside of the Moon.

■ MONICA YOUNG

Booster Impacts Lunar Farside

On March 4th, a rocket booster impacted the farside of the Moon, crash-landing in Hertzsprung Crater. Bill Gray (Project Pluto) first noticed the upcoming encounter in January, when a close flyby of the Moon set the booster up for impact in March. Gray put out an appeal to the Minor Planet Mailing List for additional observations to pin down the errant booster's orbit. While the impact itself wasn't observed, NASA's Lunar Reconnaissance Orbiter should be able to target the area to return images of the fresh crater. The event is reminiscent of the Lunar Crater Observation and Sensing Satellite (LCROSS), which observed its spent Centaur upper stage booster hitting Cabeus Crater in 2009. Which booster is hitting the Moon this time, though, remains up for debate: Originally identified as a SpaceX Falcon 9 upper stage, further observations (including a spectrum detailing its composition and archived pings from a now-defunct amateur radio attached to the booster) showed it to be a discarded segment of the Chinese Chang'e 5-T1 mission, which launched in October 2014. However, China's Ministry of Foreign Affairs denied it was theirs. Regardless of who it belonged to, the errant booster highlights a need for better tracking of high-altitude objects.

■ DAVID DICKINSON

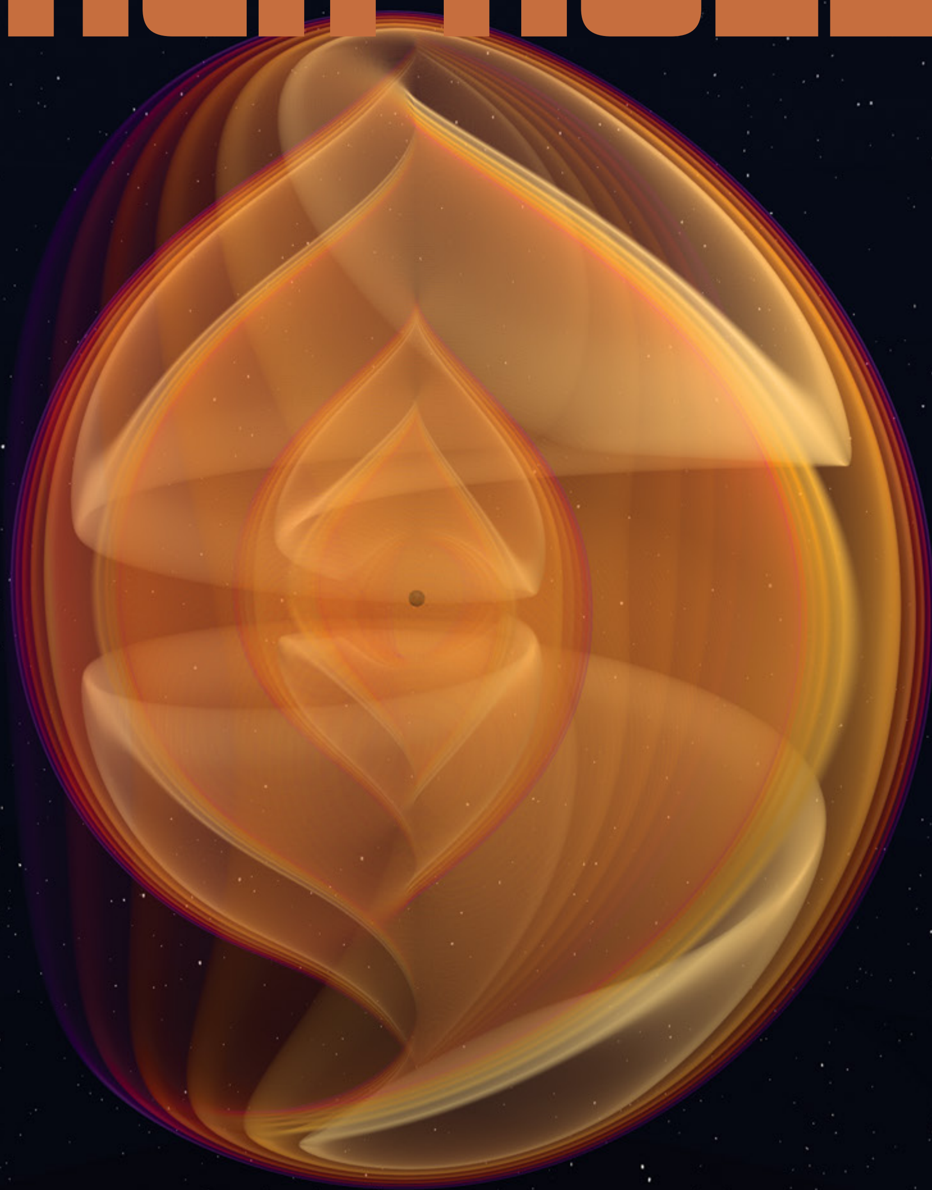
TESS Reaches 5,000

Since its 2018 launch, NASA's $200 million Transiting Exoplanet Survey Satellite (TESS) has found 199 confirmed exoplanets among 5,459 "objects of interest" (current numbers as of press time). The TESS team typically finds exoplanets by monitoring hundreds of thousands of the brightest nearby stars for brief dips in their light, inspecting discoveries by eye. However, much of the TESS catalog's recent gain comes from an effort led by Michelle Kunimoto (MIT). As part of the Faint Star Search, she wrote an algorithm to investigate the millions of dimmer stars that TESS observes. The program doubled the total number of objects of interest over the last year alone. These additional objects await confirmation as exoplanets. A second mission extension, which seems to be in the cards, will also enable synergy with the recently launched and deployed James Webb Space Telescope, which the team had planned from the beginning. With hundreds of TESS objects confirmed as planets, the team is keen to use Webb to take a closer look.

■ ARWEN RIMMER

 by Camille M. Carlisle

What Gravitational Waves Have Taught Us About BLACK HOLES



N. FISCHER, S. OSSOKINE, H. PFEIFFER, A. BUONANNO (MAX PLANCK INSTITUTE FOR GRAVITATIONAL PHYSICS), SIMULATING EXTREME SPACETIMES COLLABORATION

MAKING WAVES This visualization is from just before the merger of the two objects involved in GW190814. Yellower colors mark stronger gravitational radiation, and the binary's orbit is from left to right.

With dozens of detections in hand, scientists are building a compelling picture of these mysterious spacetime objects.

The typical waves washing over LIGO and Virgo change the detectors' lengths by a factor of 10^{-21}, which is like changing the size of Earth's orbit by the diameter of a hydrogen atom.

A tsunami has hit astrophysics. Before 2015, we knew of a smattering of star-size black holes, usually thanks to the glow from the gas they're slurping off companion stars. We also had indirect evidence that the fabric of spacetime can undulate, and that these ripples — called gravitational waves — can emanate from tight binary systems and rob them of orbital energy, ultimately sending the two objects crashing into each other.

But we'd never actually detected gravitational waves. Nor did we know of any binaries made solely of black holes. Many astronomers were skeptical that black holes would pair up and merge, or that gravitational-wave detectors would sense them — if the detectors saw anything at all, that is. Well-intended friends fretted about the futures of young scientists going into the field, advising them to turn elsewhere.

Then GW150914 happened. The crash of two distant black holes, each with about 30 times the Sun's mass, sent swells through the cosmos. More than a billion light-years from their point of origin, these waves infinitesimally stretched and squeezed our planet and the twin Laser Interferometer Gravitational-Wave Observatory (LIGO) detectors in the U.S.

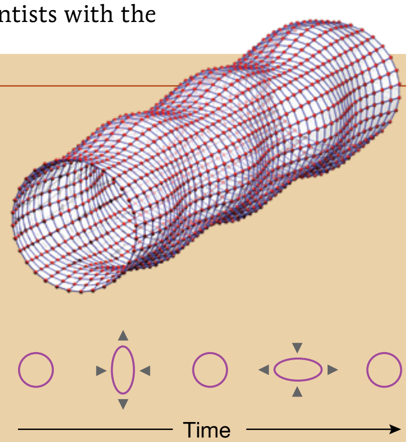
Within a few months, "[I] changed from basically the most useless astrophysicist in the world to somebody everybody really wanted to discuss with," says black hole researcher Michela Mapelli (University of Padova, Italy), a member of LIGO's European counterpart, Virgo.

Since that first, watershed detection, scientists with the LIGO and Virgo collaborations have tallied 90 spacetime-shaking events. Each was the merger of two *compact objects*, a catchall term for the skeletons of dead stars that includes both neutron stars and black holes. Almost all of the gravitational-wave events have involved only black holes, though, and the discoveries have multiplied the number of star-size black holes for which we have good mass measurements by a factor of 10. We now estimate that a pair of black holes merges in the local universe every 15 days.

Researchers call the flood of discoveries "dreamlike" and "shocking." "I don't appreciate it enough," says leading LIGO astrophysicist Vicky Kalogera (Northwestern University), laughing. In the first few years, wonder would overwhelm her at the reality she was dealing with — that we can not only detect gravitational waves but also use them to study real objects in the universe. "It would send shivers down my spine," she says.

But with the latest catalog of detections, released in November 2021, she realized the revolution has become run-of-the-mill. "I was thinking, 'Shame on you, Vicky! You know, you should be more appreciative of what you got to experience in life, because that is dumb luck!'"

The detections have brought key insights into black holes, from their fundamental nature — incredibly simple, just as predicted — to their sizes and origins. But the discoveries are also about more than black holes. They're about writing the story of stars, particularly the massive ones that blaze in brilliant but brief lives and seed the galaxy with heavy elements like the iron in our blood. And on that front, spacetime isn't the only thing that's been shaken up.



PROPAGATION OF A WAVE A gravitational wave stretches and squeezes the spatial dimensions that are perpendicular to its direction of motion. Here, the red dots represent particles floating in space; the blue grid is just to show how the particles are positioned relative to one another. The ellipses are cross sections.

Catching Waves

Gravity is the warping of spacetime by mass. If a massive object accelerates, then the warp itself becomes dynamic, propagating away as a gravitational wave. The ripples are tiny: The typical waves washing over LIGO and Virgo change the detectors' lengths by a factor of 10^{-21}, which is like changing the size of Earth's orbit by the diameter of a hydrogen atom.

But don't be fooled into thinking the waves are weak. Spacetime is stiff, so it resists flexure. If you could convert the energy of a binary black hole merger into light, it would be brighter than all the stars in the observable universe.

Two compact objects whirling around each other create gravitational waves that carry energy away, which in turn causes the objects to spiral closer together. The orbital

BLACK HOLE BACKGROUND: SUDAKARN VIVATVANICHKUL / SHUTTERSTOCK.COM; 3D WAVE: MARKUS PÖSSEL / HAUS DER ASTRONOMIE / MPI FOR ASTRONOMY; CROSS SECTIONS: LEAH TISCIONE / *S&T*

period sets the waves' frequency, so as the objects inspiral, the waves' frequency rises, sweeping up until the objects suddenly plunge toward each other and collide, creating a "chirp" in the signal. The resulting remnant rings like a bell as it settles down. This *ringdown*, as well as the objects' masses, spins, and distance from Earth, is encoded in the gravitational waves.

LIGO and Virgo can detect waves from roughly 10 hertz to a few kilohertz. Although two black holes might spend a billion years inching closer to each other, the detectors won't "hear" them until the last few seconds or so.

When something hits the detectors that looks like a gravitational-wave event, it triggers an automated public alert. Dozens of team members get calls — usually in the middle of the night for the U.S., when noise from human activity is low and detectors are therefore more sensitive, says LIGO's Chad Hanna (Penn State). The scientists jump to vet the signal. Events that make the cut prompt a more detailed alert to the astronomical community.

The LIGO and Virgo collaborations issued 39 public alerts — about one per week — during the second half of the latest observing run, which lasted from November 2019 to March 2020. Speed is key, because if the event involves a neutron star, then observers must rally to search the skies for a flash of light (*S&T:* Dec. 2021, p. 36).

"We've totally baffled a lot of the theorists, because our mass distribution looks nothing like any mass distribution drawn before."

—MAYA FISHBACH

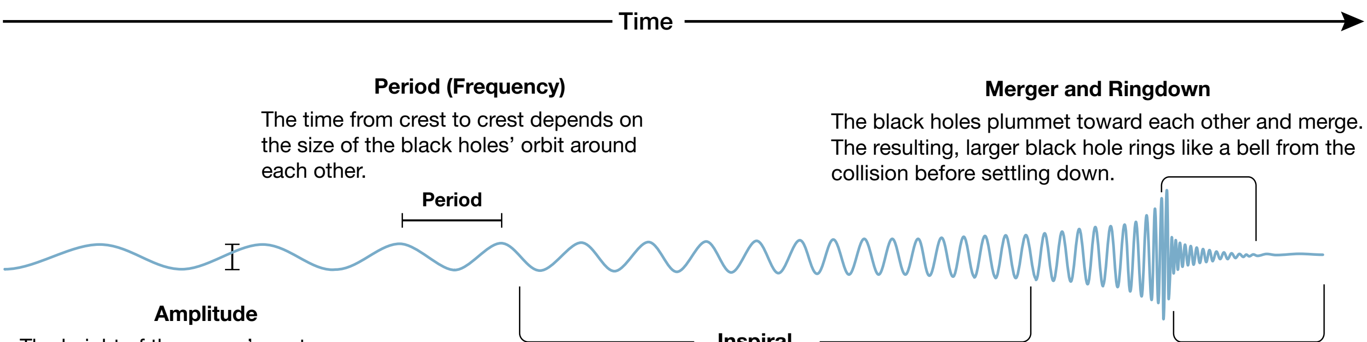
After the observing run, collaborators do a much deeper analysis, spending months assessing thousands of data streams that record things like the detectors' physical environments and laser power. "People invest a lot of time in really trying to get the right answers," Hanna says — especially early-career scientists, he emphasizes, who are often the ones "banging their heads against the supercomputers."

The final tally can fluctuate a lot: Only 18 of the 39 alerts survived. Scientists also found another 17 that the automated system hadn't spotted. The less-than-optimal success rate stems in part from the fact that every observing run involves new hardware, as researchers try to squeeze every improvement they can out of the instruments. As a consequence, each time they must relearn the system's vagaries.

Down in the Valley

The black holes LIGO and Virgo caught colliding generally had masses from 7 to 50 times that of the Sun. They were usually paired up pretty equally, mass-wise, which is unsurprising because most ways to build a black hole binary tend to join objects of near-equal masses. Independent teams have also trawled the gravitational-wave data and found events beyond the 90 in the collaborations' catalog, and these follow the same trends.

BREAKDOWN OF A GRAVITATIONAL-WAVE EVENT



Period (Frequency)
The time from crest to crest depends on the size of the black holes' orbit around each other.

Merger and Ringdown
The black holes plummet toward each other and merge. The resulting, larger black hole rings like a bell from the collision before settling down.

Amplitude
The height of the waves' crests encodes information about the black holes' masses, spins, and distance from Earth:

- Gravitational waves fade as they travel, so smaller amplitudes (a.k.a. quieter signals) come from more distant sources.
- More massive black holes create stronger waves.
- If the black holes spin and lean at an angle as they orbit each other, then the orbit will wobble around and the amplitude will vary.

Inspiral
As the black holes spiral in toward each other, their orbit shrinks. This causes the waves' frequency to increase.

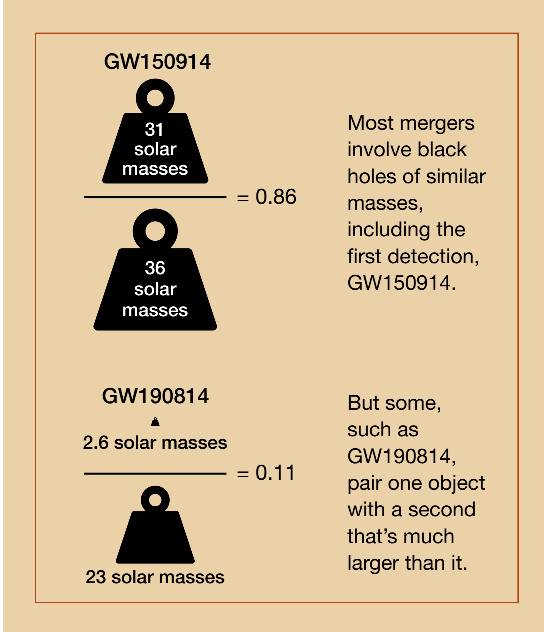
- Smaller black holes come closer together before they collide, so their waves reach a higher frequency.
- The black holes' spins will affect how close the objects approach before merger.
- The black holes' masses determine how quickly the inspiral proceeds.

The exact shape and behavior of the ringdown depend on the black holes' spins when they collide, as well as the remnant's mass and spin.

BLACK HOLE BACKGROUND: SUDAKARN VIVATVANICHKUL; GRAVITATIONAL-WAVE EVENT: GREGG DINDERMAN / *S&T*

Researchers use advanced statistical techniques to take a step back from these individual finds and study the big picture. This *population analysis* tells astrophysicists what they would detect if their instruments were perfect, explains LIGO's Zoheyr Doctor (Northwestern). "What we're after is what's going on out in the universe, not just what our detector is seeing," he says.

This extrapolation has turned up something unexpected: Black holes tend to cluster at 10 and 35 solar masses. "We've totally baffled a lot of the theorists, because our mass distribution looks nothing like any mass distribution drawn before," says LIGO's Maya Fishbach (also Northwestern).



"There were no theoretical reasons," says Feryal Özel (University of Arizona), who helped bring the paucity to astronomers' attention. Small stars are more common than big ones, she explains, "and if the evolution does nothing special and the explosion mechanism does nothing special, then there should have been far more low-mass black holes in the 2- to 5-solar-mass range than, for example, the 5- to 10-solar-mass range."

Gravitational waves have turned up a few objects in the valley, notably the smaller member of GW190814. This event involved a 23-solar-mass black hole swallowing a mystery object of 2.6 solar masses. Many astrophysicists think the mystery object was a tiny black hole, although a rapidly spinning neutron star might be able to withstand collapse at that mass.

Below roughly 10 solar masses, the number of black holes plummets, creating a valley in the plot. This dearth of small black holes has puzzled astronomers long before the advent of gravitational-wave science. Neutron stars can only survive up to maybe 2½ solar masses before they collapse under their own weight; black holes should appear just above that limit. Yet observations of compact objects in stellar binaries have found almost no black holes between 2 and 5 solar masses.

Other observations also suggest the low-mass valley isn't empty. Careful monitoring of tiny flashes created as unseen objects pass between us and our galaxy's stars, bending and magnifying the stars' light, have turned up eight objects that might lie in the valley, Łukasz Wyrzykowski (Warsaw

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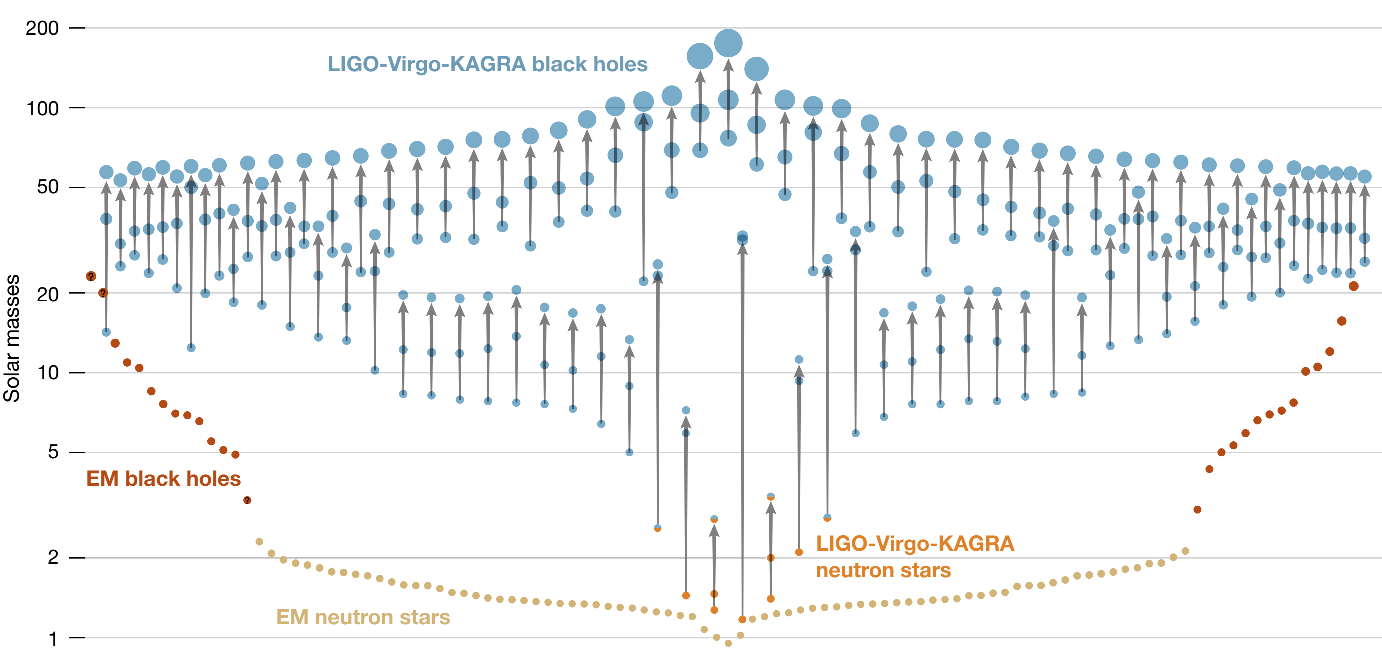
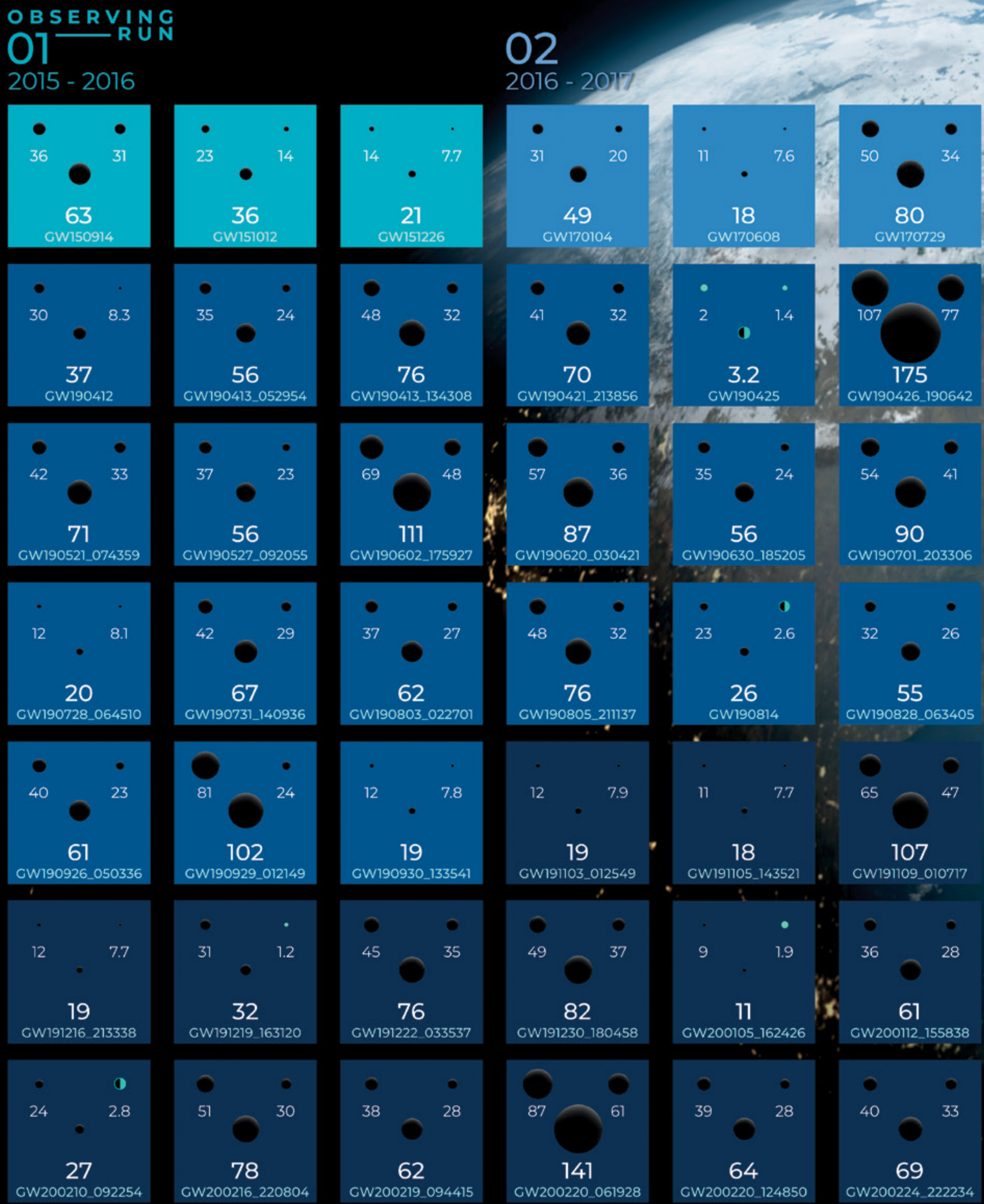


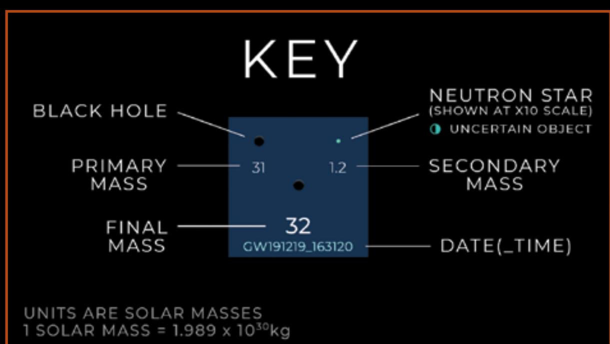
▲ **THE TALLY SO FAR** Scientists have now detected 90 gravitational-wave events (blue and orange), expanding considerably on the compact objects detected at various wavelengths of light (electromagnetic, or "EM"). The dots indicate the two masses of the objects that merged and of the object they created. Almost all of the new discoveries appear to be black holes. Objects that lie just above 2 solar masses are of uncertain nature.

MASS COMPARISONS: GREGG DINDERMAN / *S&T*, SOURCE: LIGO-G2000963;
TALLY: LIGO-VIRGO / AARON GELLER / NORTHWESTERN UNIVERSITY

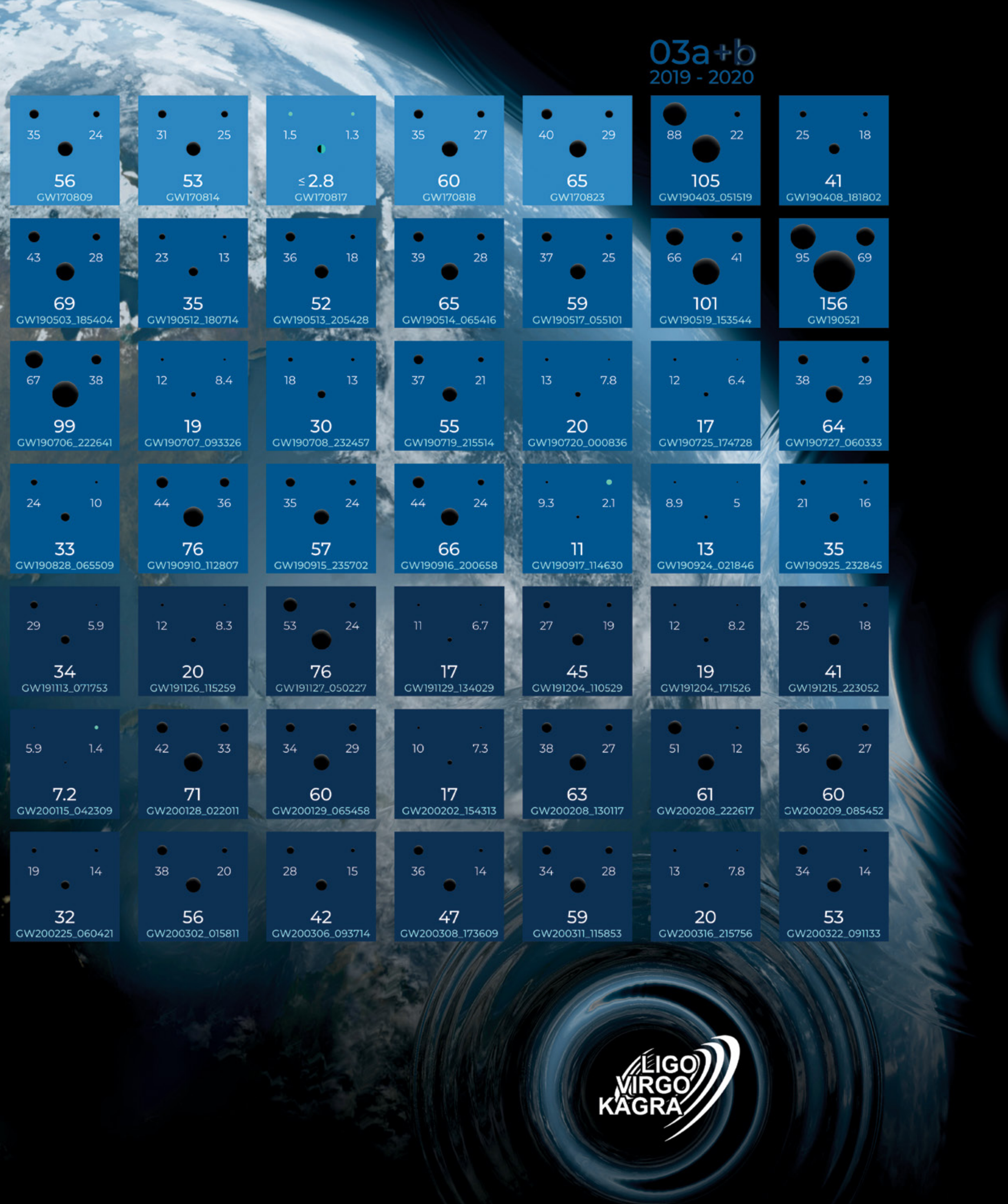
MERGERS DETECTED SINCE 2015



LIGO's first and second observing runs (O1 and O2) bagged 11 gravitational-wave events, including the now-famous double-neutron-star merger GW170817. The third observing run, split into two periods spanning April to October 2019 and November 2019 to March 2020, brought another 79 discoveries. The mass estimates shown here don't include uncertainty ranges, which is why the numbers don't always add up. (In fact, the final mass is always smaller than the sum of the two objects, because some mass is lost as energy in the gravitational waves.)



CARL KNOX / OZGRAV, SWINBURNE UNIVERSITY OF TECHNOLOGY


O3a+b
2019 - 2020
35 24 56 GW170809
31 25 53 GW170814
1.5 1.3 ≤2.8 GW170817
35 27 60 GW170818
40 29 65 GW170823
88 22 105 GW190403_051519
25 18 41 GW190408_181802
43 28 69 GW190503_185404
23 13 35 GW190512_180714
36 18 52 GW190513_205428
39 28 65 GW190514_065416
37 25 59 GW190517_055101
66 41 101 GW190519_153544
95 69 156 GW190521
67 38 99 GW190706_222641
12 8.4 19 GW190707_093326
18 13 30 GW190708_232457
37 21 55 GW190719_215514
13 7.8 20 GW190720_000836
12 6.4 17 GW190725_174728
38 29 64 GW190727_060333
24 10 33 GW190828_065509
44 36 76 GW190910_112807
35 24 57 GW190915_235702
44 24 66 GW190916_200658
9.3 2.1 11 GW190917_114630
8.9 5 13 GW190924_021846
21 16 35 GW190925_232845
29 5.9 34 GW191113_071753
12 8.3 20 GW191126_115259
53 24 76 GW191127_050227
11 6.7 17 GW191129_134029
27 19 45 GW191204_110529
12 8.2 19 GW191204_171526
25 18 41 GW191215_223052
5.9 1.4 7.2 GW200115_042309
42 33 71 GW200128_022011
34 29 60 GW200129_065458
10 7.3 17 GW200202_154313
38 27 63 GW200208_130117
51 12 61 GW200208_222617
36 27 60 GW200209_085452
19 14 32 GW200225_060421
38 20 56 GW200302_015811
28 15 42 GW200306_093714
36 14 47 GW200308_173609
34 28 59 GW200311_115853
13 7.8 20 GW200316_215756
34 14 53 GW200322_091133
LIGO VIRGO KAGRA

(continued from page 15)
University Astronomical Observatory, Poland) and others have reported.

Such discoveries don't settle the problem, though. "They should have been *most* numerous," Özel says. "Why aren't these low-mass objects forming at the high numbers that we expected before?"

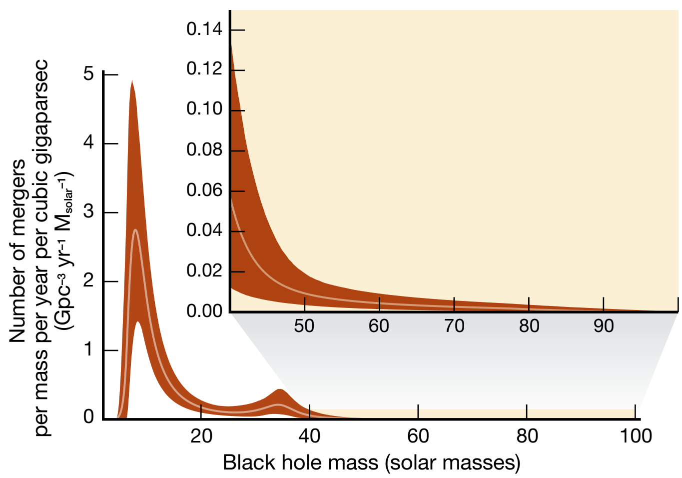
One possibility, she says, is the way stars die. Massive stars have a dense core swaddled in layers and sheathed in a fluffy outer envelope of hydrogen. When a star explodes, it can easily doff the hydrogen envelope, but the layers just above the core tend to implode with the core, as a unit. "And that tends to be five solar masses or more," she says. "Is this the right explanation? I'm not sure."

When Stars Fail

At the other extreme of the mass range, the heftiest objects present their own mystery.

The radiation shining from a star's heart creates an outward pressure that prevents the star from collapsing under its own weight. As massive stars age and fusion runs rampant in their cores, the cores heat up. If the core becomes hot and dense enough, photons can spontaneously transform into pairs of electrons and their antimatter partners, positrons.

But when the photons go poof, so too does the star's defense against implosion. The star's core will suddenly collapse and reignite in an explosion that either throws off vast amounts of material or destroys the star entirely, leaving no remnant. This untimely demise is thought to afflict stars of a certain mass range, preventing the creation of black holes with masses of roughly 50 to 120 Suns.



▲ **HOW BIG ARE BLACK HOLES?** Based on detections so far, researchers can calculate the number of black holes of a given mass that are merging each year in a given volume of space. Doing so reveals that black holes tend to come in two masses: roughly 10 and 35 Suns. Zooming in on the highest masses (inset) also reveals that, contrary to expectations, there are some black holes above 50 solar masses. These plots are for the larger member of the black hole binary, but since black holes tend to pair up equally, the pattern holds for merging black holes overall. Red shading marks the uncertainty range for this model.

GREGG DINDERMAN / S&T, SOURCE: ZOHEYR DOCTOR / CIERA / LVK

Astrophysicists went looking for this theoretical *pair-instability gap* in their gravitational-wave data. Initially, they thought they had found it: An earlier catalog showed hints of a drop in the number of black holes above 45 solar masses. But the latest data complicate matters. The number of black holes falls off at high masses, yes, but it doesn't go to zero. Furthermore, LIGO and Virgo haven't yet detected any merging black holes above the predicted gap, so researchers can't see if there's an upper edge.

It's possible that the uptick in black holes of about 35 solar masses is related to the pair instability. Stars should naturally pile up near the mass gap, because instabilities will cause stars of a range of initial masses to lose enough material to edge themselves down into the safe zone, where they'll ultimately create similar-size black holes. But we shouldn't see the pileup peak right at the mass gap's edge, explains Mapelli, because stars that form black holes of 35 solar masses are far more common than those that form 50-solar-mass ones. When you take that into account, the peak should be around 35 Suns.

Peak aside, there are still about 15 mergers that involved at least one black hole in the upper mass gap. It's entirely possible that the gap doesn't lie quite where astronomers predicted — changes in rotation, composition, nuclear-reaction rates, the way material mixes in the star, and how much mass the star throws off late in life (or loses to a companion) can all shift the mass gap, even 10 to 15 solar masses higher, Mapelli says. Massive stars are messy, especially those born in binaries, and astronomers still have only a patchy picture of what happens as they age and die.

But shifting stellar physics can't solve everything, she and others avow. Take GW190521. The merger of a 95-solar-mass black hole with a 69-solar-mass one, GW190521 was the proverbial canary in the coal mine. No fiddling with stellar evolution can explain that 95-solar-mass object.

There's more than one way to make a black hole, however. Researchers have two broad categories of formation scenarios for black hole binaries. In the *isolated binary scenario*, stars are born together and die together, their remnants merge, and the story ends. In *dynamical scenarios*, however, black holes form, then pair up and merge . . . and maybe merge again with something else.

Dynamical pair-ups can happen in the hearts of stellar clusters, where stars are packed 10,000 to 100,000 times tighter than in the solar neighborhood. They can also occur near galaxies' central supermassive black holes, around which stars and their remnants swarm. The small objects become caught inside the leviathan's huge skirt of hot gas. "The gas will tend to 'organize' the orbits of the black holes so they pair up nicely, like dancers in a formal minuet, rather than the gas-free version, which looks more like a mosh pit," says Saavik Ford (CUNY Borough of Manhattan Community College).

Black holes easily swap partners in dense environs, often multiple times. The compact object their collision creates — called a *second-generation* black hole — can then nab another partner and merge again. Repeat mergers might be rare in star clusters, though: The merger process can come with a recoil that sends the remnant rocketing away at speeds exceeding the cluster's escape velocity. On the other hand, half of the mergers that occur in the gas swirling around a supermassive black hole — known as an *active galactic nucleus (AGN) disk* — may be second-gen events.

"I suspect that many of the highest-mass black-hole mergers we've seen with LIGO and Virgo originate in AGN disks," says Ford. So, too, may events that pair two unequally matched masses, she adds, of which there are a handful in the latest catalog. Unlike starbirth and clusters, AGN disks tend to unite black holes of different sizes, due to the way the gas pushes and traps objects.

Black hole mergers are normally invisible — except in AGN disks, where the rocketing remnant rams through the surrounding gas, heating it up. In a tantalizing result, Ford, Matthew Graham (Caltech), and their colleagues spotted a flare from an actively accreting supermassive black hole in the same region of sky that GW190521 came from. Based on the flare's appearance, and assuming it's not the AGN playing tricks, the astronomers think that the collision kicked the remnant up out of the disk but that it will come whizzing back through, hopefully sometime in the next few years. They're actively watching for a second flare.

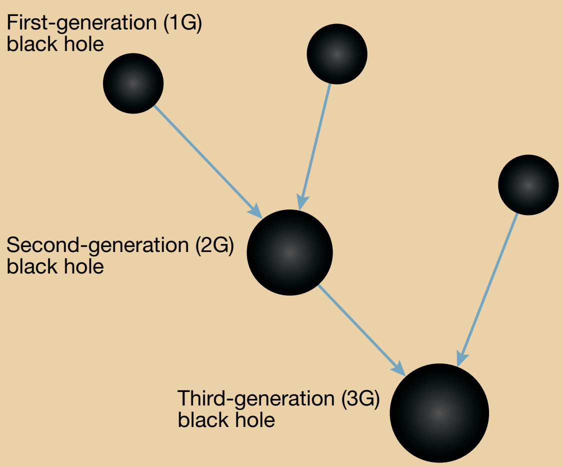
Black holes easily swap partners in dense environs, often multiple times. The compact object their collision creates can then nab another partner and merge again.

Give It a Whirl

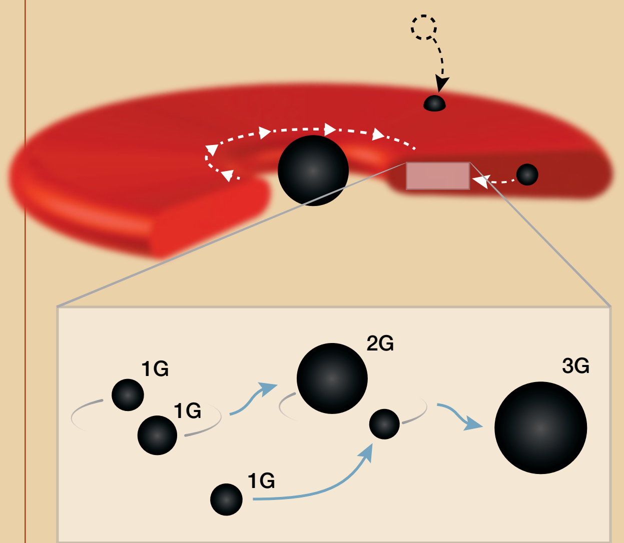
Mass is not enough to distinguish how a black hole was made, though. The hole's spin actually tells you more. As a star ages it puffs up and, like a figure skater throwing out his arms, puts the brakes on its whirl. Assuming the star's core also slows, when the core later collapses into a black hole, the black hole won't spin much. A second-gen black hole, on the other hand, will usually have a spin of 70% of its maximum twirl rate, due to the way it reappropriates the inspiral energy of its forebears.

The tilt of an object's spin axis matters, too. Black holes born from stellar binaries tend to spin upright as they circle each other, because of the stars' interactions before they died. Black holes that partnered up dynamically, however, have no reason to align — they're "bouncing off each other and getting all of their spin directions all jumbled up," Doctor says.

Unfortunately, spin leaves a subtler imprint on gravitational waves than mass does, making it hard to measure



MULTIPLE MERGERS A black hole made from a star's death is called a *first-generation* (1G) black hole. When two 1G black holes merge, they create a *second-generation* (2G) black hole. If a 2G black hole merges with yet another black hole, the result is a 3G black hole. Such chains of mergers are only possible in extremely dense environments, where black holes can easily catch each other.



IN AN AGN DISK Star-size black holes orbiting a supermassive black hole will interact with the leviathan's gas disk and gradually shift their trajectories until their orbits lie within the disk. Once they're inside, the gas forces the small black holes to migrate inward, where they're trapped together and can easily merge multiple times.

BLACK HOLE BACKGROUND: SUDAKARN VIVATVANICHKUL; MERGER CHAIN: GREGG DINDERMAN / *S&T*, SOURCE: LIGO-G2001426; BH MERGERS IN AN AGN DISK: GREGG DINDERMAN / *S&T*, SOURCE: V. GAYATHRI ET AL. / *ASTROPHYSICAL JOURNAL LETTERS* 2020 for the merging objects except in special cases. (The remnant's spin is pretty clear.) The 23-solar-mass black hole in GW190814, for example, was so much larger than its companion that its properties dominated the encounter and the resulting waves, like a booming voice overwhelming the other object's whisper. The waves show that the big black hole essentially wasn't spinning, indicating it's likely a stellar skeleton.

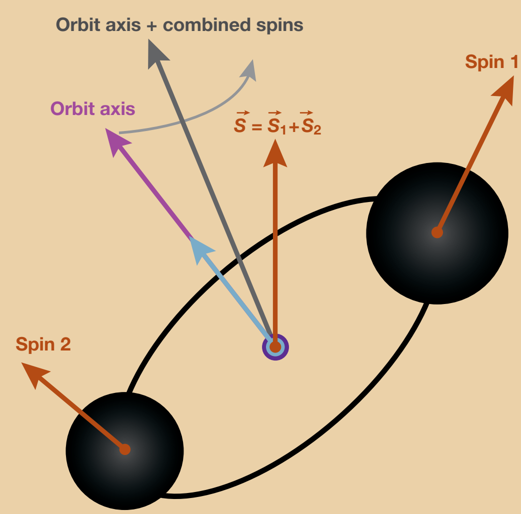
But most of the spin information we have comes from the population analysis, because hints in the cohort add up to reveal trends that a single system can't. The results are intriguing. Statistically speaking, the black holes that collided show a small preference for aligned spins, but roughly 30% were likely askew, telling us that we're indeed seeing binaries made multiple ways. The merging objects also spun slowly, if at all, which sets them apart from the fast-spinning black holes astronomers have seen paired up with stars in the Milky Way. (No one knows why.) Notably, the range of spins widens above 30 solar masses, which might also confirm that the biggest black holes have diverse origins.

One of the biggest surprises is a connection between spins and mass ratio, says LIGO astrophysicist Salvatore Vitale (MIT). The black holes in binaries fall into two camps: either equal mass and no spin, or mismatched in size with notable aligned spins. "None of the traditional formation channels can easily explain this, which is why it's so interesting and beautiful," he says.

"None of the traditional formation channels can easily explain this, which is why it's so interesting and beautiful."
—SALVATORE VITALE

There's a chance that AGN disks *could* explain it, he adds. Mismatched systems can form there, and the gas could override the usual pell-mell nature of dynamical hookups and force the black holes to spin the same way as the disk does. "The usual joke in Bayesian analysis is, 'Would you bet a coffee, a dinner, or your house on this?'" he says, referring to the statistical method used in this work. "I would bet between a coffee and a dinner."

Scientists likely won't have an answer until we've found closer to 1,000 events, says Fishbach. Most collisions so far involve pairs of roughly 30-solar-mass black holes, the detectors' sweet spot. "The things we're really confused about are, what is happening at 60 solar masses and what's happening at 3 solar masses? We only have a handful of detections there now. So even going from a sample size of one or two to, like, five or 10 will be huge."



SPIN Two black holes that orbit each other sometimes also spin. Their spin axes can point parallel to the axis of their orbital motion (as shown for object 2, a setup called *aligned*), or they can be tilted (as with object 1) or even upside-down (in which case the spin axis would be parallel to the orbit's axis but the object would spin, say, clockwise while orbiting counterclockwise). If the spins are misaligned, the orbital plane will wobble (gray arrow).

Rising Tide

During the latest run, LIGO and Virgo saw gravitational waves that had traveled up to 8 billion years to reach us. That covers the last half of cosmic history, revealing how the rate of mergers has changed with time. "Black holes were merging more often in the past than they are now," Doctor says. "Now is the first time when we can confidently say that."

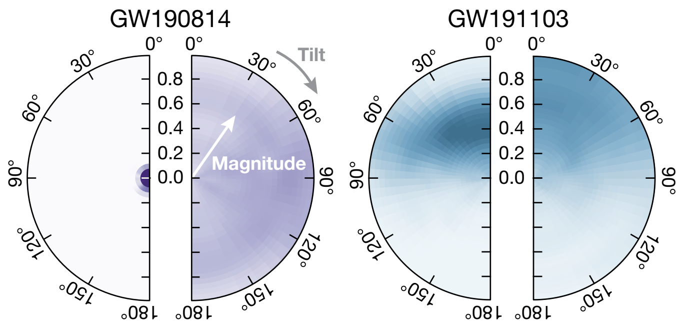
The rate changes in step with star formation across the universe, which peaked about 10 billion years ago. That suggests that the vast majority of the black holes detected either came from stars or were second-generation remnants instead of being *primordial black holes*, hypothetical objects formed in special conditions in the early universe. If such objects exist, then they should merge at a roughly constant rate over time.

Primordial black holes are one of many suggestions to explain dark matter. "This is one of these things that comes in and out of fashion," Hanna says. "It's a polarizing thing. People are like, 'Oh, yeah, of course,' or 'No, you're nuts. Why don't you go join the crackpots?'"

It's unlikely that observations will reach back to the peak of cosmic starbirth in the next run, scheduled to begin at the end of 2022. But the detections could still enable researchers to determine how long a delay there is between star formation and black hole mergers and if the merger rate changes for different mass ranges, Kalogera says. "That is definitely where we want to go next."

This information could help scientists tease apart how the binaries formed, down to the details of the original stel-

BLACK HOLE BACKGROUND: SUDAKARN VIVATVANICHKUL; SPIN: GREGG DINDERMAN / S&T, SOURCE: BHDYNAMICS.COM



◀ **SPINS** Each black hole involved in a merger might be spinning, but scientists can usually only calculate a range of possibilities in terms of how fast and in what direction. Spins are measured from 0 to 1, where 1 is the maximum possible for a given black hole. The coordinates around the circumference indicate the tilt of a black hole's spin axis relative to its orbit: Zero degrees means the black hole was pointing straight up, 90° that it was rolling on its side, and 180° that it was upside-down. Darker colors indicate more likely spin values, and the larger object is the left-hand hemisphere of each pair. For GW190814 *(far left)*, the 23-solar-mass black hole overwhelmed the signal, giving clear signs that it essentially wasn't spinning while also masking any information about its companion's spin. For GW191103, which involved black holes of about 12 and 8 solar masses, it's hard to tell how much the black holes spun or leaned.

lar systems. For example, stars with lower levels of heavy elements grow larger than ones with higher levels, and they make bigger back holes as a result. Galaxies' star-forming gas was more pristine earlier in cosmic history, so bigger black holes might thus be commoner at early cosmic times.

But even if they're made early, that doesn't mean they'll merge early. Recent calculations by Lieke van Son (Center for Astrophysics, Harvard & Smithsonian) suggest that stars able to form black holes above 30 solar masses will also end up in wider binaries than other stellar pairs. Wider binaries take longer to merge, so we should see more high-mass black holes merging *later* in cosmic history, she predicts.

Open the Floodgates

"If, for some reason, we never turned the detectors on again — we're like, 'We're done, and we don't want to detect any gravitational waves anymore — this would be a very unfulfilling end to the story," says Fishbach. "It really feels like we're just at the beginning."

Thanks to upgrades and the addition of a fourth detector (Japan's mine-dwelling KAGRA), the next observing run will have heightened sensitivity. Alerts will come every few days. The rapid-response team will need a new strategy, perhaps limiting wake-up calls to events that the automated system flags as oddballs or involving neutron stars. "It's just a matter of survival," Hanna says. "My graduate students are unwilling to not sleep. I've asked them, they've said no."

But even with the brilliant upgrades that instrumentalists devise, LIGO, Virgo, and KAGRA will ultimately be limited by every astronomer's problem: size. "As scientists, we always think about what comes next," Vitale says. "We never live in the moment."

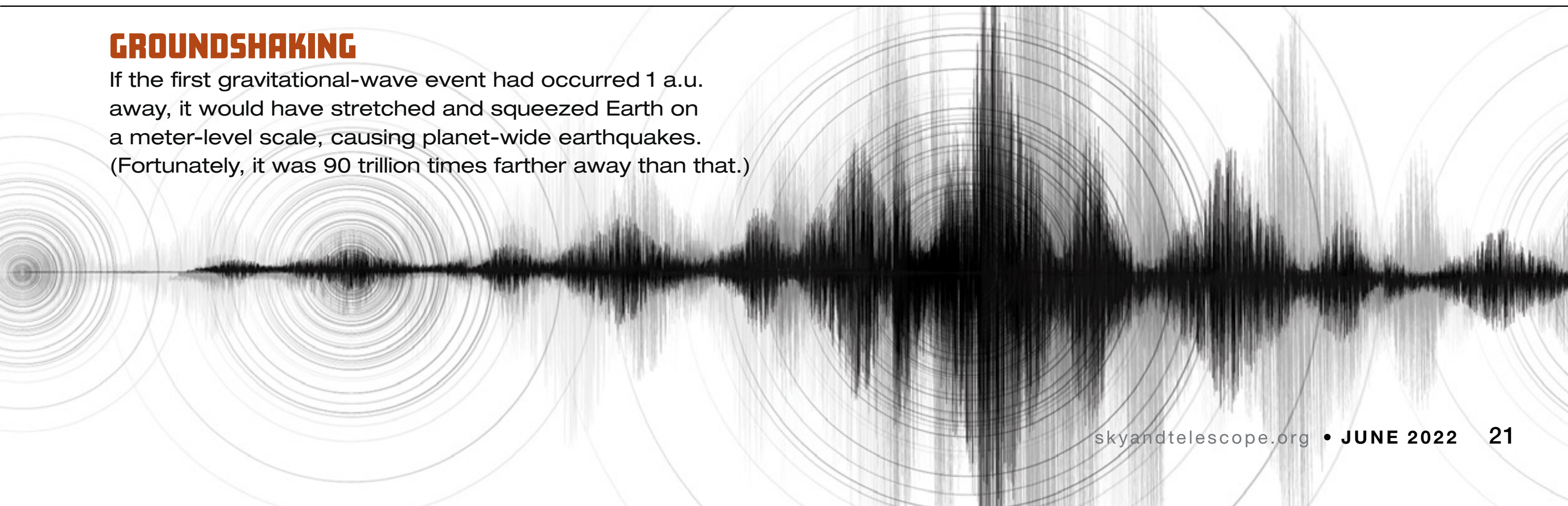
That next thing could be Cosmic Explorer, a proposed pair of gigantic, ground-based detectors that would be 10 times more sensitive than LIGO. "That simple factor of 10 brings you from seeing one black hole every few days to seeing all of the black holes in the universe, no matter where they are," he says. First light could come in the mid-2030s, around the same time that astronomers will launch the Laser Interferometer Space Antenna (LISA). LISA's sensitivity to lower-frequency gravitational waves will enable it to sense not only smashing supermassive black holes but also stellar-mass black holes years before they merge, giving ground-based detectors a head's up.

In 15 years, astronomers may have seen more than 100,000 black hole collisions. The flood of discoveries will answer questions about the objects' spins, formation, and behavior across cosmic time, as well as what's happening at the smallest and largest masses.

And hopefully, something unexpected will come, too. "It's why I love what we are doing," says Vitale. "Very often, when we see something, it's the first time that humans have seen it."

■ Science Editor **CAMILLE CARLISLE** adores black holes of all sizes. Follow discoveries in her blog, The Black Hole Files: **https://is.gd/bhfiles**.

GW190814: R. ABBOTT ET AL. / *ASTROPHYSICAL JOURNAL LETTERS* 2020, CC BY 3.0; GW191103: R. ABBOTT ET AL. / ARXIV 2111.03606; GROUNDSHAKING: VARUNYUUU / SHUTTERSTOCK.COM



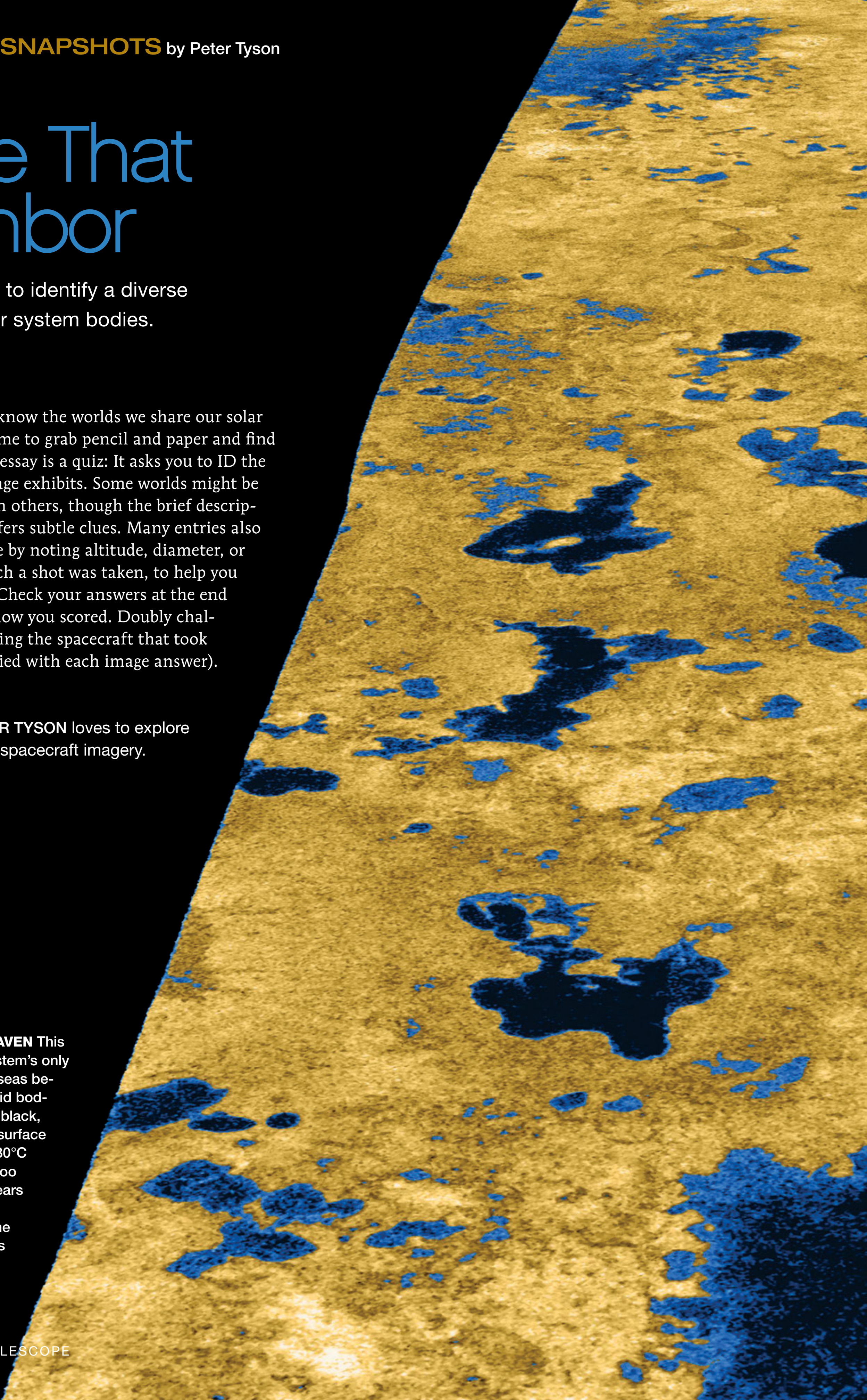
GROUNDSHAKING
If the first gravitational-wave event had occurred 1 a.u. away, it would have stretched and squeezed Earth on a meter-level scale, causing planet-wide earthquakes. (Fortunately, it was 90 trillion times farther away than that.)

Name That Neighbor

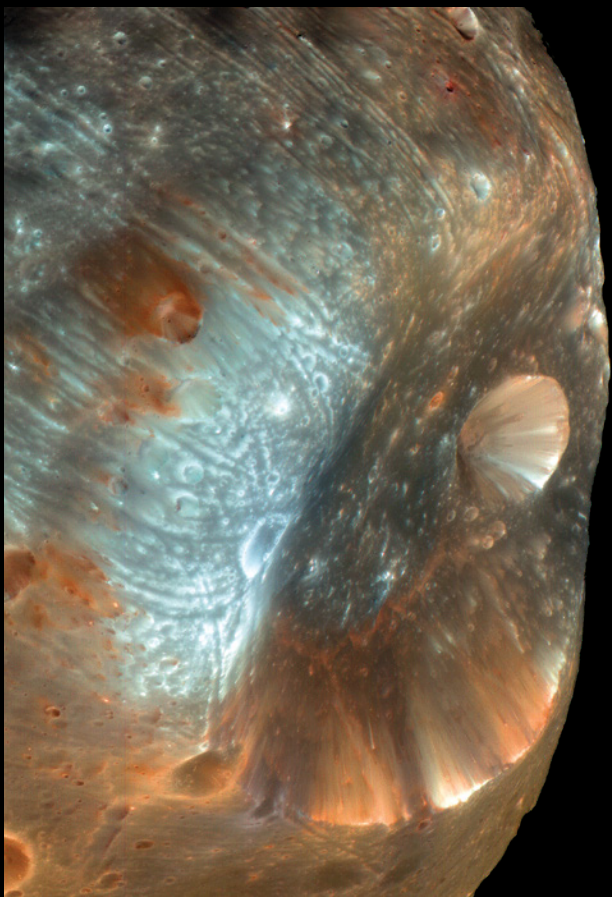
Challenge yourself to identify a diverse assortment of solar system bodies.

How well do you know the worlds we share our solar system with? Time to grab pencil and paper and find out. This photo essay is a quiz: It asks you to ID the celestial body each image exhibits. Some worlds might be more recognizable than others, though the brief description of each picture offers subtle clues. Many entries also provide a sense of scale by noting altitude, diameter, or the distance from which a shot was taken, to help you get a better visual fix. Check your answers at the end (don't peek!) and see how you scored. Doubly challenge yourself by guessing the spacecraft that took each shot (name supplied with each image answer). Good luck!

■ Editor in Chief **PETER TYSON** loves to explore the solar system using spacecraft imagery.

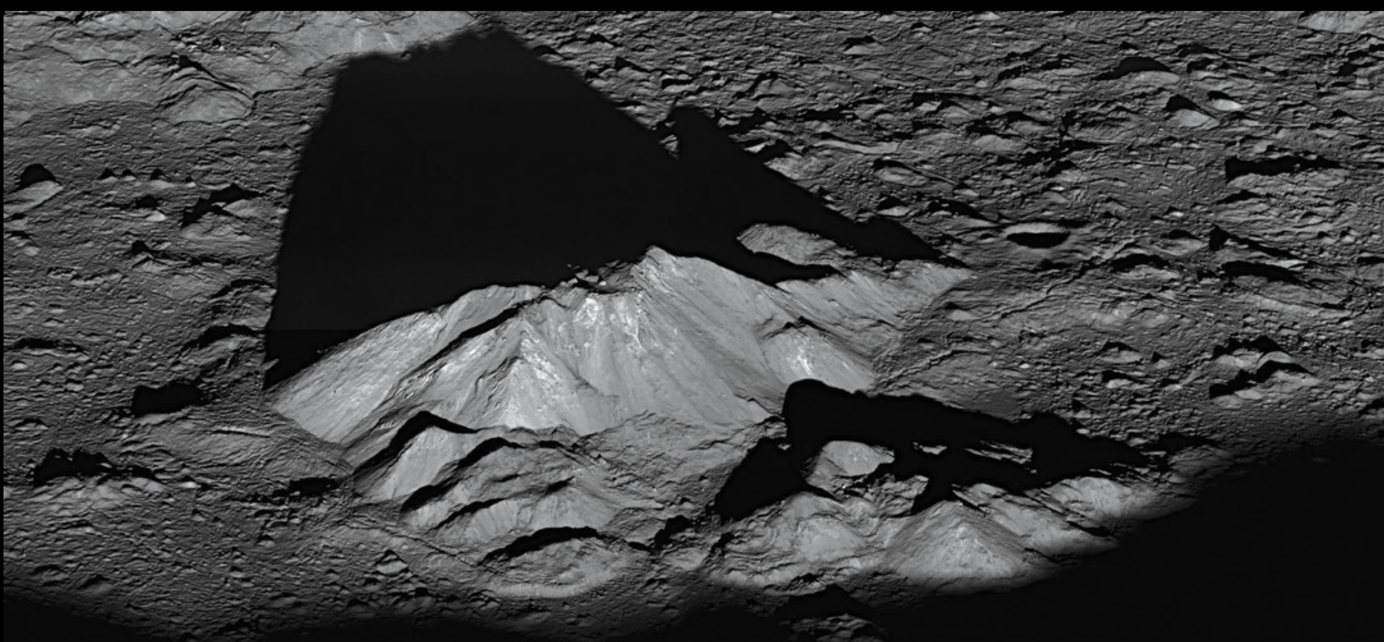


#1 ▶ HYDROCARBON HAVEN This globe boasts the solar system's only known surface lakes and seas beyond Earth. But these liquid bodies, seen here in blue and black, don't contain water. With surface temperatures of about –180°C (–290°F), this world is far too cold for that. Instead, it bears lakes and seas of liquid methane and ethane. Some are hundreds of kilometers across and up to several hundred meters deep.



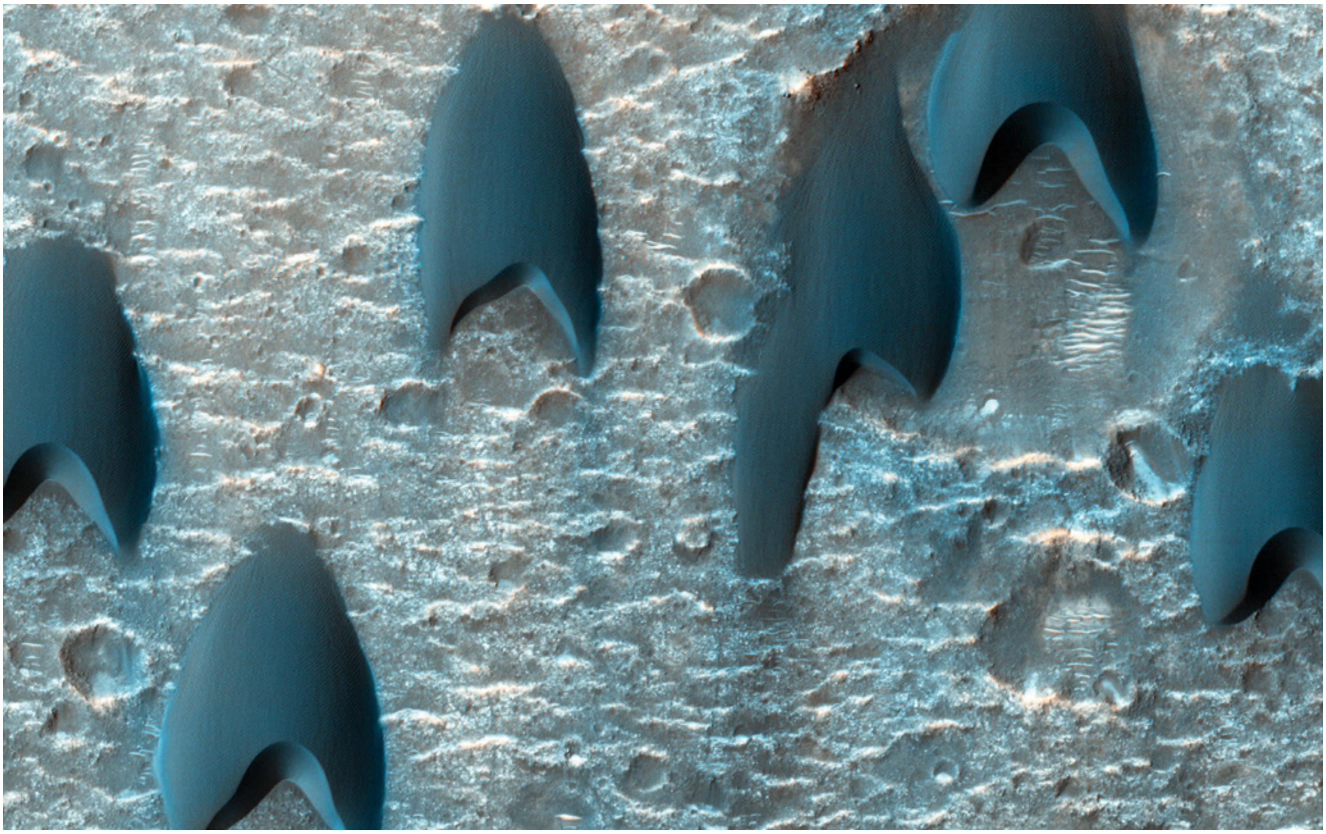
#2 ◀ BIG MOUTH Like the gaping maw of some obscure deep-sea fish, the impact crater Stickney dominates this view. The orangey, lineated features within the crater are land-slides that tumbled into the interior by the force of the object's weak gravity, which is just $\frac{1}{1000}$ that of Earth. The crater is 9 km (5.6 mi) wide; the entire sphere's average width is 22 km (13.7 mi).

#3 ▲ BIG EYE Named after William Herschel, who discovered this celestial body in 1789, the crater seen here is 130 km across, while its host is just under 400 km in diameter. How much bigger would the impactor have to have been, one wonders, to have shattered the world when it struck? A spacecraft obtained this image in visible light from about 103,000 km away.

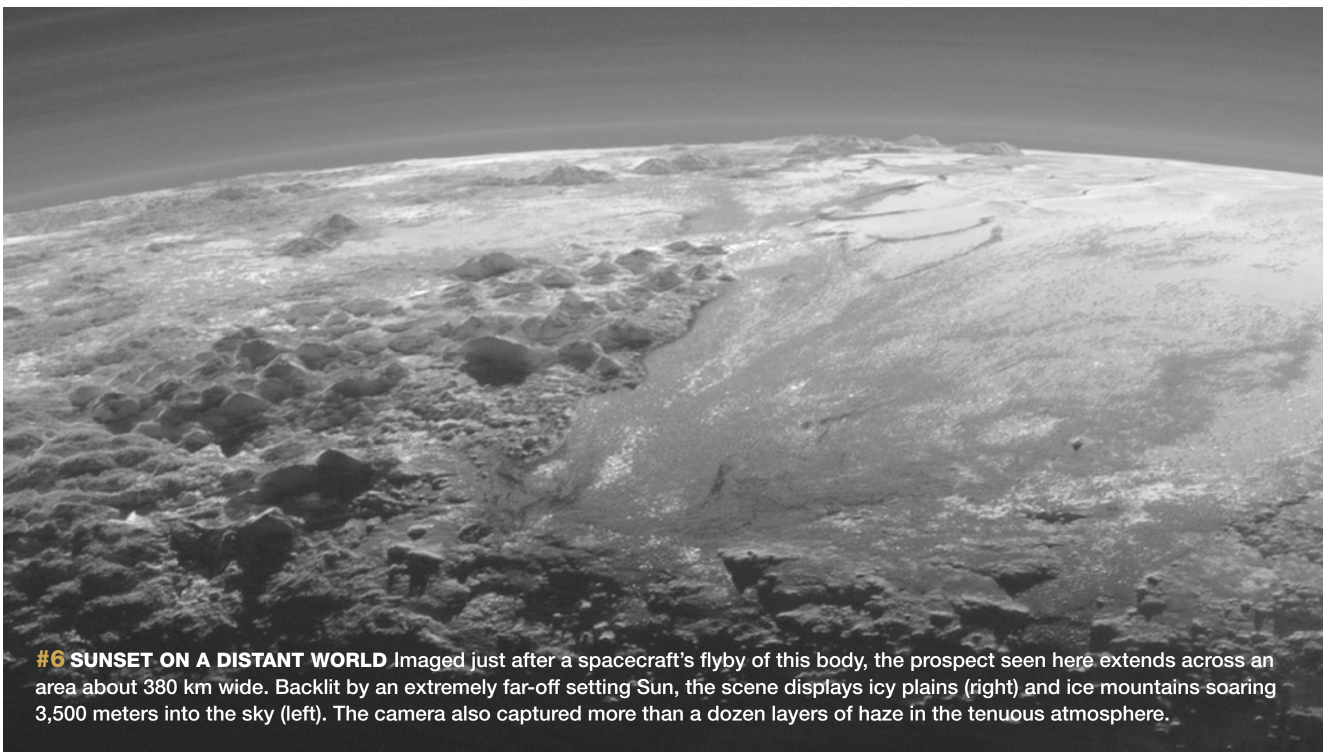


#4 ▲ LOW-ANGLED LIGHT It's hard to say which is more arresting above: the steep-sided peak or its shadow rearing up behind it like a dark premonition. To celebrate the fifth anniversary of the spacecraft that captured this image, NASA asked the public to vote for their favorite picture the craft had shot — this is it. The peak complex seen here is about 15 km wide, with the summit roughly 2 km above the surrounding crater floor.

#1: NASA / JPL-CALTECH / USGS; #2: NASA / JPL / UNIVERSITY OF ARIZONA; #3: NASA / JPL-CALTECH / SPACE SCIENCE INSTITUTE; #4: NASA / GODDARD / ARIZONA STATE UNIVERSITY

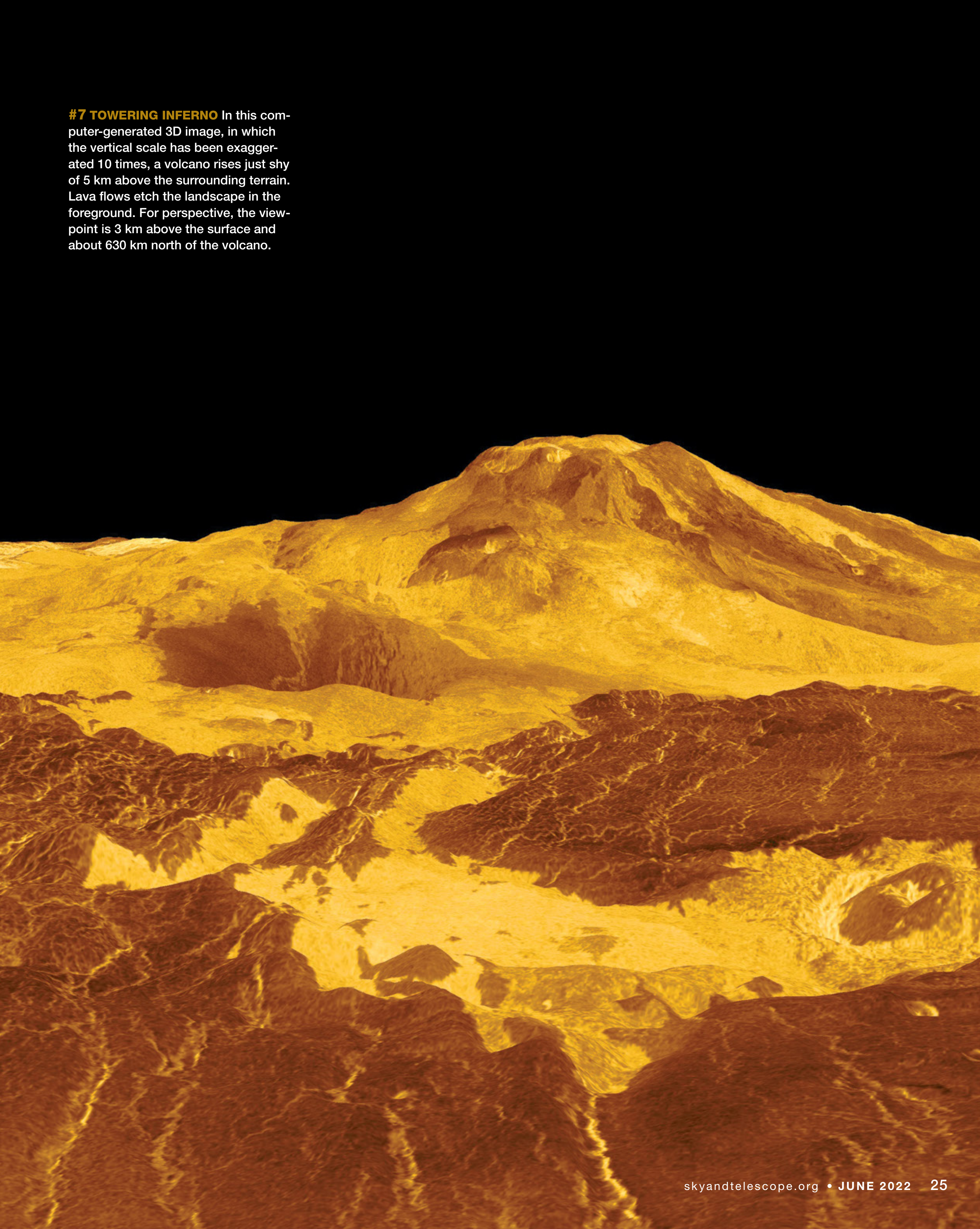


#5 ▲ FLOTILLA OF DUNES These chevron-shaped dunes are carved by wind acting on the sandy topography in a valley called Mawrth. Acquired on December 30, 2013, this image was taken from about 287 km above the surface, with the Sun about 48° above the horizon.



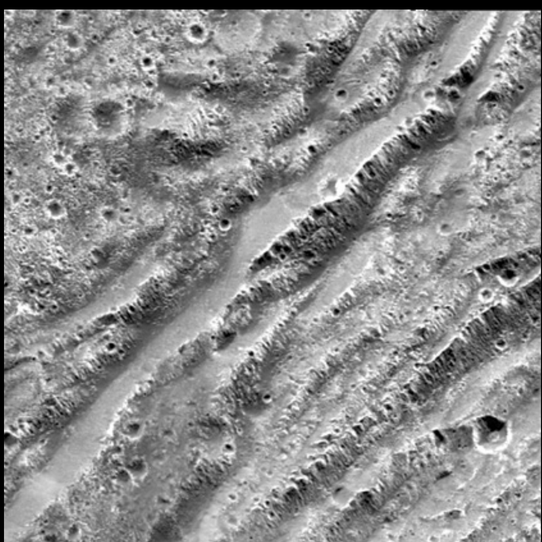
#6 SUNSET ON A DISTANT WORLD Imaged just after a spacecraft's flyby of this body, the prospect seen here extends across an area about 380 km wide. Backlit by an extremely far-off setting Sun, the scene displays icy plains (right) and ice mountains soaring 3,500 meters into the sky (left). The camera also captured more than a dozen layers of haze in the tenuous atmosphere.

#5: NASA / JPL / UNIVERSITY OF ARIZONA; #6: NASA / JOHNS HOPKINS UNIVERSITY APPLIED PHYSICS LABORATORY / SOUTHWEST RESEARCH INSTITUTE; #7: NASA / JPL

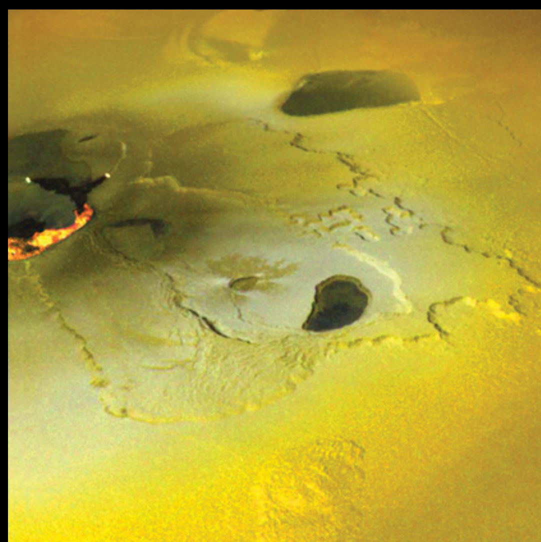


#7 TOWERING INFERNO In this computer-generated 3D image, in which the vertical scale has been exaggerated 10 times, a volcano rises just shy of 5 km above the surrounding terrain. Lava flows etch the landscape in the foreground. For perspective, the viewpoint is 3 km above the surface and about 630 km north of the volcano.

#8 ▶ GUSHING ORB This body is one of the most promising sites in the solar system to search for life beyond Earth. Backlighting by the Sun reveals a plume shooting from the small globe; the nearside is lit by a large neighboring world, similar to the way the sunlit Earth can illuminate the Moon with earthshine. The image was taken in blue light on April 2, 2013.

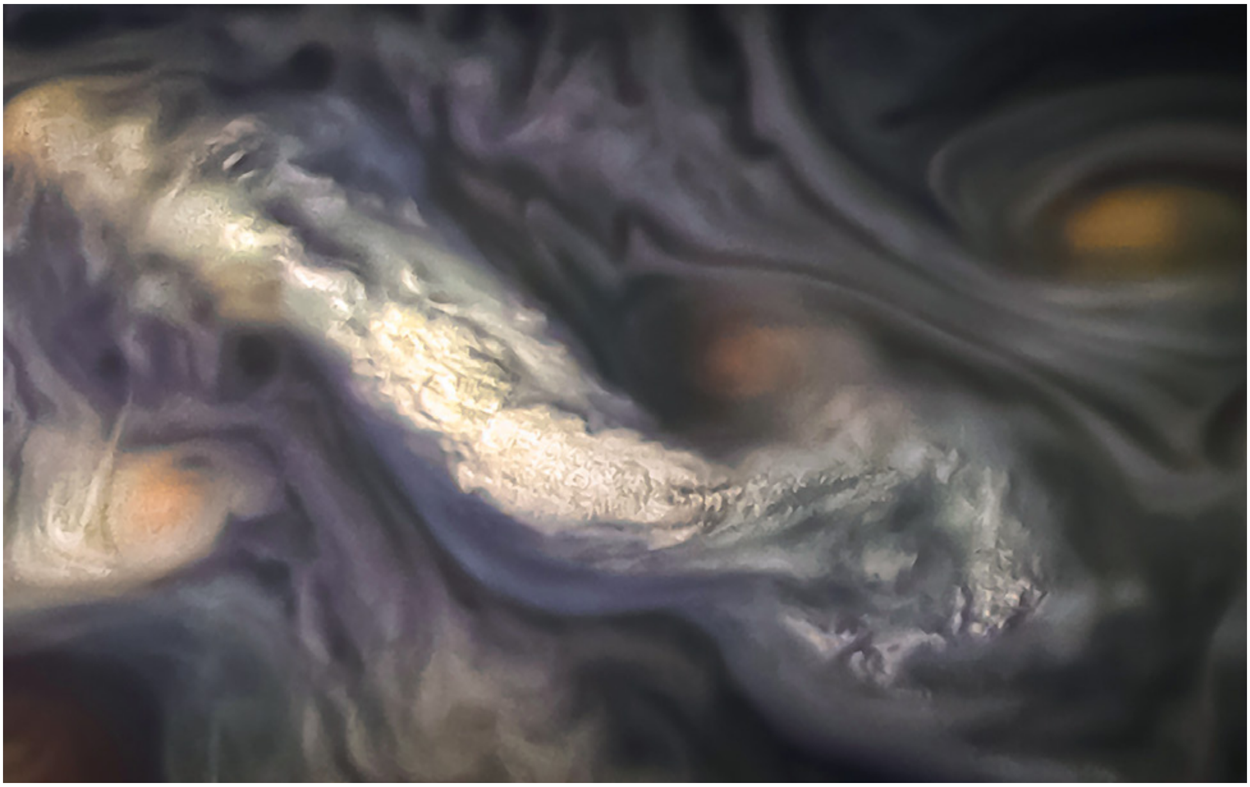


#9 ▲ PRIMEVAL LAND Geologists think that the ages-old, heavily cratered terrain seen here owes its rugged appearance to tectonic faulting akin to that found on Earth. Sunlight comes in from the west (top) of this image, which displays an area of about 16 km by 15 km.

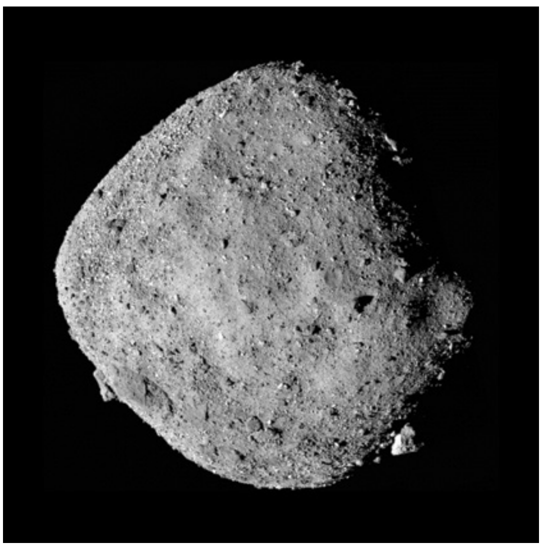


#10 ▲ VOLCANIC FLOW A spacecraft secured the images in this mosaic of a volcanic eruption on February 22, 2000. The yellow-orange arc at far left is a cooling lava flow about 60 km long, while the two bright dots near it indicate where molten rock has reached the surface at the toes of lava flows. The colorized image combines pictures using near-infrared, clear, and violet filters. The scene is about 250 km across.

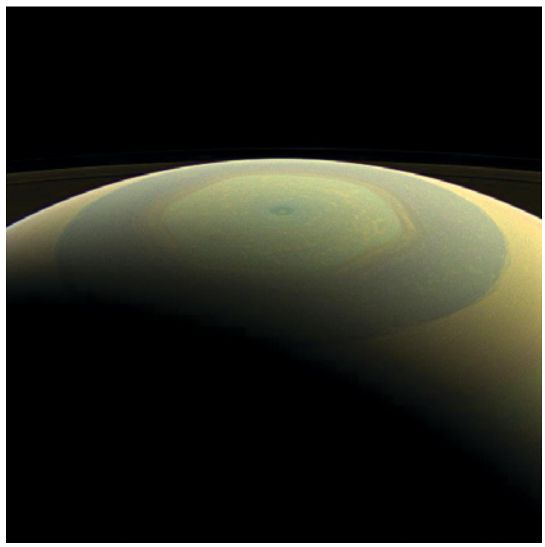
#8: NASA / JPL-CALTECH / SPACE SCIENCE INSTITUTE; #9: NASA / JPL / BROWN UNIVERSITY; #10: NASA / JPL / UNIVERSITY OF ARIZONA



#11 ▲ WHIRLING DERVISH High-altitude clouds rise above other swirling clouds in this color-enhanced image procured on July 15, 2018. The spacecraft that took the shot was about 6,200 km from the cloudtops, which scientists have since determined extend about 3,000 km down. Citizen scientist Jason Major created this striking vignette from spacecraft data.

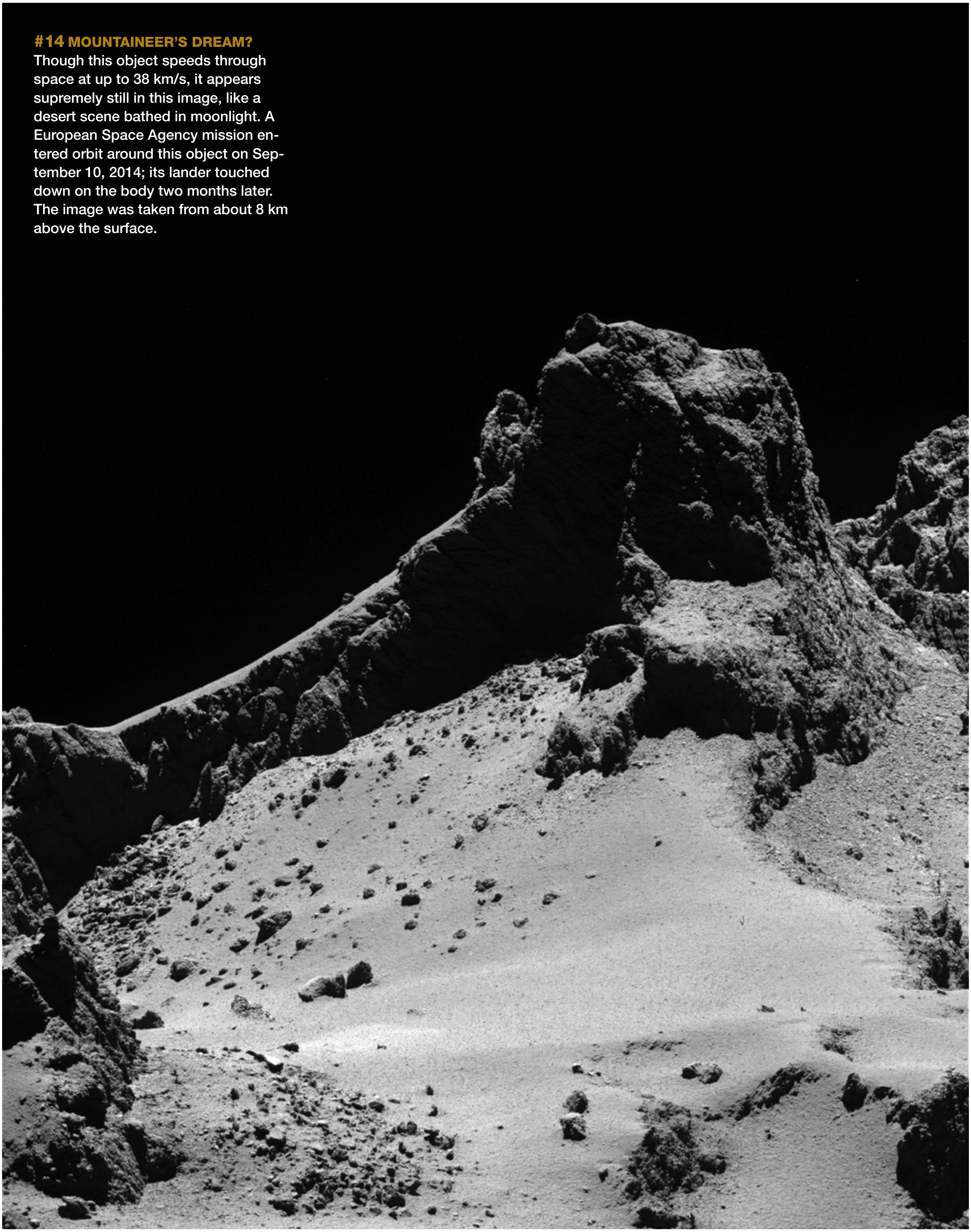


#12 ▲ SPHERICAL CUBE Appearing oddly die-shaped, this object has a diameter of just 490 meters. The images used to create the mosaic seen here were obtained on December 2, 2018, at a distance of about 24 km. The spacecraft that took the images later successfully retrieved a sample of this small body's rubble, which, if all goes well, will be returned to Earth in 2023.



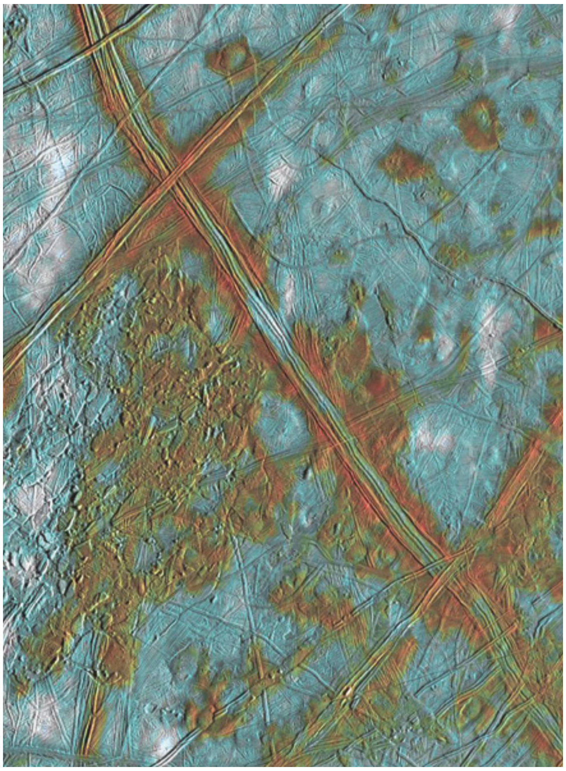
#13 ▲ BROAD SPECTACLE This wide-angle view was captured on July 22, 2013, from a distance of almost 1 million km. It combines red, green, and blue spectral filters to create a natural-color scene. This world's hexagonal northern jet stream surrounds a pole-centered storm resembling a hurricane, complete with an eye.

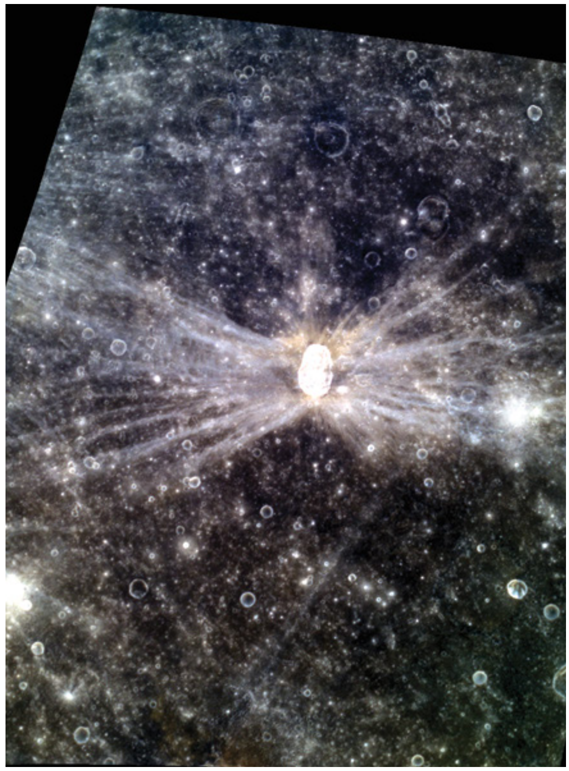
#11: NASA / JPL-CALTECH / SWRI / MSSS / JASON MAJOR; #12: NASA / GODDARD / UNIVERSITY OF ARIZONA; #13: NASA / JPL-CALTECH / SPACE SCIENCE INSTITUTE



#14 MOUNTAINEER'S DREAM?
Though this object speeds through space at up to 38 km/s, it appears supremely still in this image, like a desert scene bathed in moonlight. A European Space Agency mission entered orbit around this object on September 10, 2014; its lander touched down on the body two months later. The image was taken from about 8 km above the surface.

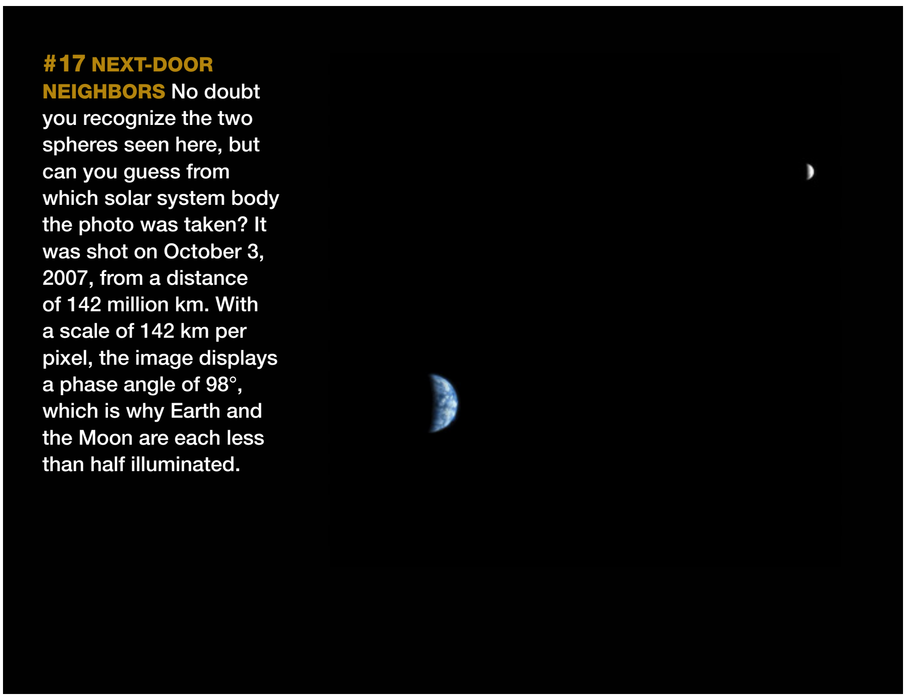
#14: ESA / ROSETTA / MPS FOR OSIRIS TEAM MPS / UPD / LAM / IAA / SSO / INTA / UPM / DASP / IDA





#15 ▲ ICY HIGHWAYS Ridges and fractures crisscross the frozen facade of this sphere. Some parts of the crust appear to have broken up, like sea ice in spring, and rafted to new positions. While this object is only about one-fourth Earth's diameter, scientists think it might contain as much as two times the water in all our planet's oceans combined.

#16 ▲ CELESTIAL BUTTERFLY Resembling a fossil insect with outstretched wings, this rayed crater is named in honor of Armenian painter Hakob Hovnatanian. The crater's oval shape and the rays' pattern imply the object that created this hole struck at a highly oblique angle. The whiteness of the rays suggests the impact was comparatively recent.



#17 NEXT-DOOR NEIGHBORS No doubt you recognize the two spheres seen here, but can you guess from which solar system body the photo was taken? It was shot on October 3, 2007, from a distance of 142 million km. With a scale of 142 km per pixel, the image displays a phase angle of 98°, which is why Earth and the Moon are each less than half illuminated.

HOW'D YOU DO?

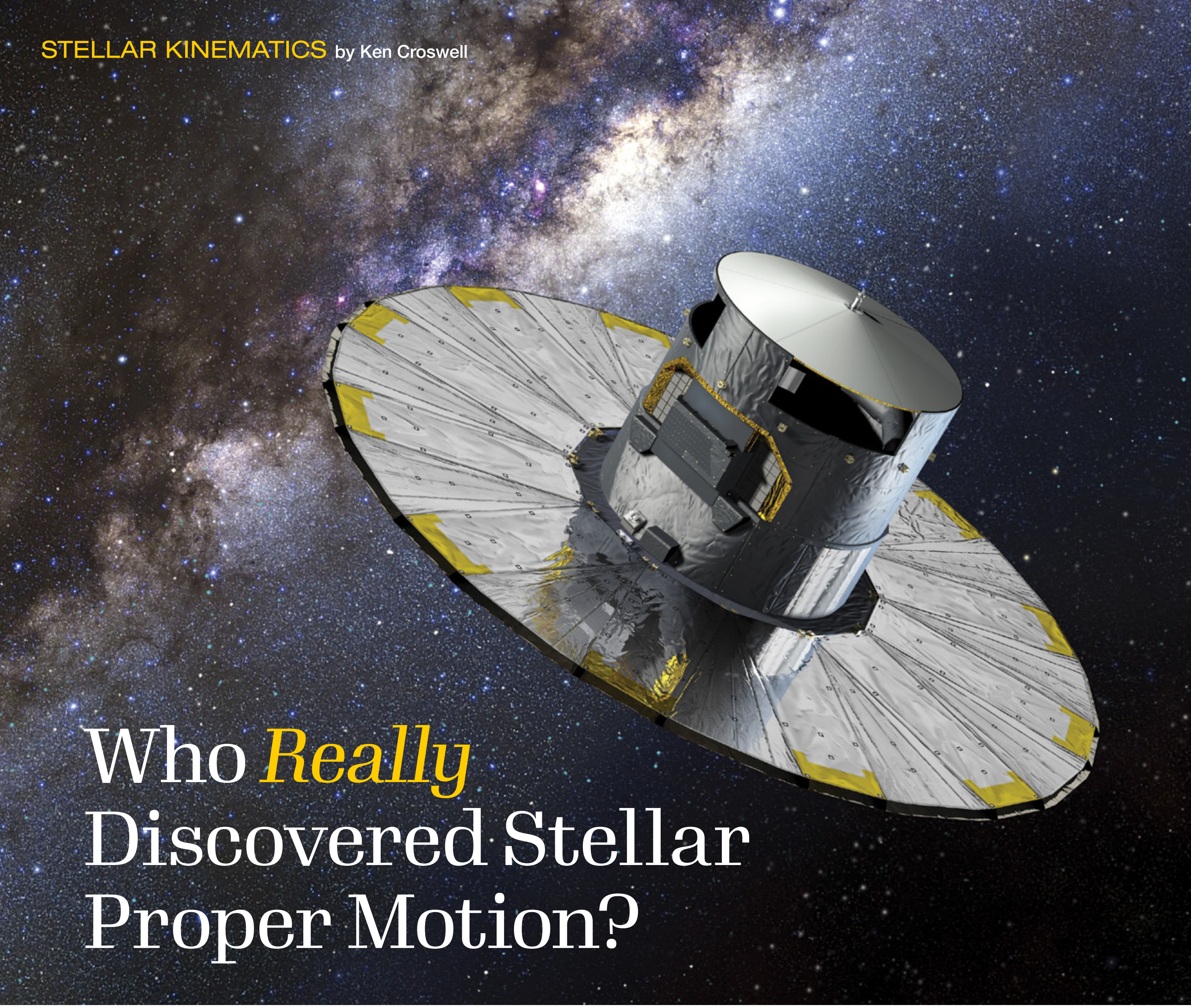
Your correct answers:

17: Planetary Scientist
13–16: NASA Devotee
9–12: Space Lover
5–8: Casual Skygazer
0–4: Astro Novice

ANSWER KEY:
#1: TITAN (CASSINI);
#2: PHOBOS (MRO);
#3: MIMAS (CASSINI);
#4: MOON (LRO);
#5: MARS (MRO);
#6: PLUTO (NEW HORIZONS);
#7: VENUS (MAGELLAN);
#8: ENCELADUS (CASSINI);
#9: GANYMEDE (GALILEO);
#10: IO (GALILEO);
#11: JUPITER (JUNO);
#12: BENNU (OSIRIS-REX);
#13: SATURN (CASSINI);
#14: COMET 67P/CHURYUMOV-GERASIMENKO (ROSETTA);
#15: EUROPA (GALILEO);
#16: MERCURY (MESSENGER);
#17: FROM MARS (MRO)

#15: NASA / JPL / UNIVERSITY OF ARIZONA; #16: NASA / JHUAPL / CARNEGIE INSTITUTION OF WASHINGTON; #17: NASA / JPL / UNIVERSITY OF ARIZONA

STELLAR KINEMATICS by Ken Croswell



Who *Really* Discovered Stellar Proper Motion?

Contrary to many books and articles, the answer isn't who you think.

Edmond Halley is one of the heroes of astronomy. The great English astronomer recognized that three supposedly separate comets were actually the same one reappearing every 75 or 76 years. He even boldly predicted the comet's return, a prediction that came true, but only after he died in 1742.

Halley also recognized that the transits of Venus in 1761 and 1769 could pin down the distance between the Sun and Earth — another prediction that came true, but again, only after his death.

However, numerous books and articles state that Halley made another key discovery, one arguably far more important than his others: stellar proper motion. In the 1710s he said that four bright stars — Sirius, Arcturus, Betelgeuse, and Aldebaran — had moved from the positions that ancient astronomers had recorded 1,800 years earlier.

"Halley was an excellent astronomer," says Frank Verbunt (Radboud University, the Netherlands). "The fact that he was wrong doesn't mean that he was a bad astronomer."

Long suspicious of Halley's proper motion work, Verbunt recently looked into it with his Radboud colleague Marc van der Sluys. They concluded that Halley didn't actually detect any movement of the stars, because positional errors in the old observations were simply too large to show reliable

▲ **PRECISION-ENGINEERED** Launched in 2013, the European Space Agency's Gaia spacecraft is measuring precise parallaxes and proper motions of countless stars. It's the successor to the Hipparcos satellite.

ESA / D. DUCROS

proper motions. Verbunt and van der Sluys instead credit the true discovery of stellar proper motion to French astronomer Jacques Cassini. Two decades after Halley's work, Cassini used better measurements to deduce that Arcturus had in fact moved.

A Proper Definition

Proper motion is the apparent movement of a star, year after year, century after century, as measured in fractions of a degree per year or century. Of all the bright stars visible to Halley in England and Cassini in France, the one with the largest proper motion is Arcturus. Modern measurements from the Hipparcos satellite indicate that the star moves 3.8 arcminutes, or about 1⁄16 of a degree, per century. That's about 1⁄8 the diameter of the Moon. The only bright star that surpasses Arcturus in proper motion is Alpha Centauri — the nearest star system to the Sun.

All other things being equal, the closer a star, the larger its proper motion, in the same way an airplane flying overhead looks like it's moving a lot faster than one near the horizon. In addition, the relationship between proper motion and distance is simple. If two stars have exactly the same true velocity across our line of sight, a star located twice as far as another will have exactly half the other's proper motion.

Proper motion is essential for calculating the paths of stars through space. Furthermore, proper motion led to an even greater discovery: the first distance measurement of a star beyond the solar system, as we'll see shortly. And through proper motion studies we've discovered many of our nearest stellar neighbors, including most of those located within 8 light-years of the Sun.

A Proper Flopper

Ancient astronomers thought that the stars were mere pinpricks in the heavens and thus didn't change position. Living in more modern times, Halley knew better, and he set out to investigate whether any star had moved within its constellation.

To do so, he compared the positions of some of the brightest stars recorded 1,800 years earlier in Ptolemy's *Almagest* with positions of the same stars measured during his lifetime. As Halley wrote in his 1718 paper in *Philosophical Transactions*, ". . . these Stars being the most conspicuous in Heaven, are in all probability the nearest to the Earth, and if they have any particular Motion of their own, it is most likely to be perceived in them, which in so long a time as 1800 Years may shew it self by the alteration of their places, though it be utterly imperceptible in the space of a single Century of Years."

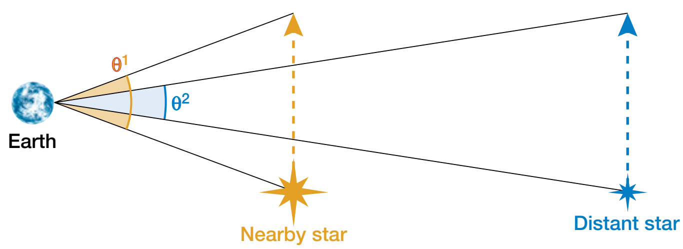
The brightest of Halley's selected stars is indeed nearby. Sirius is not only the brightest star in the night sky, but it's also only 8.6 light-years away — twice the distance of Alpha Centauri. Halley claimed Sirius was moving south relative to the ecliptic, and indeed that's what the star is doing. Furthermore, Halley also got the size of its proper motion right. Over

▲ **HALLEY'S LUCKY STAR** Edmond Halley reported what turned out to be the correct proper motion for Sirius, the brightest star in the winter constellation Canis Major. However, recent research finds that he did so by accident — the proper motions he deduced for three other bright stars were all wide of the mark.

1,800 years, Halley noted, Sirius had moved 42 arcminutes south — close to the correct figure of 38.6 arcminutes, which Verbunt and van der Sluys derived from Hipparcos data.

So far, so good. But Halley stumbled badly with Arcturus, the next brightest star on his list. He said that during the past 1,800 years the star had moved south relative to the ecliptic by 33 arcminutes. That's less than half the correct number, which Verbunt and van der Sluys calculate to be 68.6 arcminutes.

Betelgeuse, the red supergiant in Orion, is the third brightest star in Halley's list. It's distant and so should have only a minuscule proper motion. Yet Halley claimed Betelgeuse had moved northward by "almost a degree." In fact, in 1,800 years the star moves in that direction by a mere 0.3 arcminutes. Halley said the faintest star of the four, Aldebaran, had moved south 35 arcminutes over that same timespan, whereas the actual number is just 5.9 arcminutes.

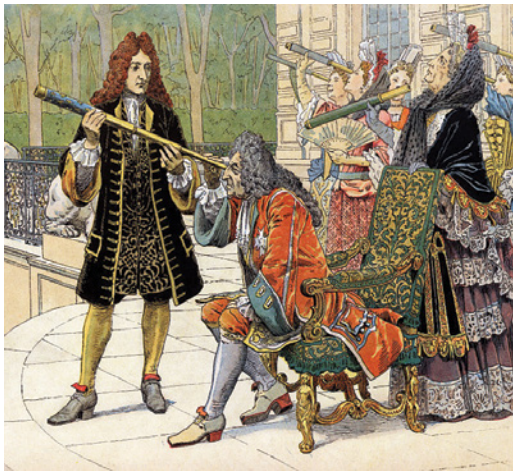


▲ **NEAR AND FAR** The closer a star, the larger its proper motion tends to be, which is why Edmond Halley focused his hunt on the brightest stars, thinking they were the nearest to Earth. Some bright stars, such as Sirius, are indeed nearby; others, such as Betelgeuse, aren't.

SIRIUS: GARY SERONIK; PROPER MOTION AND DISTANCE: GREGG DINDERMAN / *S&T*

"So Halley has four stars," Verbunt says. "In three cases he's far off, and in one case he's more or less correct, and I claim that this is by accident." Verbunt says the typical latitude error (measured with respect to the ecliptic) in Ptolemy's catalog is about 23 arcminutes, which explains Halley's results. In like fashion, if someone measures the heights of four people with a typical error of several inches, one of the measured heights may turn out to be right, but it's impossible to know in advance which one it will be.

In spite of all of Halley's efforts in England, the first successful detection of stellar proper motion came instead from across the Channel in France.



◀ **FAMOUS FAMILY** The Cassini name is familiar today thanks to the work of astronomer Giovanni Domenico Cassini. However, it was his son Jacques (depicted here holding a telescope to the eye of King Louis XIV) who discovered stellar proper motion.

The French Connection

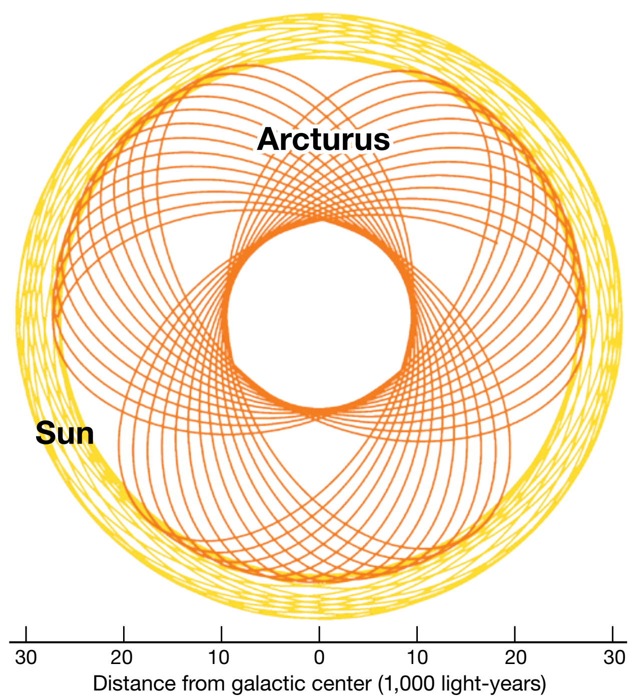
Giovanni Domenico Cassini was born in Italy in 1625 and moved to France in 1669, soon becoming director of the newly built Paris Observatory (*S&T:* May 2021, p. 58). While in Italy, Cassini measured the rotation periods of Mars and Jupiter, and later in France he discovered four moons orbiting Saturn, as well as the dark gap in its rings that today bears his name. His name was also on the Saturn-orbiting spacecraft that plunged (intentionally) into the planet in 2017.

Despite his accomplishments, for many years Cassini didn't think the Earth circled the Sun. In contrast, his younger son Jacques, born in France in 1677, had no problem with heliocentrism, but he didn't care for Isaac Newton's newfangled theory of gravity. "The Cassinis had a knack for being slightly behind the times," astronomer Barbara Ryden (Ohio State University) once wrote.

No matter. In 1738, Jacques Cassini looked carefully into Halley's work on proper motion. "He concluded that the measurements reported by Ptolemy were simply not accurate enough to do this, which is exactly the correct statement," Verbunt says.

So Cassini took a different approach. Since the ancient observations weren't sufficiently precise, he examined measurements from the 1500s, 1600s, and 1700s. Although this

▲ **GOLD STAR** One of the most beautiful stars in the heavens, Arcturus is a *K*-type giant located 37 light-years from Earth and is the brightest star north of the celestial equator. Also known as Alpha Boötis, it's a prominent sight on June evenings.



▲ **A PROPER STAR** Arcturus boasts a large proper motion because it's nearby and has a highly elliptical orbit (orange) around the galaxy's center, whereas the Sun's orbit (yellow) is fairly circular.

JACQUES CASSINI: STEFANO BIANCHETTI / CONTRIBUTOR / GETTY IMAGES; ARCTURUS: AKIRA FUJII; ARCTURUS ORBIT DIAGRAM: GREGG DINDERMAN / *S&T*; SOURCE: ADRIAN PRICE-WHELAN (HTTP://GALA.ADRIAN.PW) AND FLATIRON INSTITUTE meant he had a shorter interval of time over which to detect stellar movements, it also meant he used only the best data.

In this way, he detected the proper motion of Arcturus. From 1584, when Danish astronomer Tycho Brahe observed the star, to 1738, when Cassini himself did, Arcturus had moved south by 5 arcminutes. That's close to the correct figure, which Verbunt and van der Sluys put at 6.4 arcminutes. In contrast, Cassini claimed he couldn't detect the proper motion of Sirius, which, as we know today, is smaller than Arcturus's.

Why Arcturus?

What makes Arcturus special? Why does this beautiful orange giant boast the largest and easiest-to-detect proper motion of all the bright stars visible from France, making it the "star" of the proper motion story?

The answer, we now know, is because Arcturus is unique. Of all the stars first magnitude and brighter, Arcturus is the only one that doesn't belong to the *thin disk*. As its name implies, the thin disk population consists of stars that lie close to the Milky Way's midplane. Most are within 1,000 light-years of this 120,000-light-year-diameter plane. The thin disk includes young stars like Betelgeuse, older (but still young) stars like Sirius, middle-aged stars like the Sun, and somewhat older stars like Alpha Centauri. These suns revolve rapidly around the Milky Way's center on fairly circular orbits and on similar paths and therefore have fairly small velocities relative to one another. As a result, their velocities with respect to the Sun are small, leading to modest proper motions.

In contrast, Arcturus is an old, somewhat metal-poor star that doesn't belong to the thin disk population. Instead, its orbit around the Milky Way's center is highly elliptical. Right now, Arcturus is much farther from the galaxy's center than usual. As a result, the star is moving slowly around the galactic center, just as Halley's Comet is slowest when farthest from the Sun. Arcturus therefore has a large velocity relative to us and a large proper motion, even though it's 37 light-years from the Sun — more than four times farther than Sirius.

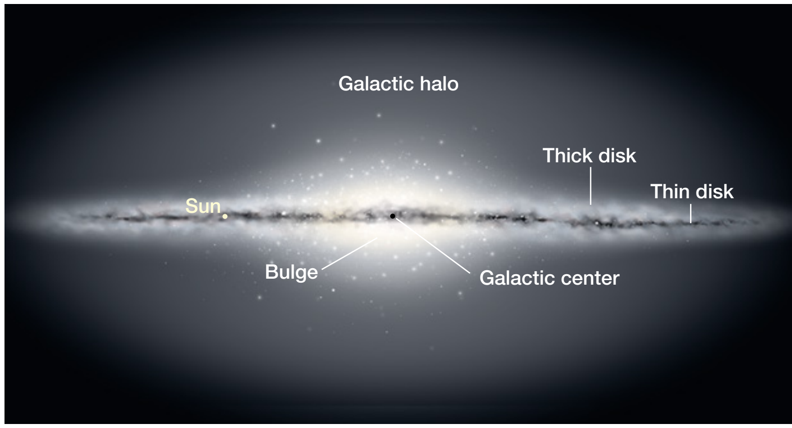
Nevertheless, contrary to a misconception that has propagated widely, Arcturus never leaves the Milky Way's thin disk. Arcturus has only a modest velocity perpendicular to the galactic plane: The star is moving upward at just 4 kilometers (2½ miles) per second. That's even smaller than the Sun's vertical velocity, which is 7 km per second, and the Sun never rises above or dives below the galactic disk.

Velocities in 3D

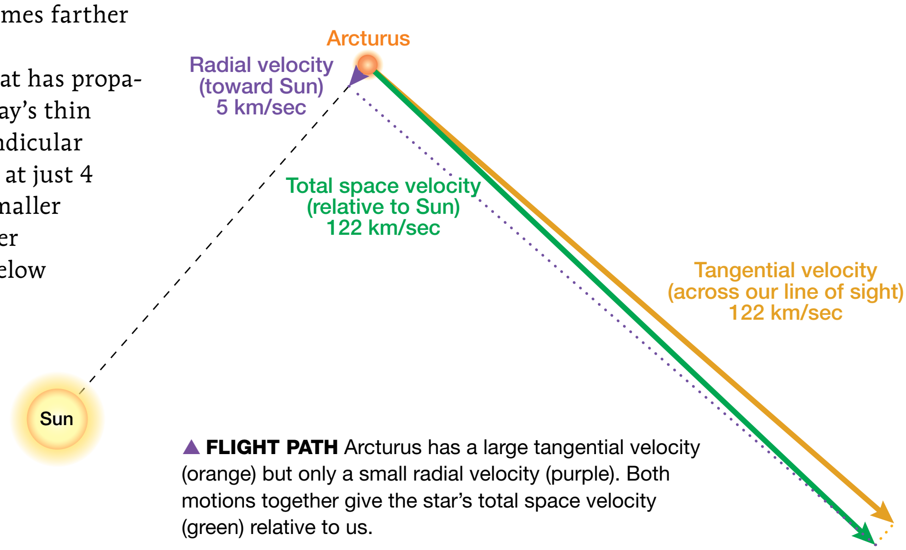
Jacques Cassini's discovery of proper motion in 1738 opened the way to determining three-dimensional velocities of stars through space. But proper motion alone doesn't tell you a star's true speed across our line of sight. To calculate that number, which is called the *tangential velocity*, astronomers also have to measure the star's distance. In Cassini's day, no one had ever done that — but proper motion played a key role in the first success.

Astronomers had long been trying to measure the distances to stars via *stellar parallax* — the tiny shift that occurs in a star's apparent position because we view the star from slightly different vantage points as Earth circles the Sun. Aristotle had cited the failure to detect stellar parallax as evidence that Earth doesn't really orbit the Sun. In fact, the farther a star, the smaller its parallax, and even the closest suns are so distant that their parallaxes are tiny, making them difficult to measure. Efforts to find stellar parallax targeted bright stars, because these were presumed to be the nearest and therefore should have easy-to-detect parallaxes.

But Friedrich Wilhelm Bessel at Königsberg Observatory in Prussia took a radically different approach, betting on a dark horse named 61 Cygni. At 5th magnitude, 61 Cygni is barely visible to the naked eye. He chose this obscure star because Italian astronomer Giuseppe Piazzi had found that it had a



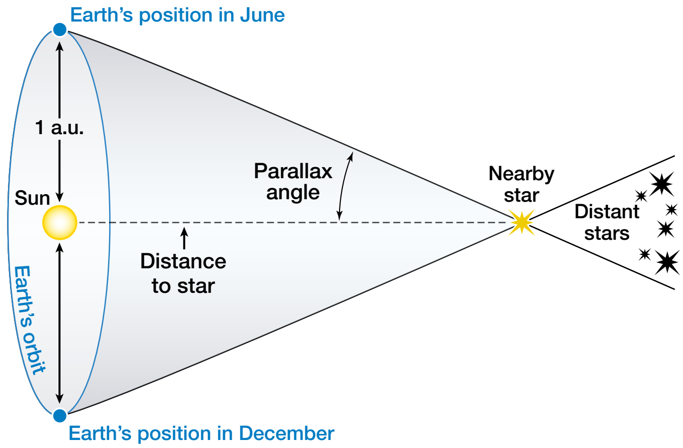
▲ **EDGE-ON VIEW** The Milky Way's thin disk population includes the Sun and most of its stellar neighbors, which revolve fast around the galactic center on fairly circular orbits.



▲ **FLIGHT PATH** Arcturus has a large tangential velocity (orange) but only a small radial velocity (purple). Both motions together give the star's total space velocity (green) relative to us.

MILKY WAY THIN DISK DIAGRAM: GREGG DINDERMAN / *S&T*; ARCTURUS VELOCITY DIAGRAM: GREGG DINDERMAN / *S&T*; *SOURCE*: KEN CROSWELL large proper motion, more than twice that of Arcturus. Bessel correctly reasoned that the large proper motion meant 61 Cygni was nearby, and in 1838 he successfully measured the star's parallax, deriving a distance close to the modern value of 11.4 light-years.

In addition to proper motion and distance, the third and final quantity astronomers usually need to calculate three-dimensional velocities of stars through space is the *Doppler shift*. Light waves from a star moving toward us get scrunched up to shorter, or bluer, wavelengths, producing a *blueshift* in the stellar spectrum; light waves from a star moving away from us get stretched out to longer, or redder, wavelengths, producing a *redshift*. The size of the blueshift or redshift reveals how fast the star is moving toward or away from us — its so-called *radial velocity*. Astronomers began detecting Doppler shifts in the late 1800s.



▲ **A MATTER OF PERSPECTIVE** Astronomers view a star from opposite sides of Earth's orbit in June then in December, imparting a slight apparent motion to the star. Known as *parallax*, the larger this movement, the closer the star is to us.

Meet the New Neighbors

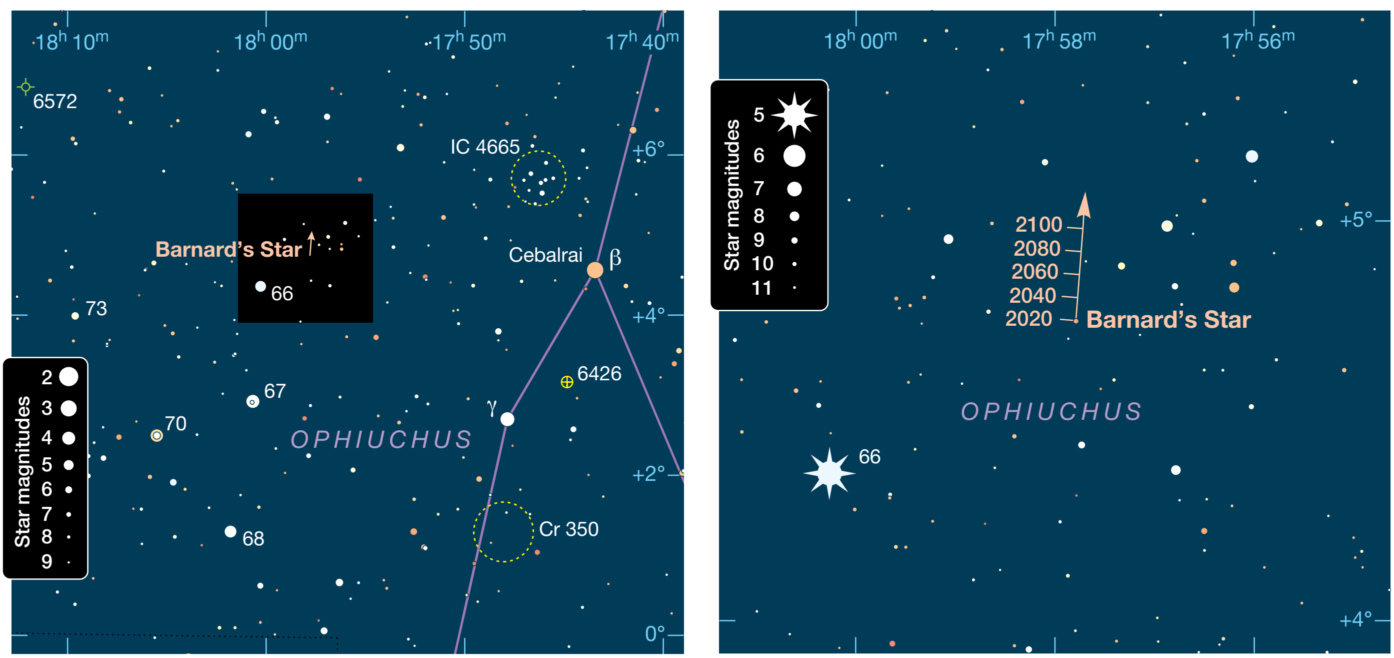
As we know today, most stars are much less luminous than the Sun. Most are red dwarfs; many others are orange or white dwarfs. That means we can't assume, as Halley had, that the brightest stars are the closest. Instead, most of the nearest stars are dim, so it takes great effort to find them. And proper motion provides the perfect clue.

Because a star's proper motion decreases the farther it is from the Sun, astronomers have identified many of our nearest stellar neighbors by seeking those with large proper motions. The 1910s saw three such discoveries, each involving a red dwarf lying within just 8 light-years of the Sun.

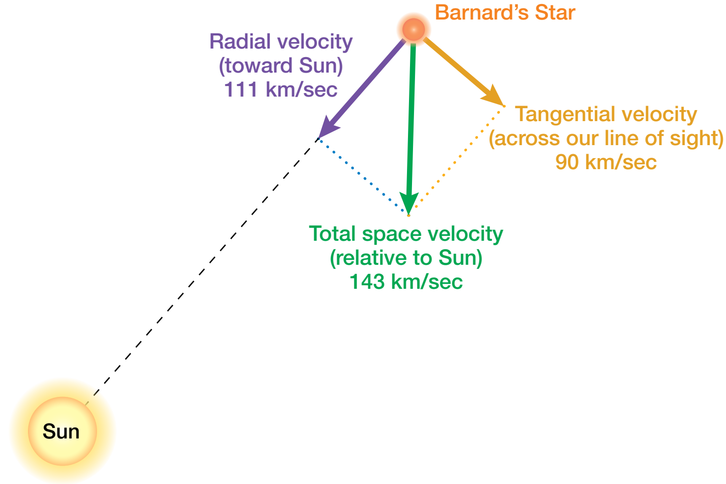
In 1915 Robert Innes, a Scottish-born astronomer working in South Africa, discovered the very nearest star to the solar system, Proxima Centauri. The red dwarf is 4.25 light-years from Earth and is a member of the Alpha Centauri system, whose proper motion Proxima shares.

Then, in 1916, American astronomer Edward Emerson Barnard discovered the star with the largest proper motion. Located in the constellation Ophiuchus, Barnard's Star moves 10.4 arcseconds a year. That works out to a bit more than half a lunar diameter per century. The 9.5-magnitude star owes its record-breaking proper motion to two factors. First, it's nearby, the second closest star system to the Sun. When Barnard spotted the star, it was 6.00 light-years from us.

▼ **FLYING THROUGH OPHIUCHUS** With the largest proper motion of any star in the night sky, 9.5-magnitude Barnard's Star dashes nearly due north in the constellation Ophiuchus by a bit more than half a lunar diameter per century.



GREGG DINDERMAN / S&T



▶ **FASTER THAN A SPEEDING BULLET** Barnard's Star has both a large tangential velocity (orange) and a large radial velocity (purple), which add together to give a large total space velocity (green) with respect to the Sun. The swift speed and close proximity of Barnard's Star mean that astronomers can now measure its radial velocity without knowing its Doppler shift.

Today it's 5.96 light-years away. And yes, thanks to the Gaia spacecraft, we really do know those numbers that precisely. Second, Barnard's Star is rushing past us. It has a much more elliptical orbit around the galactic center than the Sun does.

Next, in 1918, German astronomer Max Wolf discovered Wolf 359, a high-proper-motion star in Leo lying 7.9 light-years from the Sun. For many years this dim red dwarf was the least luminous star known.

A century then passed with no further discoveries of any stars within 8 light-years of the Sun. In the 2010s, however, Kevin Luhman (Pennsylvania State University) used proper motion to detect two nearby star systems — that is, if you consider brown dwarfs to be stars (*S&T:* April 2022, p. 34). The closer system, named Luhman 16 and located in Vela just 6.5 light-years from Earth, consists of two brown dwarfs that orbit each other. The other system, WISE J0855-0714, is 7.3 light-years away in Hydra. It's a single brown dwarf that's the coldest yet seen, with a temperature measured at a chilly 250 kelvin, or –23°C (–10°F).

Today, because of the data gathered by the Hipparcos and Gaia spacecraft, we know the parallaxes and proper motions of countless stars. Furthermore, these data are so precise that astronomers can now calculate the velocities of several nearby stars without measuring their Doppler shifts. Instead, changes in proper motions reveal the stars' radial velocities (see box below).

During the past century stellar kinematics have revealed much about the stars as well as the origin and evolution of the Milky Way Galaxy. Historically, the field began with proper motion — a discovery that Jacques Cassini made in 1738 both because he used the best data available and because Arcturus breaks the rules and doesn't follow the stellar crowd.

■ **KEN CROSWELL** earned his PhD at Harvard University for studying the Milky Way Galaxy. He is the author of eight books, including *The Alchemy of the Heavens* and *Planet Quest*.

FURTHER READING

"Why Halley Did Not Discover Proper Motion and Why Cassini Did" by Frank Verbunt and Marc van der Sluys. *Journal for the History of Astronomy*, 50, 383-397 (2019): **https://is.gd/JHA_Halley**

"Astronomers Uncover New Way to Measure the Speed of Stars" by Ken Croswell. *Proceedings of the National Academy of Sciences*, 119 (3) e2122586119 (2022): **https://is.gd/PNAS_Croswell**

Say Goodbye to the Doppler Shift?

The Hipparcos and Gaia spacecraft have provided such precise stellar positions that, in a few cases, they now reveal how quickly stars move toward or away from us, with no need to measure their Doppler shifts.

Here's how it works. Suppose someone hurls a baseball at you that barely misses your head. When the ball is far away, its speed toward you is high (it has what astronomers call a large radial velocity), but its proper motion is tiny since it has almost no apparent sideways motion. As the ball speeds past your head, though, the ball's radial velocity drops to zero (thankfully, the ball doesn't hit you!), but its proper motion reaches a peak, because now the ball is racing across your line of sight. Then, as the ball begins to recede, its radial velocity away from you increases, but now the proper motion decreases. Thus, as the radial velocity goes down, the proper motion goes up, and vice versa. By measuring the increase or decrease in proper motion, along with the ball's distance and proper motion, you can determine how fast the ball is moving toward or away from you.

This technique is ideal for measuring stars that are both nearby and moving fast relative to the Sun. That's why Barnard's Star is the best target. In 2021 Lennart Lindegren and Dainis Dravins (both at Lund Observatory, Sweden) compared proper motion data from Hipparcos and from Gaia to deduce that the star is rushing our way at 111 kilometers per second, with an uncertainty of just 0.4 kilometers per second. Furthermore, this speed agrees with the star's Doppler value. Lindegren and Dravins also measured accurate radial velocities for several other nearby stars, including Proxima Centauri and 61 Cygni B, all without using their Doppler shifts.

GREGG DINDERMAN / *S&T*, SOURCE: KEN CROSWELL

MERGING SPRINGTIME SPIRALS by Steve Gottlieb

Let's Get TOGETHER

Get your big scope out and feast your eyes on some remarkable distorted galaxies.

Galactic mergers play a key role in the formation and evolution of galaxies, with the most spectacular examples involving massive, gas-rich spirals. When galaxies resembling the Milky Way collide, gravitational tides fracture the delicate pinwheels, producing dramatic bridges, plumes, and tails that stretch for more than 100 million light-years. The real action, though, occurs in the centers of these galaxies, which are deeply buried inside a shroud of obscuring dust. Despite this barrier, astronomers have succeeded in modeling the evolution of spiral mergers using computer simulations and multiwavelength studies.

During a smash-up, galactic bars funnel a massive inflow of molecular gas and dust to the region of the nucleus. The gas can ignite a nuclear starburst, or it may trigger an *active galactic nucleus* (AGN) by feeding a gas-guzzling *supermassive black hole* (SMBH). The surrounding dust absorbs most of the optical and ultraviolet radiation produced by newborn massive stars or emitted by the SMBH's accretion disk. This energy is re-emitted as heat, boosting the galaxy's infrared luminosity. In a *luminous infrared galaxy* (LIRG), the output surpasses 100 billion times the Sun's luminosity.

As a merger advances, the dust-enshrouded nucleus launches a fast outflow of heated gas. In a feedback process, the energy can both spark and stifle star formation, and regulate the feeding of the SMBH. These episodic processes occur in the nuclei of both merging galaxies. Eventually, the coalescing merger is depleted of dust and gas — some is blown out into intergalactic space — and star production is

▲ **ARP 302** These two merging galaxies in Boötes, both gas-rich spirals, are at the very early stages of their interaction. The Hubble Space Telescope image beautifully reveals that the galaxy at lower left (VV 340b) is face-on while the one at upper right (VV 340a) is edge-on.

ALL IMAGES UNLESS OTHERWISE NOTED: NASA / ESA / THE HUBBLE HERITAGE TEAM / STSCI / AURA / A. EVANS (UNIVERSITY OF CHARLOTTESVILLE / NRAO / STONY BROOK UNIVERSITY) shut down. The metamorphosis results in a massive, gas-poor elliptical galaxy.

Astronomers identify five stages in a major merger, involving two or three close encounters over a billion-year time frame. Several details remain poorly understood, but future research with the James Webb Space Telescope, which operates in the dust-busting infrared, should help resolve several open questions. The stages are:

M1: pre-merger pair on their first approach with no prominent tidal features.

M2: early-stage interacting pair with obvious tidal tails and a bridge.

M3: mid-stage with multiple nuclei in a disturbed overlapping disk, with visible tidal tails.

M4: late-stage with a single nucleus and some remaining tidal features.

M5: coalescent remnant with a diffuse envelope and perhaps shells, but no tidal trauma.

Let's tour seven mergers well placed in springtime that highlight the stages in order from M1 through M4, with views through my 18-inch and a couple of mega-size telescopes.

The Sole M1

Arp 302 (VV 340) is an early M1 interaction involving two gas-rich spirals of equal magnitude, with their cores 38″ apart. The northern galaxy's infrared emission surpasses 500 billion times that of our Sun's, while massive star clusters line the spiral arms of the southern galaxy. Arp 302 is located 3.6° southeast of 2.4-magnitude Epsilon (ε) Boötis, also known as Izar, a gorgeous pair separated by 2.9″ with a 2.6-magnitude yellow-orange primary and 4.8-magnitude secondary. The 6.9-magnitude star HD 132304 is 10′ northeast of the galaxies and provides a handy signpost.

I found a single extended glow at 175× with my 18-inch reflector, but boosting the magnification to 285× split the duo. The northern edge-on appears as a fairly thin 30″ slash. The face-on spiral hovers just to its south as a hazy circular glow, about 20″ in diameter. A 15th-magnitude star at its northern edge separates the two galaxies.

A Pair of M2s

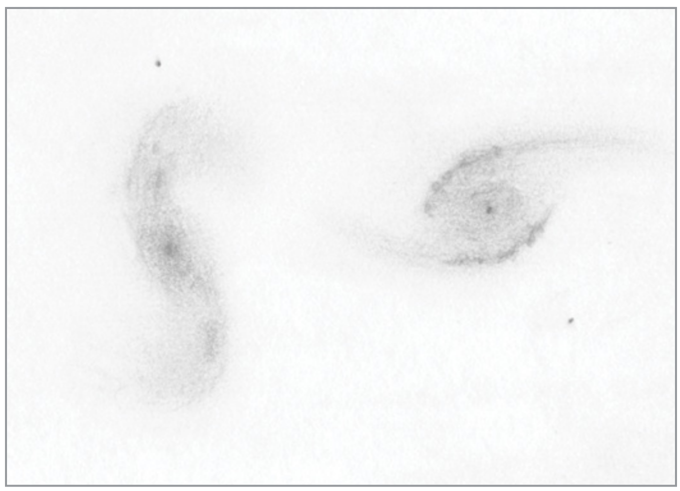
NGC 5257 and NGC 5258 form **Arp 240**, an elegant M2 pair of LIRGs connected by a filament of dust and gas. Simulations show that their closest approach occurred about 250 million years ago. To find this pair, point to 3.4-magnitude Zeta (ζ) Virginis and slide 2° to the northeast.

Viewed at 175× in my 18-inch, the two spirals are similar in size and brightness, with weakly condensed cores. NGC 5258 elongates 5:2 southwest to northeast and runs 1′ in length. Using 285×, a 15.5-magnitude star popped into view at the northern edge. NGC 5257 spans 0.9′ × 0.6′ and slopes perpendicular to its companion. A brighter, 14th-magnitude star sits off its western flank.

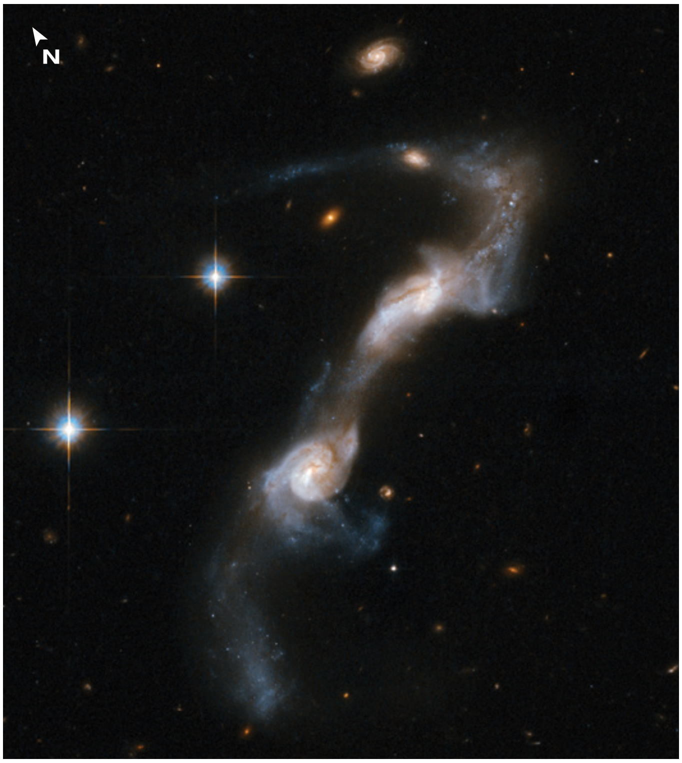
When I observe with Jimi Lowrey and use his superb 48-inch telescope, interacting pairs are always high on our observing list — this stunning duo illustrates why. At 610×, NGC 5258 flaunts its two spiral arms. The main body stretches 3:1 and houses a small bright core. I noticed an H II region midway between the core and the northern tip along the major axis. A strong spiral arm emerges at the southwestern end and hooks sharply to the east. A much fainter arm

USEFUL SOURCES

Halton Arp's *Atlas of Peculiar Galaxies* (1966) and Boris Vorontsov-Velyaminov's *The Atlas and Catalogue of Interacting Galaxies* (1959) contain many examples of photogenic M2 and M3 mergers such as The Antennae (NGC 4038-39) and The Mice (NGC 4676). The names of objects in Vorontsov-Velyaminov's catalog begin with VV.



▲ **ARP 240** This glorious duo in Virgo comprises NGC 5257 (right) and NGC 5258 (left), spirals that are very similar both in mass and size. A dim bridge of gas, dust, and stars connects the pair. Howard Banich sketched the view at the eyepiece of Jimi Lowrey's 48-inch at magnification 690×.



▲ **ARP 238** Head over to Ursa Major to find this pair, heavily distorted by tidal forces. Both galaxies exhibit dust lanes at their centers.

curls west from the northeast side, passing the 15.5-magnitude star, and points towards its companion.

Switching my attention to NGC 5257, I noted thin, high-surface-brightness arcs bordering its southwestern and northeastern flanks. Both arcs are convex and form a striking pair of parentheses enclosing the core. With closer scrutiny, thin dust lanes line the insides where the surface brightness drops dramatically. The northern parenthesis appeared to lengthen into a spiral arm to the west-northwest, stopping near a 15th-magnitude star. The southern parenthesis blends into a narrow, dim bridge towards NGC 5258 but falls just short of the companion.

Arp 238 (VV 250) is a tight M2 pair locked in a gravitational embrace. It's a great example of the havoc wreaked by a strong tidal grip. A gas and dust bridge entangles the duo, and each galaxy displays wildly contorted tails. In addition, deep images show fountains of freshly minted hot blue stars that appear ripped out of the plane of the southeastern spiral.

This diminutive twosome lies 6° southwest of 3.7-magnitude Thuban, or Alpha (α) Draconis, in Ursa Major and 40′ east of 6.5-magnitude HD 114504. In my 18-inch, just a tiny gap (35″ between their centers) separates the pair. The slightly brighter southeastern galaxy spans 20″, while its intertwined partner is a dim 15″ smudge. Some 30″ northeast is a duo of 14th-magnitude stars that mimic the orientation and separation of the galaxies.

The 48-inch showed the western tidal tail as a low-surface-brightness extension with a sharp hook to the north. The eastern member has a bright core that intensified toward the center; I spotted its debris tail as a feeble arc bending south. Completing the scene, a luminous bridge of misty haze links the pair.

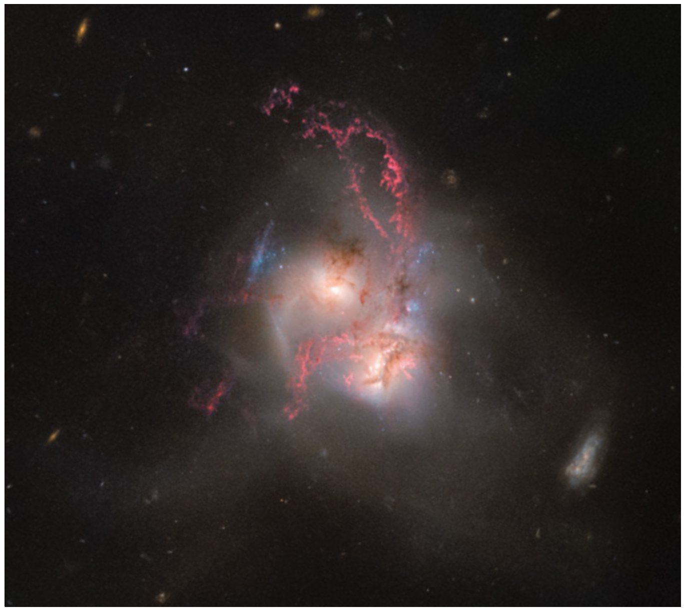
A Trio of M3s

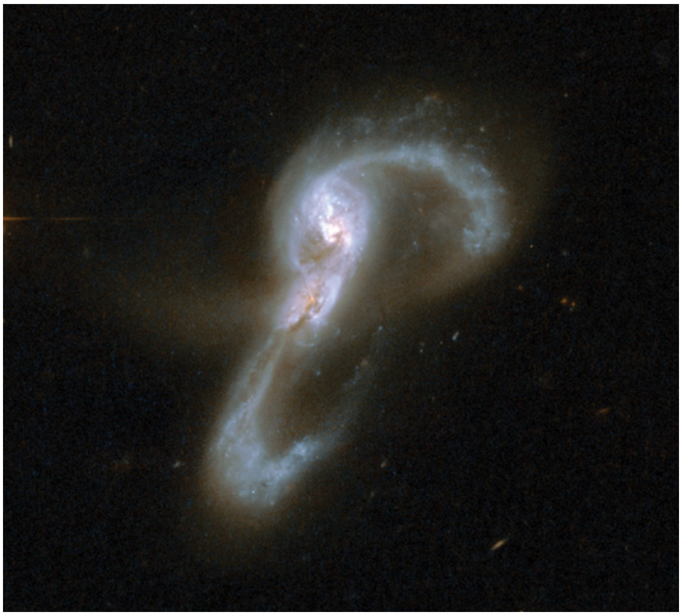
Arp 299 (NGC 3690), which lies in the bowl of the Big Dipper, is a deformed M3 crash. It ranks as the brightest galaxy in the infrared within 150 million light-years. Enveloped in its single halo are two nuclei separated by 20″, and a frenzy of star formation just north of the western nucleus. Although most of the infrared emission originates from the dust-enshrouded eastern nucleus, both may contain a composite AGN/nuclear starburst. Arp 299 is producing supernovae at a furious rate — at least seven have exploded since 1992.

Springtime Mergers

Object	Other designation	Type	Dist. (M l-y)	Mag(v)	Sep. Nuclei	Size	RA	Dec.
Arp 302	VV 340a; UGC 9618N	M1	460	~14.5	38″	0.8′ × 0.2′	14^h 57.0^m	+24° 37′
	VV 340b; UGC 9618S			~14.5		0.6′ × 0.6′	14^h 57.0^m	+24° 36′
Arp 240	NGC 5257	M2	315	12.4	1.4′	1.6′ × 0.8′	13^h 39.9^m	+00° 50′
	NGC 5258			12.3		1.4′ × 0.9′	13^h 40.0^m	+00° 50′
Arp 238	VV 250	M2	435	~14.0	36″	1.7′ × 0.7′	13^h 15.5^m	+62° 08′
Arp 299	NGC 3690W	M3	145	11.2	20″	1.6′ × 1.4′	11^h 28.5^m	+58° 34′
	NGC 3690E			10.9		2.0′ × 1.4′	11^h 28.6^m	+58° 34′
NGC 5256	Mrk 266	M3	390	13.2	10″	1.2′ × 1.1′	13^h 38.3^m	+48° 17′
VV 705	Mrk 848	M3	560	~15	6″	0.8′ × 0.4′	15^h 18.1^m	+42° 45′
Mrk 273	VV 851; UGC 8696	M4	520	14.9	1″	1.1′ × 0.3′	13^h 44.7^m	+55° 53′

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





◀▲ **ARP 299** Staying in Ursa Major, we find this duo in which a close encounter some 700 million years ago triggered a burst of star formation. Various sources misidentify Arp 299 as NGC 3690 and IC 694, or apply the latter designation to the eastern component. Instead, IC 694 is a 16th-magnitude elliptical 1′ to the northwest. Observers using the 72-inch Leviathan reflector of William Parsons, the Third Earl of Rosse, first noted this dim speck in 1852.

▲ **NGC 5256** This twosome, also in Ursa Major, dramatically shows the effects of merging: The red streamerlike features are gas and dust spilled from the guts of the galaxies, while the blue patches are regions of recent star formation.

◀ **VV 705** Back in Boötes, we come to this tight pair — the cores of these galaxies are only some 16,000 light-years apart; in fact, the system is likely midway through a merger.

Using my 18-inch at 285×, the bright western half (NGC 3690W) encompasses a conspicuous starlike nucleus, while the fainter eastern member (NGC 3690E) shows little concentration. A common irregular envelope, which spans 1.25′ in diameter, enfolds the pair.

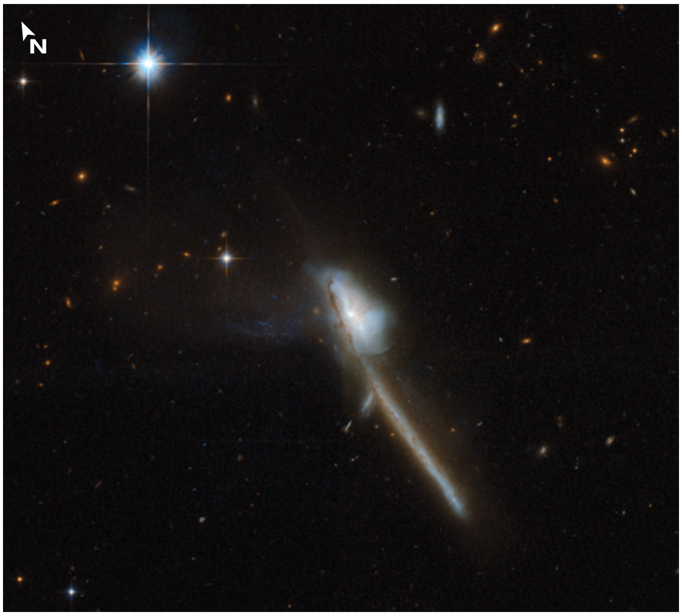
At 610× in Jimi's scope, NGC 3690W was a dazzling, irregular knot of high surface brightness with a brilliant quasi-stellar nucleus. Larger NGC 3690E held a small vivid core. A very low-surface-brightness, asymmetric halo spread northwest, and a detached H II region briefly materialized off its edge. Hovering nearby are two more galaxies. I easily viewed IC 694, a 16th-magnitude companion 1′ northwest, along with Arp 296, an interacting pair 2.5′ northeast that lies far in the background.

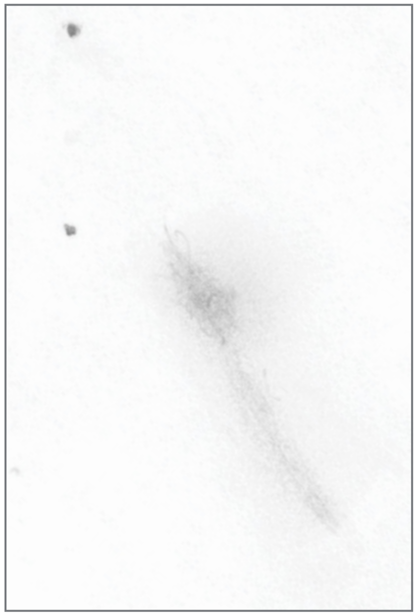
NGC 5256 is a mid-merger (M3) train wreck hosting a dual AGN separated by just 15,000 light-years. The SMBHs each weigh in at a hefty 200 million solar masses. According to a 2012 study at infrared and X-ray wavelengths, a fierce "superwind" is driving an intense outflow of gas and dust, forming ionized ribbons of nebulosity to the north.

To locate NGC 5256, point to 1.9-magnitude Alkaid, Eta (η) Ursae Majoris, the end star in the handle of the Big Dipper. Our target is just 1.8° southwest of the star, midway between Alkaid and the showpiece Whirlpool Galaxy (M51)!

In my 18-inch, I found a moderately bright 40″ × 30″ oval, leaning southwest to northeast. The surface brightness appeared uneven, though I couldn't resolve the dual nuclei, a mere 10″ apart. But jumping to 375× in my 24-inch exposed the quasi-stellar eastern nucleus. Viewed with Jimi's 48-inch, a fainter outer halo encased the luminous central region, and I easily resolved both nuclei.

At a distance of 560 million light-years, **VV 705** is the most remote M3 pair on our tour. So there's no surprise a whisker-thin 6″ separates its nuclei. This dusty LIRG sports a pair of looping tidal arms that make a wild U-turn and even overlap each other. A 2019 spectroscopic study detected





◀ **MRK 273** In May 2019, the author and Banich observed Mrk 273 in a private viewing session with fellow amateur and telescope operator Jim Chandler. This was at the end of a weekend celebration of the 80th anniversary of the 82-inch Otto Struve telescope at McDonald Observatory, which at dedication was the second-largest in the world. For two and a half hours they were treated to views of objects of their choosing. Banich sketched this view of Mrk 273 through the eyepiece of the 82-inch at magnification 617×.

a galactic-wide outflow of gas driven by either AGN or starburst activity.

To find VV 705, look 3.8° northeast of 3.5-magnitude Beta (β) Boötis, the star marking the head of the Herdsman. My 24-inch displays a small oval tilting north-northwest with a tiny but conspicuous nucleus offset to the eastern side. I had no luck seeing two cores, at least not at 282×.

The 48-inch cleanly split the two tight cores at 610×, with the brighter northern one increasing to a stellar peak. I caught the northern tidal tail as a hairline arc bending clockwise towards the west. The larger southern tail brightened and widened before turning a short distance west.

The Forlorn M4

The monsters of the gas-rich mergers are *ultraluminous infrared galaxies* (ULIRGs). Their prodigious quasarlike luminosity exceeds 1 trillion Suns and 100 times the entire Milky Way. ULIRGs form during the final merger stages (M4 and M5) and contain voraciously feeding SMBHs.

Our last stop is **Markarian 273** in Ursa Major, the second-closest ULIRG at 520 million light-years away. (The nearest is Arp 220, or IC 4553, in Serpens; at a distance of 250 million light-years, it emits 99% of its energy in the far-infrared.) As a relatively nearby laboratory, this M4-class powerhouse is a favorite target for researchers, with 854 (and counting) references in the SIMBAD bibliographic database. The power source is a dual AGN separated by less than 2,500 light-years. The southwest nucleus is a *Type II Seyfert galaxy* with narrow emission lines, while the northern nucleus — a scant 1″ away — contains an extreme starburst producing 60 solar masses per year. A slender tidal tail stretches south for 130,000 light-years with fainter diffuse plumes extending a similar distance north and east.

To reach Mrk 273, you can sweep 3° east-northeast of 2.2-magnitude Mizar, Zeta Ursae Majoris, or head the same distance northwest of M101. Unfortunately, our target lies 4′ west of the glare of 6.5-magnitude HD 119992, so park this luminary outside your eyepiece field. My 18-inch shows a pale gray oval running north to south, and my 24-inch provides tantalizing glimpses of the southern tail.

In May 2019, Howard Banich and I had a stunning view of Mrk 273 through the 82-inch Otto Struve telescope at McDonald Observatory. At 617×, the mashed-up body intensified to an elongated core with a vivid nucleus. But the real thrill was its prominent tail, which looked like a jet contrail streaming away from Mrk 273!

Keep in mind that when we observe these spiral mergers, we're getting a sneak preview of our own galaxy's future destiny. The Milky Way is on an inevitable collision course and eventual merger with the Andromeda Galaxy (M31) in several billion years.

EXTREMES

Even more exotic are *hyper-luminous infrared galaxies* (HyLIRGs), which top 10 trillion times (10^{13}) the Sun's luminosity. The current titleholder for the most prodigious output is WISE J224607.55-052634.9, discovered in 2015. It blazed in the very early universe (light-travel time of 12.5 billion years) with an infrared luminosity of 220 trillion Suns.

■ Contributing Editor **STEVE GOTTLIEB** chases colliding LIRGs and other exotic targets from northern California. He can be reached at **astrogottlieb@gmail.com**.

EXTRA MATERIAL Go to **https://is.gd/merging_spirals** for finder charts for the targets discussed here.

1 MORNING: If you're awake in the wee hours, face east to watch Jupiter and Mars rise in tandem 2° apart.

2 DUSK: The thin, waxing crescent Moon, Castor, and Pollux form a triangle above the west-northwestern horizon after sunset.

4 DAWN: Make sure you head out before sunrise to see a display of all five naked-eye planets stretching in a long line from very low in the east to higher in the south. Catching Mercury will be a challenge, though. Turn to pages 46 and 48 for further details.

5 EVENING: Look west to see the lunar crescent in Leo some 4½° from Regulus. (It's even closer to Eta Leonis — go to page 49 to read on how to view this event.)

9 EVENING: The waxing gibbous Moon is high in the south-southwest in Virgo; around 6° separates it from Spica.

13 MORNING: The Moon, one night before full, graces Scorpius, where it sits less than 6° from Antares.

18 DAWN: The waning gibbous Moon hangs some 6° below Saturn in the south. Turn to the east-northeast to see Mercury, Venus, and the Pleiades arranged in a triangle.

21 THE LONGEST DAY OF THE YEAR in the Northern Hemisphere. Summer begins at the solstice, at 5:14 a.m. EDT.

21 DAWN: High in the southeast the Moon, only just past last quarter, and Jupiter are a little more than 4° apart.

22 DAWN: Face east-southeast to see the Moon 4½° right of Mars. Jupiter gleams to the pair's upper right, while Venus blazes lower in the east.

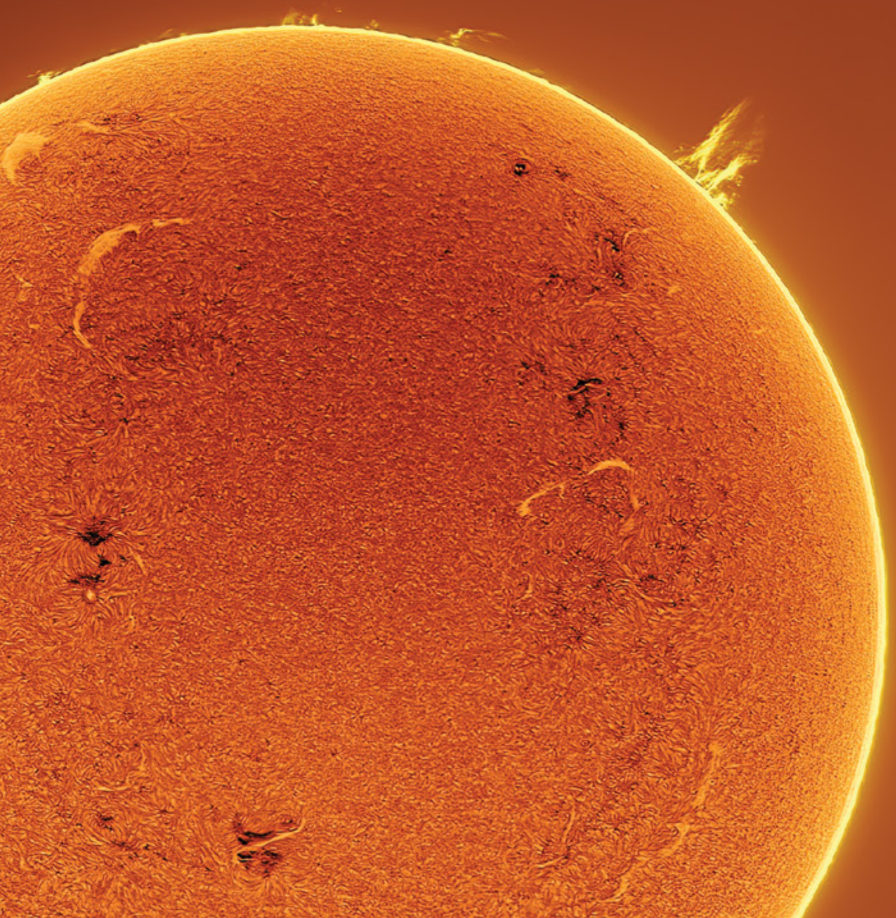
24 DAWN: Five planets reach across a span of sky from low in the east-northeast to higher in the south — they're a bit more spaced out this morning than on June 4th. The waning crescent Moon infiltrates the scene and hangs delicately between Mars and Venus. Make sure you don't miss this delectable sight! Go to pages 47 and 48 for more.

25 DAWN: The thin lunar crescent, Venus, and Mercury, strung in a line some 20° long, adorn the east-northeastern horizon.

26 DAWN: The earthlit Moon is 2½° from Venus, with Mercury lower left of the pair.

27 DAWN: The thinnest sliver of the Moon, just one day before new, visits Mercury — look for it some 3½° left of the tiny world.

— DIANA HANNIKAINEN



Many cultures around the world celebrate the Sun during June, the month that brings the longest day of the year to the Northern Hemisphere. ARTURO BUENROSTRO

JUNE 2022 OBSERVING

Lunar Almanac

Northern Hemisphere Sky Chart

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

NASA / LRO

MOON PHASES

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

FIRST QUARTER

June 7
14:48 UT

FULL MOON

June 14
11:52 UT

LAST QUARTER

June 21
03:11 UT

NEW MOON

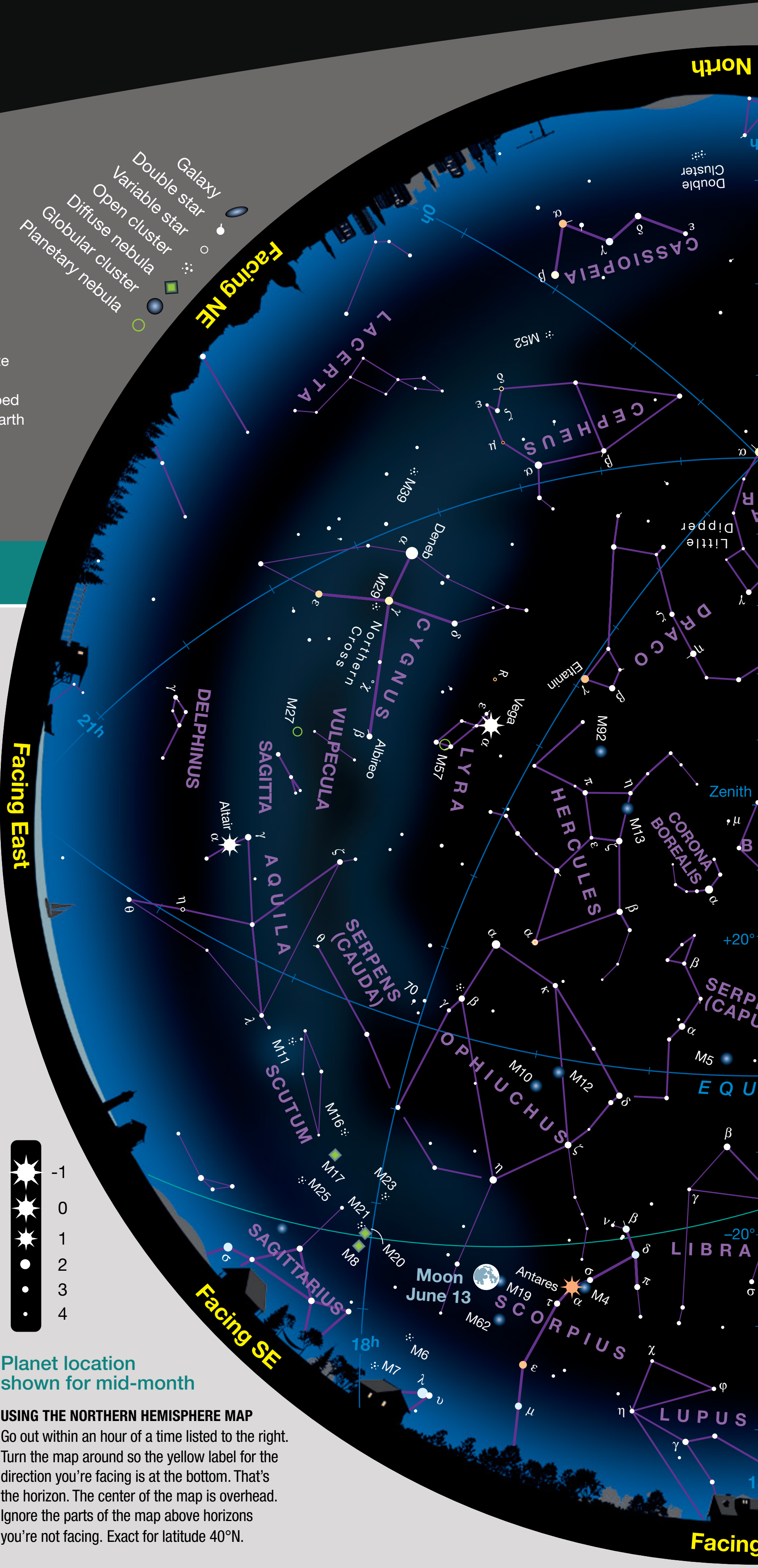
June 29
02:52 UT

DISTANCES

Apogee	June 2, 01^h UT
406,191 km	Diameter 29′ 25″
Perigee	June 14, 23^h UT
357,436 km	Diameter 33′ 26″
Apogee	June 29, 06^h UT
406,579 km	Diameter 29′ 23″

FAVORABLE LIBRATIONS

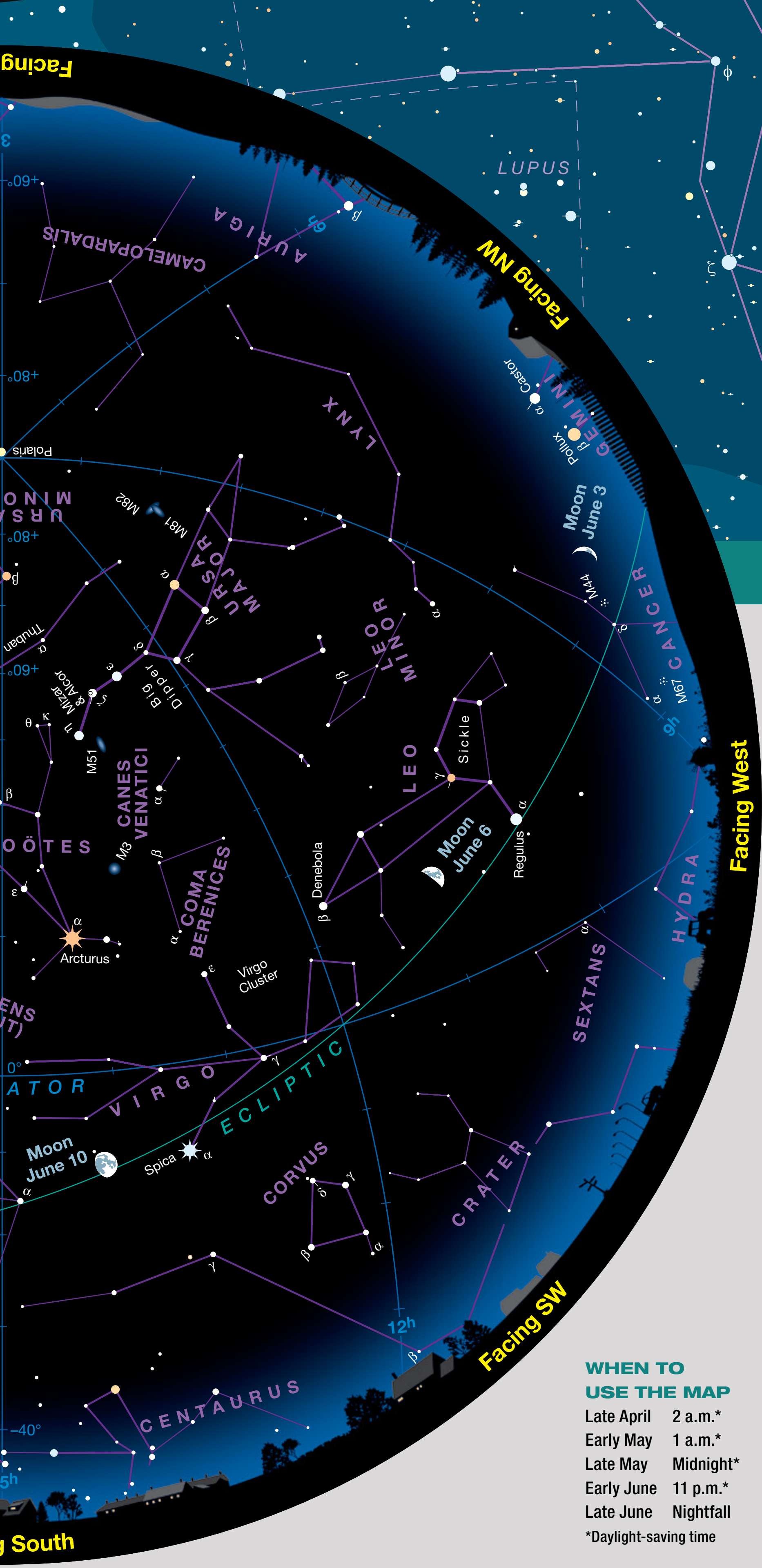
• Galvani Crater	June 14
• Sylvester Crater	June 15
• Peterman Crater	June 16

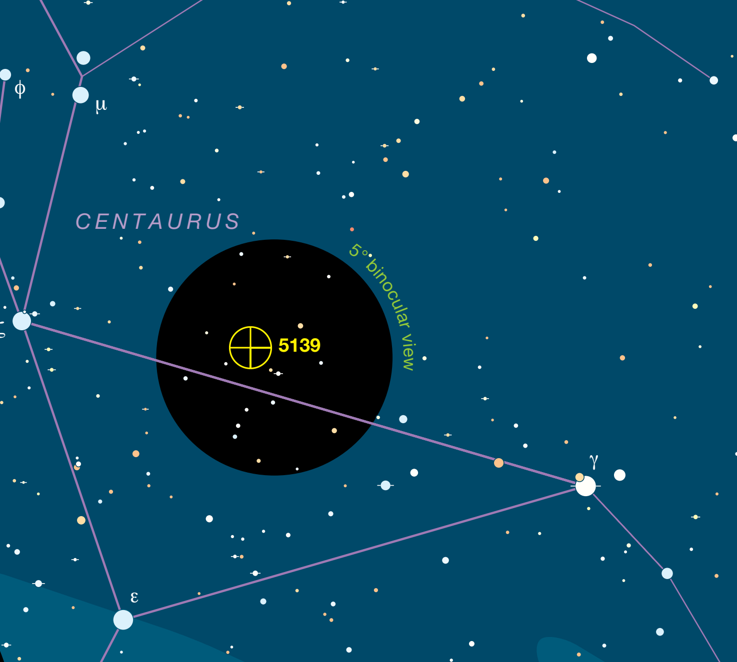


Planet location shown for mid-month

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

A Swarm of Stars

In late spring and early summer, the crooked, asymmetric star patterns of Centaurus rear above the southern horizon like the rigging of a wrecked ship. There's treasure to be found here: **Omega (ω) Centauri**, or NGC 5139, the largest globular cluster in the Milky Way. It's legitimately vast, containing several million stars; most globs have a few hundred thousand to perhaps one million. At magnitude 3.9, the cluster is fairly bright, but at declination –47°, a clear and dark southern horizon is a must (for observers in the Northern Hemisphere). Omega Centauri has been spotted from southern Canada, so, even if not necessarily easy, it should be possible to see it from much of the continental U.S. (but not for viewers north of 43°N). In addition to finding an advantageous horizon, you'll want to be fanatical about dark adaptation and catch the cluster when it culminates, a little before 9:30 p.m. local daylight time in early June.

Once, on a dinosaur dig in Montana, I watched a hive of bees relocate between homes. After leaving their former residence in a hollow tree, the swarm settled into a temporary bivouac in a sagebrush, gradually condensing out of the air to form a basketball-size sphere of bees. It was profoundly strange and moving to be confronted by such an impressive process, proceeding completely apart from human intelligence.

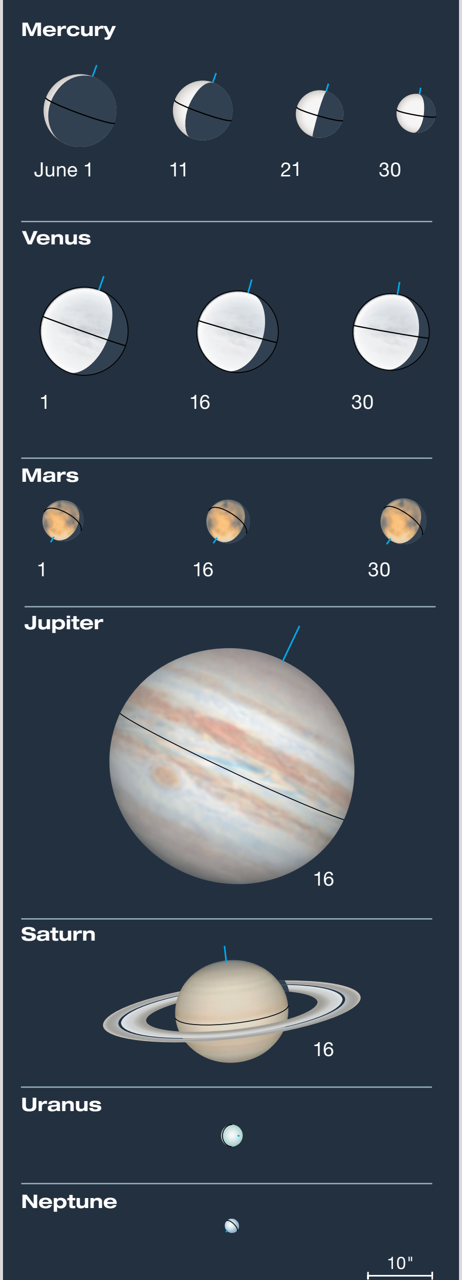
That's something like the feeling I get when I observe Omega Centauri, rising above the southern horizon like a globe, immense, ancient, dusted with golden suns like pollen on a flower. I can't actually resolve any stars at 10× or 15×, but I can feel their combined light pressing on my mind, as well as on my retinas. Omega Centauri is one of those objects that everyone should see. Go get glob-struck.

■ **MATT WEDEL** doesn't spend enough time exploring south of –30°. You should demand better of him.

WHEN TO USE THE MAP

Late April	2 a.m.*
Early May	1 a.m.*
Late May	Midnight*
Early June	11 p.m.*
Late June	Nightfall

*Daylight-saving time



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

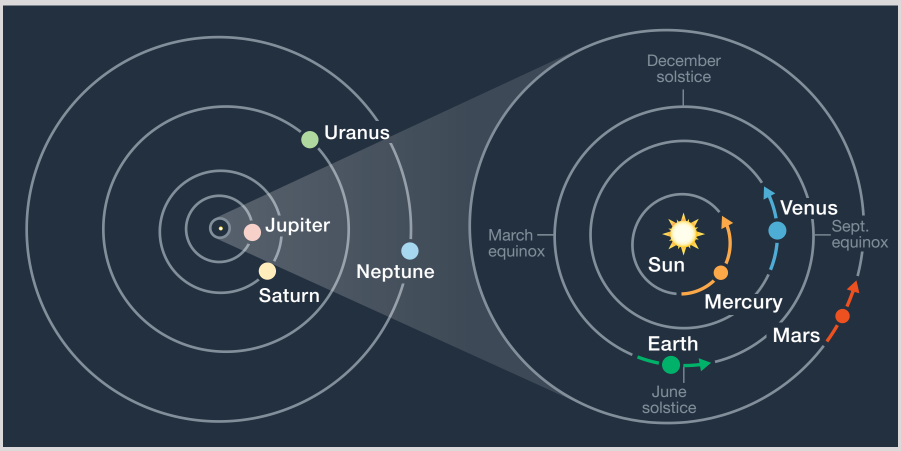
▶ **ORBITS OF THE PLANETS** The curved arrows show each planet's movement during June. The outer planets don't change position enough in a month to notice at this scale.

PLANET VISIBILITY (40°N, naked-eye, approximate) **Mercury** visible at dawn beginning on the 16th • **Venus** visible in the east at dawn all month • **Mars** and **Jupiter** visible at dawn all month • **Saturn** rises around midnight and is visible until dawn.

June Sun & Planets

	Date	Right Ascension	Declination	Elongation	Magnitude	Diameter	Illumination	Distance
Sun	1	$4^h\ 34.3^m$	+21° 59′	—	–26.8	31′ 33″	—	1.014
	30	$6^h\ 34.5^m$	+23° 12′	—	–26.8	31′ 28″	—	1.017
Mercury	1	$3^h\ 38.1^m$	+15° 48′	15° Mo	+2.9	11.3″	8%	0.594
	11	$3^h\ 46.5^m$	+15° 50′	22° Mo	+1.0	9.3″	25%	0.724
	21	$4^h\ 22.3^m$	+18° 35′	23° Mo	0.0	7.4″	47%	0.911
	30	$5^h\ 17.0^m$	+21° 49′	18° Mo	–0.7	6.1″	70%	1.102
Venus	1	$2^h\ 08.5^m$	+10° 51′	37° Mo	–3.9	13.7″	78%	1.219
	11	$2^h\ 54.2^m$	+14° 38′	34° Mo	–3.9	13.0″	81%	1.285
	21	$3^h\ 41.6^m$	+17° 54′	32° Mo	–3.9	12.4″	83%	1.347
	30	$4^h\ 25.9^m$	+20° 15′	30° Mo	–3.9	11.9″	86%	1.399
Mars	1	$0^h\ 20.8^m$	+0° 21′	65° Mo	+0.7	6.4″	87%	1.457
	16	$1^h\ 01.5^m$	+4° 36′	69° Mo	+0.6	6.8″	86%	1.377
	30	$1^h\ 39.1^m$	+8° 21′	72° Mo	+0.5	7.2″	86%	1.303
Jupiter	1	$0^h\ 14.5^m$	+0° 18′	67° Mo	–2.3	37.3″	99%	5.278
	30	$0^h\ 28.0^m$	+1° 38′	91° Mo	–2.4	40.7″	99%	4.843
Saturn	1	$21^h\ 50.4^m$	–14° 16′	105° Mo	+0.8	17.4″	100%	9.571
	30	$21^h\ 48.6^m$	–14° 30′	133° Mo	+0.6	18.2″	100%	9.153
Uranus	16	$2^h\ 57.6^m$	+16° 30′	38° Mo	+5.8	3.4″	100%	20.492
Neptune	16	$23^h\ 43.8^m$	–3° 01′	89° Mo	+7.9	2.3″	100%	29.909

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**.



A Bevy of Boötes Beauties

The Herdsman has gathered a stellar flock.

The zero-magnitude, champagne-colored star called Arcturus dominates the June evening sky (*S&T:* June 2021, p. 45). But even Arcturus doesn't completely overwhelm the rest of Boötes, the conspicuous and fascinating constellation it resides in.

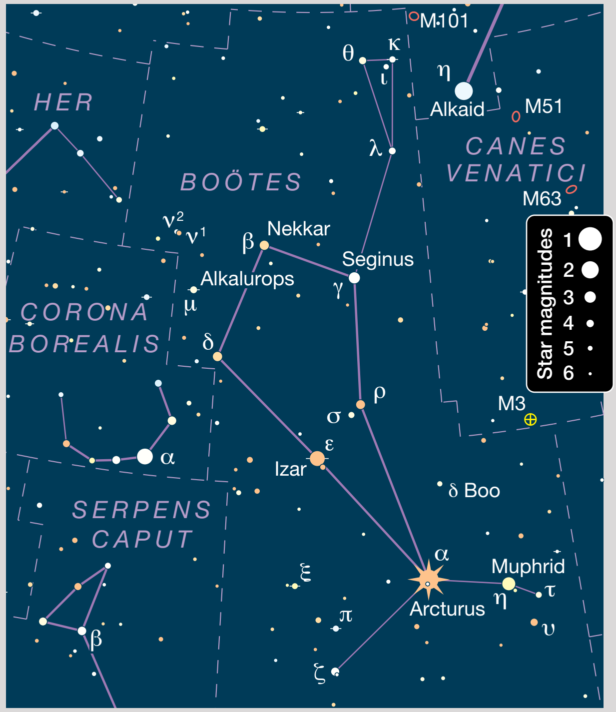
Boötes is officially the Herdsman, though the name really means "ox-herd" or "cowherd" — note the relation of "bovine" to Boötes (pronounced bo-OH-teez). In modern times, the constellation is sometimes connected in lore with Canes Venatici, the Hunting Dogs, which occupy the space between Boötes and Ursa Major. The name Arcturus itself means "bear guard," so one tale has Boötes and his dogs preventing Ursa Major, the Great Bear, from attacking the other constellations.

Boötes can be pictured as the human form of a herdsman, but in contemporary times it's often seen as either a kite (a fitting plaything for windy, spring days) or an ice-cream cone (a cool treat for late spring and early summer). Arcturus in these arrangements marks the point at the bottom of the kite or ice-cream cone.

The constellation has only one 2nd-magnitude star but boasts three 3rd-magnitude stars and nine of 4th magnitude. After Arcturus, the brightest star is 2.4-magnitude Epsilon (ε) Boötis, located about 10° northeast of Arcturus. Many readers may remember that in late March of 1996, the head of brilliant Comet Hyakutake passed in front of this star. Epsilon Boötis is also known as Izar, Arabic for "loincloth" or "girdle." Famed observer F. G. W. Struve named it Pulcherrima, Latin for "most beautiful," evoking the splendid double's colorful telescopic appearance.

The third-brightest star in Boötes is Eta (η) Boötis, which shines at magnitude 2.7. Its proper name is Muphrid, "the solitary one," though it's actually located only 5° west of Arcturus. Interestingly, Muphrid is not only close to Arcturus in the sky but also in space — both stars are 37 light-years away and just 3.3 light-years from each other. An observer on a planet circling Arcturus would see Muphrid as a point of light of about magnitude –2.6. Someone in the Muphrid system would see Arcturus gleam brighter than Venus does from Earth.

Gamma (γ), Delta (δ), and Zeta (ζ) Boötis are, respectively, magnitudes 3.0, 3.5, and 3.8. Gamma, also known as Seginus, shines as the western shoulder of the Herdsman and is the first bright star of Boötes reached by following the southward arc of the Big Dipper's handle. Delta Boötis marks the eastern shoulder of the Herdsman, located not far from the conspicuous semicircle of stars that is Corona Borealis, the Northern Crown.



▲ **HIGH-FLYING KITE** Boötes is the Herdsman of mythology, but modern eyes connect the dots more prosaically into an ice-cream cone or a kite caught in a spring breeze.

The northernmost part of Boötes — the head of the Herdsman — is represented by Beta (β) Boötis, Nekkar (a name which means "ox-driver"). It shines at magnitude 3.5 and passes almost exactly overhead for observers at 40° north latitude. The radiant point of the usually weak June Boötid meteor shower lies a little north of Nekkar. The display is expected to peak on June 27th this year (near new Moon). Very rarely, these extremely slow meteors have come at the rate of 100 per hour — the most recent outburst occurred in 1998.

There are several enjoyable naked-eye double stars in Boötes. One fairly bright duo is magnitude-3.6 Rho (ρ) and magnitude-4.5 Sigma (σ) Boötis, both a few degrees northwest of Izar. A challenge for dark skies and sharp eyes is the pair Nu^1 (ν^1) and Nu^2 (ν^2) Boötis, two 5th-magnitude stars a healthy 10′ apart. Last but not least, near the end of the Big Dipper's handle, are Theta (θ), Iota (ι), and Kappa (κ) Boötis, with magnitudes of 4.0, 4.7, and 4.4 respectively. The trio are also called the Three Donkeys and bear the Latin names Asellus Primus, Asellus Secundus, and Asellus Tertius.

■ **FRED SCHAAF** can be contacted via e-mail at **fcschaaf.gmail.com.**

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

All Planets on Deck

The solar system is neatly arrayed across the dawn sky this month.

WEDNESDAY, JUNE 1

When May wrapped up, **Mars** and **Jupiter** were enjoying a close conjunction that climaxed on May 29th with the two planets a touch more than one Moon diameter apart. The gap between them has been growing ever since, and as June begins they remain eye-catchingly close. This morning, slightly less than 2° separates Mars from Jupiter. There's quite a brightness mismatch, however. Jupiter gleams brilliantly at magnitude –2.3 while Mars is +0.7 — respectably bright, but still some 16 times fainter than Big Jove. This morning's pairing is part of a wonderful dawn planet parade that lasts all month.

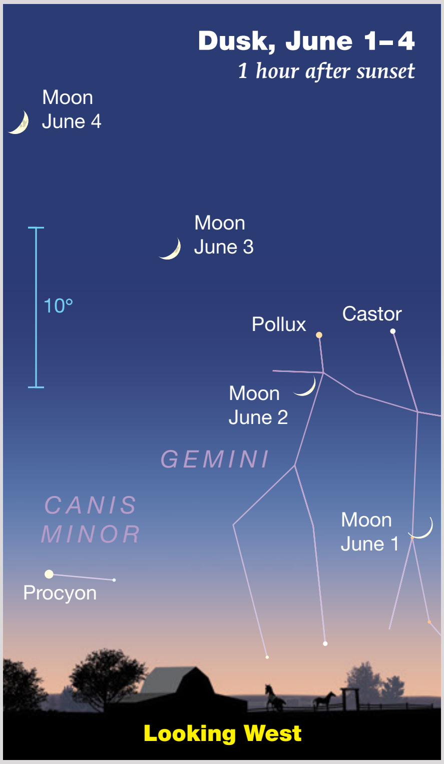
FRIDAY, JUNE 3

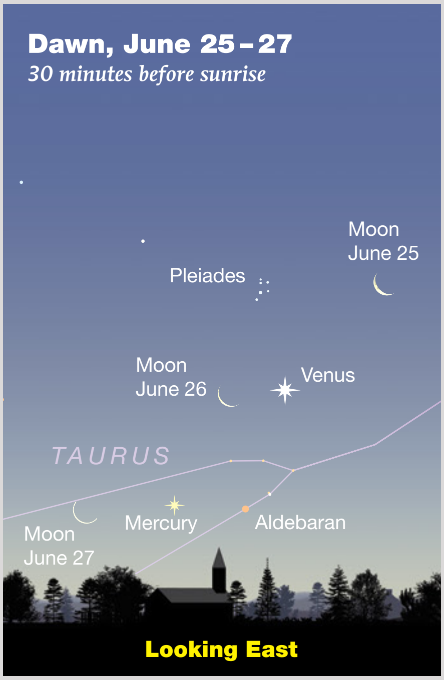
All's quiet on the dusk horizon this month, at least so far as planetary action is concerned. But that doesn't mean there's nothing to see. This evening, look to the west as twilight fades to catch the crescent **Moon** parked about 5° to the right of the Beehive Cluster, **M44**. You'll have to use binoculars to appreciate this sight. The wide perspective presented by 7×50s is ideal since they offer a field of view of about 7°, which is what you need to squeeze in both objects. Early June is a great time to see the Beehive and Moon together because that's when the Moon is a narrow crescent in the evening sky; a fatter, brighter Moon makes the cluster's "bees" harder to see. Tonight, the Moon is about 18% illuminated, which means you should be able to catch earthshine on the "dark" portion of the lunar disk. This is also the final observable evening meeting between M44 and the Moon in 2022. All the more reason to look in.

SATURDAY, JUNE 4

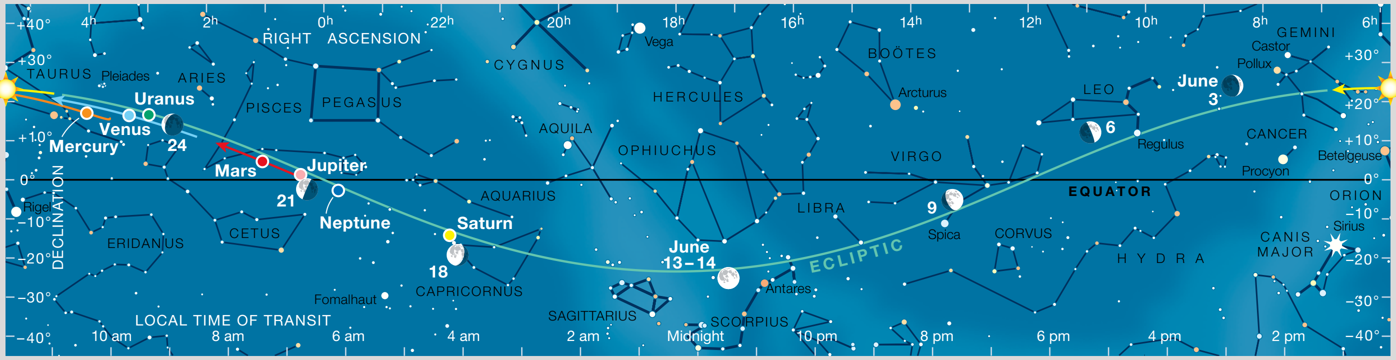
This morning presents one of those events that perhaps looks more impressive on paper than it does in the sky. At dawn, all five naked-eye planets are arrayed from east to south along the horizon. Yes, that's pretty remarkable, but what's even more unusual is that they appear in the same sequence in the sky as they are in their orbits around the Sun. In other words, scanning from left to right, we have **Mercury**, **Venus**, **Mars**, **Jupiter**, and **Saturn** creating an arc that spans 91° from Mercury to Saturn. Such a configuration doesn't happen very often. Indeed, it's been about 100 years since a similarly compact parade of planets graced our skies, and you'll have to wait until 2041 to see such an arrangement again.

This morning Mercury and Venus are 18° apart; Venus and Mars are separated by 30°; Mars is 4° from Jupiter; and Saturn lies 39° west of Jupiter. Certainly, that *seems* impressive, so what's the catch? The problem (as usual) is Mercury. The innermost planet is not especially bright (magnitude 2.1), and it pops up in brightening twilight to achieve an altitude of only 6½° at sunup. To claim Mercury in this solar-system survey, you're going to need an unobstructed eastern horizon and binoculars.





▶ These scenes are drawn for near the middle of North America (latitude 40° north, longitude 90° west). For clarity, the Moon is shown three times its actual apparent size.



▲ The Sun and planets are positioned for mid-June; 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.

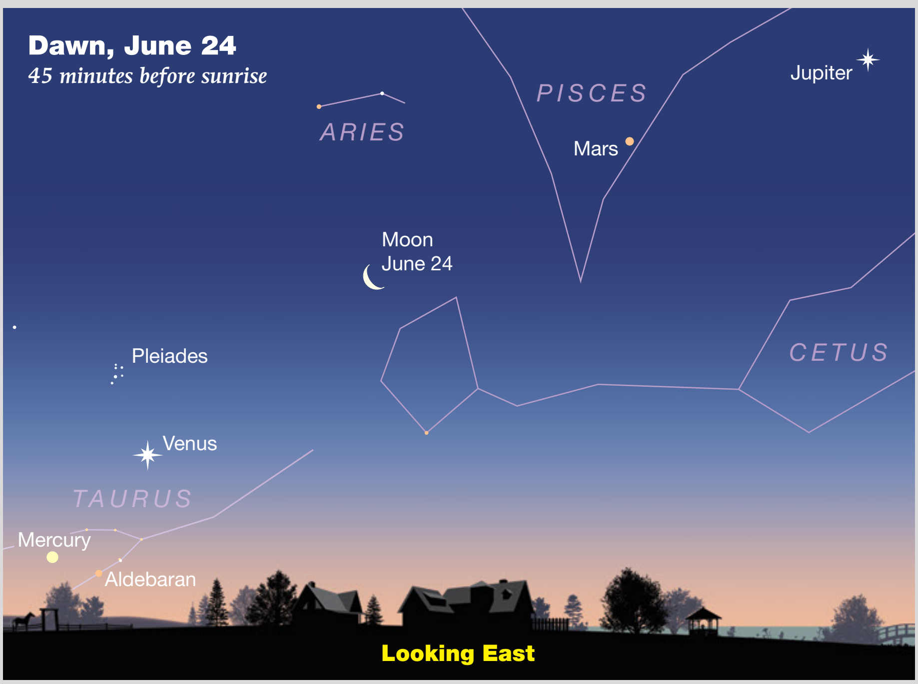
SUNDAY, JUNE 5

Each month the **Moon** passes by a handful of bright stars as it makes its way along the ecliptic. One of the best June encounters occurs this evening when the waxing crescent sits roughly 4½° above right of 1st-magnitude **Regulus** in Leo. It's a pretty, naked-eye pairing. But if you look carefully, you might notice a fainter spark just above the Moon — that's Eta (η) Leonis. Depending on when you look, the 3.4-magnitude star may be lost in the lunar glare, so get out your binoculars once again. Even with modest optical aid, spotting Eta should be a snap. And some lucky observers will get to see the Moon's dark limb eclipse the star. (Turn to page 49 for details.)

FRIDAY, JUNE 24

For naked-eye skywatchers, the planetary line-up this morning is quite a bit more compelling than it was on June 4th, even if that date attracts more publicity. Yes, it's true that the gap between the marker planets (**Mercury** and **Saturn**) has grown from 91° to something closer to 107°, but the spectacle has improved in two important ways.

First, problem planet Mercury is now much more conspicuous, glowing at magnitude –0.2. That's more than eight times brighter than it was on the 4th. Just as important, the innermost world now sits twice as high (12°) above the east-northeastern horizon at sunrise. Those two factors make Mercury a relatively easy naked-eye target. The second improvement comes courtesy of the Moon. The earthlit lunar crescent is attractively positioned this morning almost exactly midway between **Venus** and **Mars**. Sublime. You can even imagine the Moon serving as an ersatz Earth to complete the planetary sequence. Add in **Jupiter**, and you have a bright and beautiful 65½°-long line. This dawn show might not be as rare as the one on the 4th, but it's visually more interesting. Why not set your alarm on both dates and see if you agree?



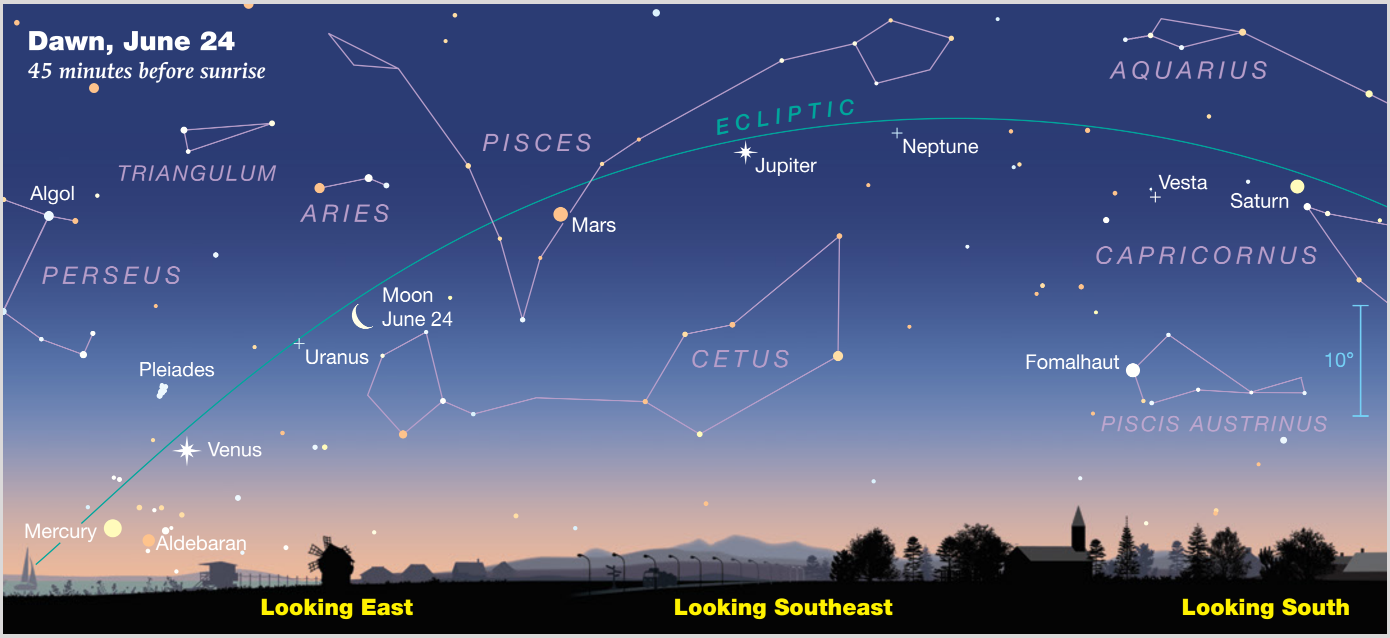
SUNDAY, JUNE 26

The final phase of June's parade of planets would be one of the biggest highlights in any other month. But, given the context of everything else that's going on, this morning's conjunction might feel a little anticlimactic. For observers in the Americas, **Venus** and the **Moon** have their closest observable encounter for 2022 at dawn today. Just 2½° separate the blazing Morning Star from a razor-thin lunar crescent. It's a remarkably striking sight that you don't want to miss, even if it means yet one more early morning.

■ Generally not a fan of morning parades, Consulting Editor **GARY SERONIK** makes a happy exception for those involving planets.

A Rare Planetary Alignment

Grab your chance to see all eight planets, a bright asteroid, and the Moon — all at the same time.



▲ This month's planetary alignment reaches its peak on the morning of June 24th. Note that Uranus, Neptune, and Vesta (indicated with crosses) require optical aid to see. In the smaller charts presented on the facing page, the objects are plotted for 0^h UT on June 24th.

In Sun, Moon & Planets on page 46, Gary Seronik describes this month's striking alignment of naked-eye planets and the Moon. Here we'll focus on their telescopic appearance and expand the list to include Uranus, Neptune, and a representative from the asteroid belt, Vesta. While all three additions require binoculars or a small telescope to view, when you're done you can say you've seen the Moon, every planet in the solar system, plus an asteroid — all before the Sun comes up.

The planetary popcorn string will be in full view from about June 16th through the 27th. Before the 16th, Mercury and Uranus will be very low in twilight's glare, and after the 27th, the Moon departs the scene and turns new. For both practical and aesthetic reasons, June 24th is the optimum date. That morning, all nine bodies are pleasingly spaced across 107° of sky.

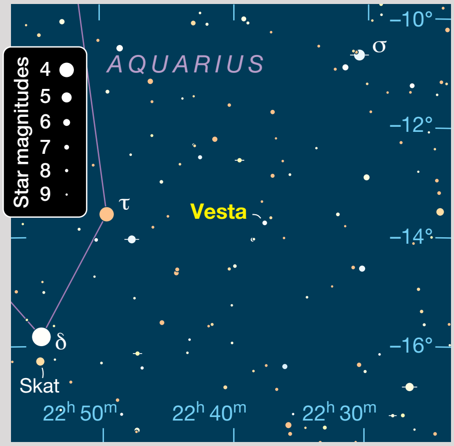
Find a location with an unobstructed horizon and start your survey with the two faintest targets, Neptune and Vesta. Neptune rises before 1 a.m. local daylight-saving time, while Vesta is up shortly after midnight. The best time to look is a little before 4 a.m., when both objects are high in the sky but before twilight sets in.

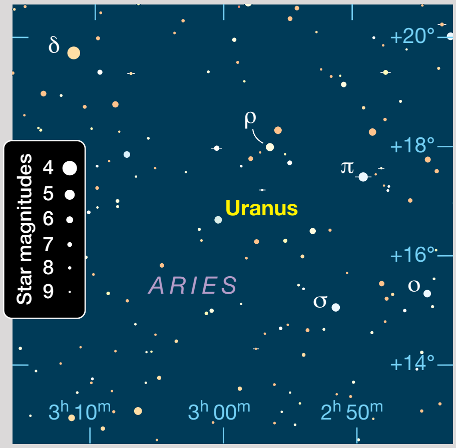
Although Vesta won't reach opposition until August 22nd, it's currently at magnitude 7.1, which is bright enough to pinpoint in a pair of binoculars. Neptune is nearly 4.5 billion kilometers (2.8 billion miles) distant and shines at magnitude 7.9, but it's an easy catch in a small telescope or even binoculars in a dark sky. Crank up the magnification to 100× and you should be able to discern its tiny, bluish disk.

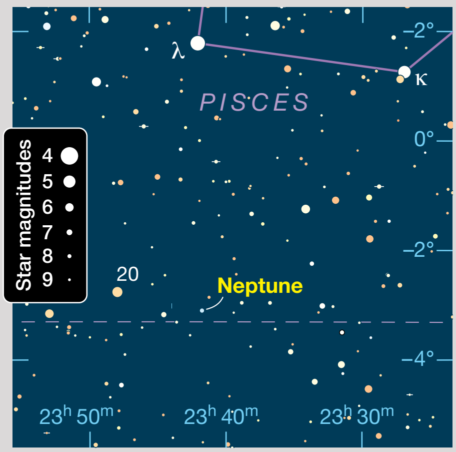
Next, take some time to admire Saturn. Given that it's finally rising before midnight, this might be your first good look at it this apparition. On the 24th its glorious rings will be very close to their minimum inclination for 2022, tilted just 12.5° with the north face of the planet's globe in view.

Jupiter gleams at magnitude −2.4, bright enough to remain visible throughout twilight. Serendipitously, on the 24th its mini-solar system of four bright moons will line up in order of their physical distance from Jupiter. From west to east we see Io, Jupiter, Europa, Ganymede, and Callisto in a neat row.

Mars glows a respectable magnitude +0.5, but even with high magnification, discerning surface details will be a chal-







lenge for visual observers. That said, the planet's south pole now tilts more than 21° in our direction, so the white gleam of the shrinking south polar cap should be apparent in 4-inch or larger scopes magnifying 150× or greater. The best is yet to come. The Red Planet will expand to a plump 17″ when it reaches opposition on December 8th.

Continuing our sweep eastward, we find the waning crescent Moon. With its belly full of earthshine, it should be a spectacular sight in binoculars or with your unaided eyes. Telescopes will show fine detail in the prominent craters Gassendi, Kepler, and Aristarchus, all positioned along the encroaching arc of the sunset terminator.

The waning crescent Moon is about 6° upper right of Uranus on the 24th, making it a useful tool for finding the distant planet during twilight. Given Uranus's magnitude of 5.8, it's best to seek it before twilight interferes. Even a small telescope magnifying around 100× will clearly show its 3.4″-wide, blue-green disk.

At magnitude –3.9, Venus is obviously the brightest planet in the alignment, though its low altitude and encroaching twilight will temper its sheen somewhat. Binoculars should reveal the Pleiades some 6° above the planet, but can you see this lovely cluster without optics?

When you train your scope on Venus, you'll see a much brighter, silvery version of Mars. Both planets show nearly the same gibbous phase (Venus is 84% illuminated, compared with Mars at 86%) and similarly small disks (12″ for Venus, 7″ for Mars).

We reach the end of the planet parade with the innermost world, Mercury. Rarely an easy catch, from mid-northern latitudes Mercury climbs only about 4° above the east-northeastern horizon 45 minutes before sunrise this morning. It shines at magnitude –0.2, but even so, you may need binoculars to nail it down due to its low altitude and encroaching twilight.

A small telescope will show that Mercury looks similar to a half-moon, but like Mars sports a tiny disk just 6.9″ across. You should use at least 75× to clearly discern its phase. If you need a hand finding Mercury, try again on the morning of the 27th when a super-skinny crescent Moon floats about 3.5° to Mercury's upper left.

The final member of this grand alignment is our blindingly bright home star. As the Sun rises, celebrate your solar system tour by treating yourself to a nice breakfast. You've earned it!

Two June Occultations

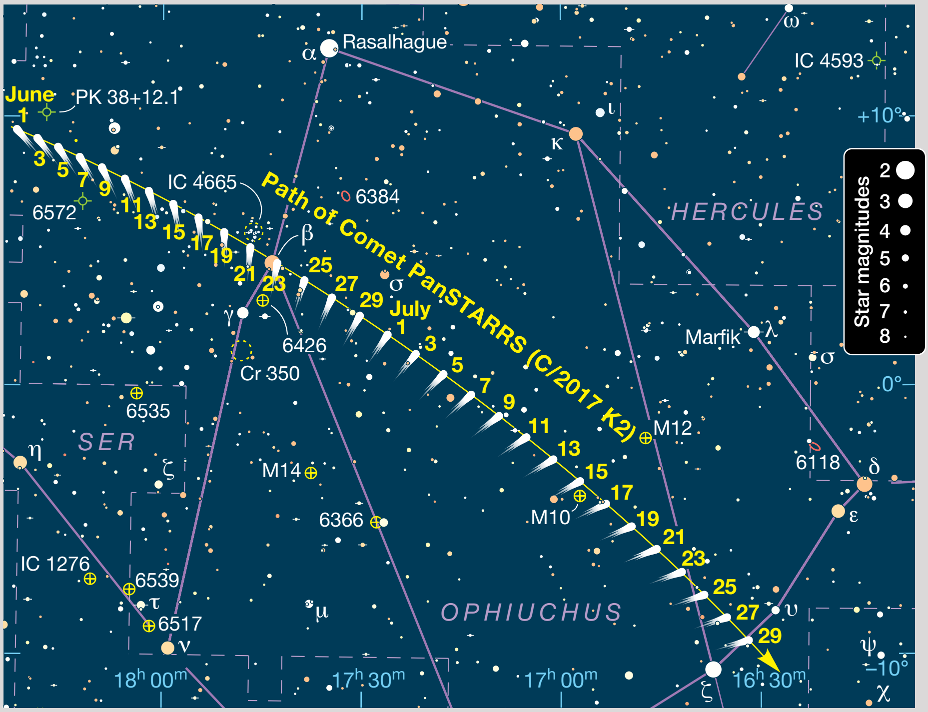
THE MOON PASSES in front of two relatively bright stars this month. The first occultation occurs on the night of June 5–6, when the lunar crescent occults 3.4-magnitude Eta (η) Leonis for the southwestern U.S., Mexico, and Central America. From Austin, Texas, the star meets the Moon's dark limb at 10:35 p.m. CDT and emerges at the bright edge a half-hour later. Farther west, in Los Angeles, immersion happens before sundown, but the star returns to view at 9 p.m. PDT in deep twilight.

Based on only seven recorded measurements, Eta appears to be a very close binary star with a magnitude-8.4 companion just 0.4″ away at a position angle of 239°. This event presents an opportunity to confirm the companion by recording carefully timed telescopic video of a potential two-step occultation.

Elsewhere in the U.S., observers can watch Eta pass just north of the Moon. For complete details, visit **https://is.gd/IOTAEtaLeo**.

On the evening of June 12th, observers in the northeastern states and eastern Canada can watch the dark edge of the nearly full Moon cover 2nd-magnitude Delta (δ) Scorpii, the star in the middle of the Scorpion's head. Delta is a close binary with a 4.6-magnitude companion nestled 0.1″ away at a position angle of 10°. The Moon covers the companion first, followed a fraction of a second later by the primary. From Boston, Massachusetts, immersion happens at 10:20 p.m. EDT, with the star returning to view at the bright limb at 11:16 p.m. For additional details, check **https://is.gd/IOTADeltaSco**.

Comet PanSTARRS Arrives



▲ The comet's position is plotted for 0^h UT.

THE PANSTARRS SURVEY at Haleakalā Observatory in Hawai'i nabbed Comet C/2017 K2 five years ago when the object was about halfway between the orbits of Saturn and Uranus. Even then, sublimating carbon dioxide, carbon monoxide, and molecular oxygen had lofted enough material from the comet's frigid surface to create a 129,000-km-wide coma. The outgassing of these exotic ices indicated that K2 was on its first visit to the inner solar system from the Oort Cloud.

Archived images from the Canada-France-Hawaii Telescope revealed activity as far back as 2013, when Comet PanSTARRS was beyond Uranus, at the time making it the most distant, active, inbound comet ever found. (That honor recently passed to Comet Bernardinelli-Bernstein, which was first imaged in October 2014 at a distance of 2.3 billion km.)

Back in mid-February, I saw K2 as a small, 12th-magnitude fuzzy patch in my 15-inch scope. The view should be much improved in June. As the comet ambles across northern Ophiuchus, it's well-placed at nightfall and expected to brighten to about magnitude 8.0.

On June 7th, K2 will pass 1½° north of the 8th-magnitude planetary nebula NGC 6572 and ½° south of the bright, binocular open cluster IC 4665 on the night of the 20th. The comet swings just northeast of the bright globular cluster M10 on the nights of July 14th and 15th as K2 has its closest approach to Earth.

The comet disappears into evening twilight around the autumn equinox but remains in view from the Southern Hemisphere. Perihelion occurs on December 19th, when K2 could peak at 6th magnitude.

Action at Jupiter

AS JUNE BEGINS, Jupiter rises at around 1:30 a.m. local daylight-saving time and attains an altitude of roughly 27° at the start of civil twilight. On June 1st, the big planet gleams brightly at magnitude –2.3 and in telescopes presents a disk 37″ across. By month's end, Jupiter rises before midnight and climbs to nearly 45° altitude as civil twilight begins.

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

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

May 1: 2:33, 12:29, 22:24; **2**: 8:20, 18:16; **3**: 4:12, 14:08; **4**: 0:04, 9:59, 19:55; **5**: 5:51, 15:47; **6**: 1:42, 11:38, 21:34; **7**: 7:30, 17:25; **8**: 3:21, 13:17, 23:13; **9**: 9:08, 19:04; **10**: 5:00, 14:56; **11**: 0:52, 10:47, 20:43; **12**: 6:39, 16:35; **13**: 2:30, 12:26, 22:22; **14**: 8:18, 18:13; **15**: 4:09, 14:05; **16**: 0:01, 9:56, 19:52; **17**: 5:48, 15:44; **18**: 1:40, 11:35, 21:31; **19**: 7:27, 17:22; **20**: 3:18, 13:14, 23:10; **21**: 9:05, 19:01; **22**: 4:57, 14:53; **23**: 0:49, 10:44, 20:40; **24**: 6:36, 16:31; **25**: 2:27, 12:23, 22:19; **26**: 8:14, 18:10; **27**: 4:06, 14:02, 23:57; **28**: 9:53, 19:49; **29**: 5:45, 15:40; **30**: 1:36, 11:32, 21:27; **31**: 7:23, 17:19

June 1: 3:20, 13:15, 23:11; **2**: 9:07, 19:03; **3**: 4:58, 14:54; **4**: 0:50, 10:46, 20:41; **5**: 6:37, 16:33; **6**: 2:28, 12:24, 22:20; **7**: 8:16, 18:11; **8**: 4:07, 14:03, 23:58; **9**: 9:54, 19:50; **10**: 5:46, 15:41; **11**: 1:37, 11:33, 21:29; **12**: 7:24, 17:20; **13**: 3:16, 13:11, 23:07; **14**: 9:03, 18:59;

15: 4:54, 14:50; **16**: 0:46, 10:41, 20:37; **17**: 6:33, 16:28; **18**: 2:24, 12:20, 22:16; **19**: 8:11, 18:07; **20**: 4:03, 13:58, 23:54; **21**: 9:50, 19:46; **22**: 5:41, 15:37; **23**: 1:33, 11:28, 21:24; **24**: 7:20, 17:15; **25**: 3:11, 13:07, 23:02; **26**: 8:58, 18:54; **27**: 4:50, 14:45; **28**: 0:41, 10:37, 20:32; **29**: 6:28, 16:24; **30**: 2:19, 12:15, 22:11

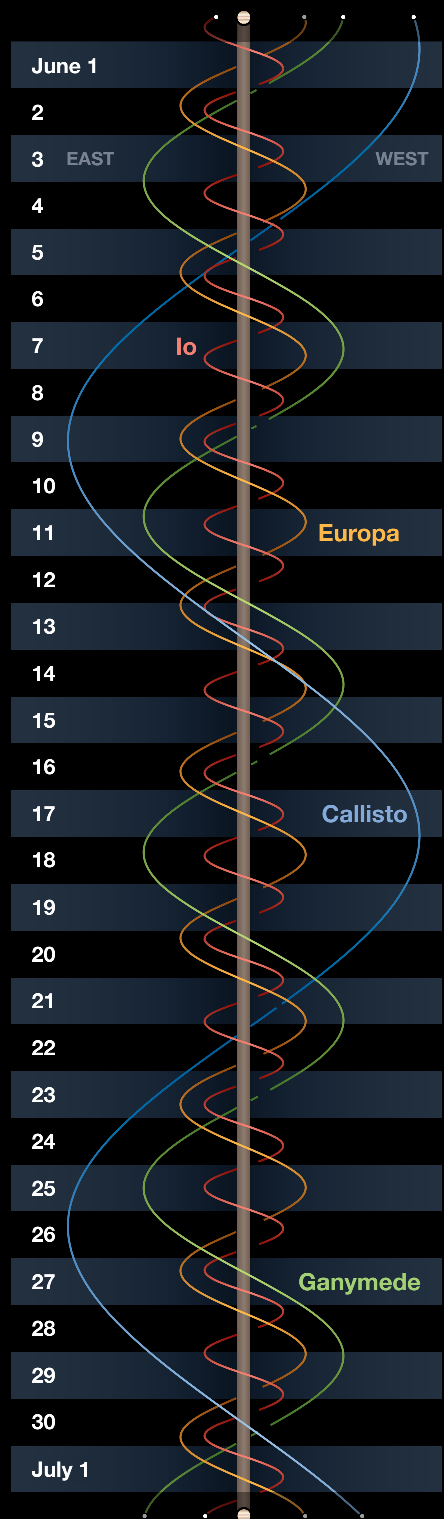
These times assume that the spot will be at System II longitude 19° on June 1st. If it has moved elsewhere, it will transit 1²/₃ minutes earlier for each degree less than 19° and 1²/₃ minutes later for each degree more than 19°.

Phenomena of Jupiter's Moons, June 2022

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

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

Jupiter's Moons



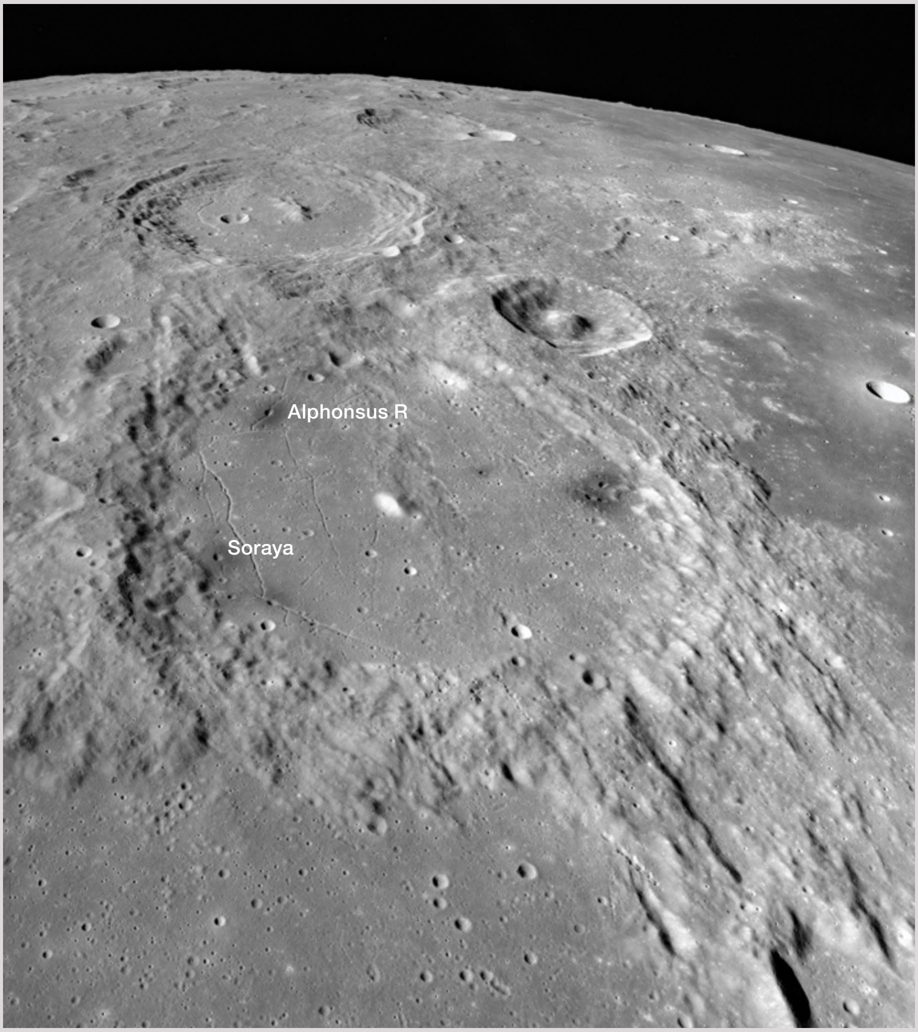
The wavy lines represent Jupiter's four big satellites. The central vertical band is Jupiter itself. Each gray or black horizontal band is one day, from 0ʰ (upper edge of band) to 24ʰ UT (GMT). UT dates are at left. Slide a paper's edge down to your date and time, and read across to see the satellites'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

Dusky Lunar Mysteries

Closely observing enigmatic dark halo craters helps to determine their true origins.

Like almost every landform on the Moon, dark halo craters (DHCs) have a history of controversial and contradictory interpretations. They're generally 2 to 5 km (1.2 to 3.1 mi) in diameter and often look like normal craters, with one exception: DHCs, as the name says, are surrounded by halos of dark material. These dark halos are best observed in your telescope when the Moon is full or nearly so.

The most famous DHCs, and the easiest to find and observe, are the ones in and near rilles along the edges of the floor of **Alphonsus**. There are no fewer than 11 DHCs within this 108-km-diameter crater. The biggest is the 3-km-wide **Alphonsus R**, which is surrounded by an 8-km-wide dark halo. Next is 2.6-km **Soraya** with its 9-km halo, followed by a pair of unnamed 2.5-km craters on the west side of Alphonsus' floor, which have a combined halo measuring some 13 km across. Considering that a 6-inch backyard telescope can show craters only as small as about 2 to 3 km wide, the dark halos are the more obvious targets, though larger apertures and higher magnification may reveal the crater pits themselves. High-resolution images from NASA's Lunar Reconnaissance Orbiter show that these DHCs in Alphonsus are rarely circular; instead they often extend along the direction of the rilles they cut, and, unlike impact craters, lack significantly elevated rims and rays. These are definitely formed by volcanic eruptions.

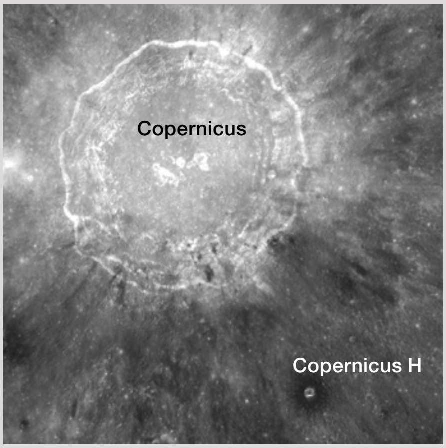


▲This Apollo 16 photograph shows the view facing south across Alphonsus and its several prominent dark halo craters.

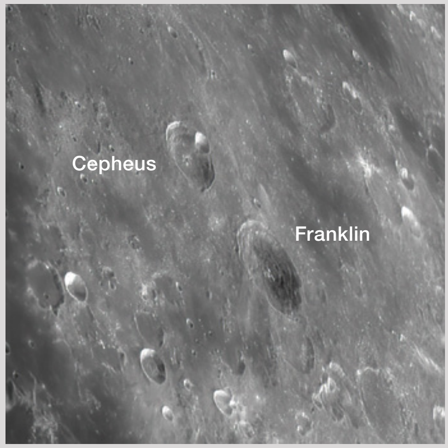
NASA / JSC / ARIZONA STATE UNIVERSITY

But other DHCs are different. A famous example is the 4.5-km-wide **Copernicus H**, which has a 10-km-wide dark halo. Spacecraft images show that Copernicus H has a raised rim, a classic conical interior with a small, flat floor, and tendrils of rays. Copernicus H matches the morphology of a fresh impact crater, with the one exception that its halo and rays are both dark. The obvious explanation is that H formed after **Copernicus** and excavated thru Copernicus' bright debris to eject underlying dark maria material. Multispectral imaging confirmed this sequence of events by showing that H's halo contains the same iron- and magnesium-rich minerals as the maria in the region.

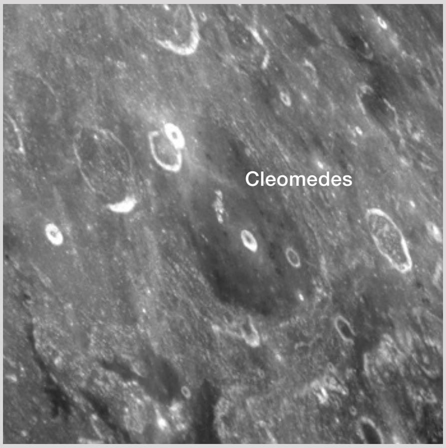
In 1998 the Association of Lunar and



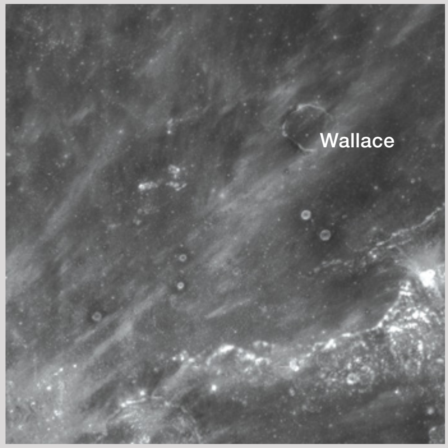
▲ The most prominent impact-generated DHC is Copernicus H, located southeast of Copernicus.



▲ Positioned in the northeast lunar quadrant, the fractured floor of Franklin contains several DHCs of volcanic origin.



▲ Located just northwest of Mare Crisium, Cleomedes contains several tiny DHCs visible in large telescopes.



▲ Several DHCs of impact origin are visible in the vicinity of Wallace, which lies to the north-east of Copernicus.

Planetary Observers (ALPO) published a Lunar Dark-Halo Crater Catalog that gives coordinates for 103 DHCs (**https://is.gd/ALPOdhcs**). But rather than trying to observe these features by plotting each one on a map, instead try surveying the lunar surface when the solar angle is high. Start with Alphonsus, then move on to areas in and around **Theophilus**, **Stadius**, **Atlas**, **Franklin**, **Schickard**, **Grimaldi**, **Triesnecker**, **Manilius**, **Cleomedes**, and **Gauss**. The latter two are especially challenging.

As you observe, you may begin to notice some patterns. The majority of the DHCs around large, fresh craters are like Copernicus H: impact craters that excavated dark lava material from below the bright ejecta rays deposited by the larger, older crater.

Craters like Alphonsus are typically located near the edges of maria and have floors that were fractured and uplifted by magma rising into the impact-fractured zone beneath the crater. Sometimes small amounts of this magma escape through fracture rilles and erupt onto the surface, producing volcanic DHCs.

A few volcanic DHCs are found not inside floor-fractured craters but rather appear as elongated depressions along rilles. The most unusual example is the 5.5-km × 1.7-km pit atop a 20-km-wide dome at the north end of **Rima Birt**, west of **Rupes Recta** (the Straight Wall). Dark halos associated with dome volcanoes are extremely rare.

Traditionally, the kinds of volcanic vents that produce massive, dark pyroclastic deposits are not designated as DHCs, but they could be. One example is the 7-km × 3-km vent that erupted the roughly 100-km-diameter Bode pyroclastic deposit abutting the east edge of **Sinus Aestuum**. Similarly, the 2-km-high volcanic cone — the Cobra Head — that was the source of the pyroclastic deposits covering the Aristarchus Plateau isn't considered a DHC.

Based on these examples, we can derive a simple rule of thumb to determine if a DHC's origin is volcanic or impact-related. If a DHC lies within a floor-fractured crater or is located along a rille, it's volcanic. All others are normal impact craters that simply scattered dark, underlying basalt debris on top of bright ejecta from a nearby rayed crater or young basin — dark ejecta atop bright ejecta. Look at the half-dozen or so DHCs splashing thru the rays northwest of Copernicus, near the crater **Wallace**. All of these are normal impacts with dark halos some 2 to 3 times bigger.

Now observe **Petavius** and **Humboldt**, large, floor-fractured craters near the Moon's eastern limb. Both have big patches of lava and pyroclastic materials around their floor edges. But there are no obvious DHCs that could be sources of this dark material — it may have erupted from rilles or from DHCs hidden by thick deposits of ash. But if you greatly enlarge LRO images, you'll see 1-km-to-2-km-wide craters in the midst of the dark pyroclastics in both. Are these DHCs big enough to be the source of the 20-km-wide patch of pyroclastics along Petavius' southern floor? I don't know.

Finally, although there is no firm count of the number of volcanic versus impact DHCs, I get the impression that the ones that formed on bright ejecta significantly outnumber those of volcanic origin. This makes sense since there are far more bright crater rays than dark, pyroclastic patches.

■ Contributing Editor **CHUCK WOOD** finds plenty of interesting features to observe when the Moon is full.

An Astrophotography Jargon Buster

Don't get tangled in the pursuit's techno-lingo.

Astronomy and photography are both topics laden with complex concepts and technical terms, so it's not surprising that combining the two can lead you into a swamp of jargon. Fortunately, however, many readers have backgrounds that afford a certain level of familiarity with optics and cameras. Perhaps you're a budding nature photographer equipped with an interchangeable lens camera and now wish to capture starry vistas over terrestrial landscapes. Or maybe you're an experienced amateur astronomer wanting to record what you see in your telescope.

But whichever route led you to consider astrophotography, you're going encounter some basic terms, many of which may be unfamiliar. Let's have a look at some of the more common ones you'll run across as you begin to capture the night sky.

Lenses by the Numbers

Look closely at the barrel of a camera lens and you'll see several numbers, such as 50 mm, 1:1.4, or perhaps 200 mm, 1:2.8. These are also often engraved 1.4/50 mm or 2.8/200 mm. The larger number indicates the lens's *focal length* in millimeters. This is the distance from the lens to the image it forms. So-called *prime lenses* have a single, fixed focal length — 50 mm or 200 mm in the examples given here. Lenses are often described as *wide angle* (with focal lengths of 35 mm or less), *standard* (35 mm to 85 mm), *short telephoto* (85 mm to 135 mm) and *telephoto* (135 mm and greater).

You'll also encounter *zoom lenses* of variable focal length, say, 28–300 mm. Chances are your camera came with a zoom lens, but for shooting the night sky a prime lens is generally preferred because the optical quality is usually better. Regardless of design, a lens's focal length governs the amount of sky you can record with your camera — the *field of view*. The longer the focal length, the smaller the field of view.

Unlike your telescope, most photographic lenses possess an internal *diaphragm* or *iris* that can open or close, much like the pupil in your eye. This mechanism regulates the amount of light entering the camera by changing the *effective aperture* of the lens. And if you divide a lens's focal length by its aperture, you'll get what's known as the *focal ratio*, or *f/ratio* — just like you would with a telescope. However, with a camera lens you don't have to do any math since you can choose the focal ratio by turning the aperture ring.

Looking at your lens, you'll notice a sequence of numbers around the lens barrel, often ranging from 1.8 to 16 or higher. These are your aperture, or *f-stop* settings, as photographers like to call them. Each successive number represents a decrease in aperture (and image brightness) of half that of the preceding

▲ The author captured this view of Cygnus and Lyra rising with a single, 60-second exposure made with a cropped-sensor Canon EOS 550D camera and 24-mm lens riding on a Sky-Watcher star tracker mount. Vega is the bright star on the right side of the frame, while Deneb and the pale red glow of the North America Nebula are visible just above the treeline.

one, so the image produced by a lens at f/2.8 is twice as bright as one set to f/4, or 16 times more luminous than one operating at f/11. A *fast* lens — one with a small f/number — is desirable for photographing *extended objects*, like galaxies and nebulae (as opposed to stars), in the shortest possible time.

As mentioned, telescope focal ratios are fixed, and usually lie between f/4 and f/15 depending on the optical design. However, the same rules for camera lenses apply here as well, so a "fast" f/4 scope is preferable for imaging a galaxy's faint light than a "slow" f/10 instrument. Some telescopes are specifically designed for imaging and are called *astrographs*. These usually offer specialized optics and sturdy construction among other photo-friendly features.

The specifics of choosing a lens for astrophotography are beyond this brief exploration of imaging jargon, but it's important to know that focal length and *image scale* are related. You could, for example, capture a galaxy with a 50-mm lens, but it will be rendered very small. A lens with a 200-mm focal length will show that same galaxy four times as large. However, lenses with less focal length excel at delivering wide fields of view, which is useful for capturing large swathes of the night sky. In other words, as with daytime photography, you choose your lens based on the kind of picture you're trying to make.

▲ One of the delights of the June evening sky is globular cluster M3, in Canes Venatici. This portrait was captured in just six minutes with a SharpStar 13028 Hyperbolic Newtonian astrographic telescope working at f/2.8 and a ZWO ASI385MC CMOS astronomical camera.

Cameras and Chips

Digital cameras use special sensors covered with a grid-like matrix of millions of microscopic photosensitive elements called *pixels* that convert light to an electrical signal that is reconstituted, row by row and column by column, into a digital image (see page 64). Camera sensors come in several sizes, but the two most common are called *full frame* and *crop sensor* (also known as APS-C). Full-frame models have sensors with the same dimensions as a 35-mm film frame, that is, 36 mm × 24 mm. Cropped-sensor cameras have slightly smaller detectors. Nikon, Pentax, and Sony cameras feature 23.6-mm × 15.8-mm sensors, while Canon models measure 22.3 mm × 14.9 mm. Smaller still are the 17.3-mm × 13-mm sensors of *Micro Four Thirds* (MFT) cameras. What's important to know is that the field of view of any given focal length lens depends on the type of camera it's used with. That's why a camera's *crop factor* matters. For APS-C cameras, it's 1.5×, while Canon's cropped-sensor cameras have a factor of 1.6×. So, a 100-mm lens in a Nikon APS-C camera would give you the same sky coverage as a 150-mm lens in a full-frame camera, and on a Canon it would be 160 mm.

Perhaps you've heard of some cameras that have been modified for astro-

▲ Lenses with fixed focal lengths are generally better performers than similar zoom models, although a single zoom lens will often be a more economical way to cover a wide range of fields of view. Shown here are three fine astrophotography lenses (from left to right): a Canon EF 200mm f2.8L USM telephoto, a Samyang 85mm f/1.4 short telephoto, and a Samyang 24mm f/1.4 wide-angle.

▲ The author gets plenty of use out of this pair of Canon DLSR cameras. At left is the crop sensor EOS 550D (also marketed as the Rebel T2i and Kiss X4 Digital), and at right is the venerable, full frame EOS 5D Mark I. The 550D camera has been astromodified to make it more sensitive to the H-alpha wavelengths of light for capturing spectacular images of red-hued emission nebulae.

▲ A star-tracking mount, such as this Sky-Watcher Star Adventurer Mini, allows you to take long-exposure images without the stars turning into little streaks because of Earth's rotation. Your camera and lens attach to the mount via a standard ball head.

nomical use. What does that mean? Off-the-shelf digital cameras have internal filters in front of their sensors to make them suitable for daytime use but limit their ability to record the part of the spectrum where many nebulae glow with their characteristic pinkish hues. However, some cameras can be professionally *astromodified* to let more of this red light through.

Cutting Through the Noise

Digital photos taken in low light also record an unavoidable amount of *noise* that needs to be subtracted from the image to produce clean and clear images. This noise arises mostly from heat building up in the sensor during a long exposure, manifesting as random, false-colored pixels scattered throughout an image. Many modern cameras have a feature called *long exposure noise reduction* (LENR) designed to automatically subtract these image artifacts. Unfortunately, your exposure times are doubled with LENR enabled, but you'll save time later on when you process your photos.

Another approach to correct this noise is to simply capture what are called *dark frames*. These are images captured with the lens cap in place that are the same length as your photos of the sky so as only to record the camera's noise signal. You subtract these frames from your nightscape images to remove the noise from your images later when you process your shots.

Another common technique of reducing random electronic noise (often in conjunction with the previously mentioned methods) is to digitally combine a large number of exposures of a single target. These are known as *subframes* and are combined into a single photo by utilizing a process known as *stacking*. The more images you stack, the higher the quality of the final result since you increase the amount of *signal* (the light from your galaxy, for example) while at the same time minimizing unwanted noise.

The essence of stacking is to combine several short exposures to produce results roughly equivalent to a single long one. In other words, a stack of ten, 2-minute subframes would yield a photo similar to a single 20-minute exposure. (Image stacking was discussed in detail in the April issue, starting on page 54.)

Astro Accessories

Unlike landscape photographers, astroimagers have to contend with subjects that are in constant motion thanks to Earth's rotation. A stationary, tripod-mounted camera is limited to exposures of mere seconds. This is the reason for the so-called *500 rule*, which states that the longest exposure you can make with a full-frame camera before stars start to trail is 500 divided by the focal length of your lens. So, a 24-mm lens is limited to just a 21-second exposure (500 ÷ 24 = 20.8). For exposures of longer duration, your camera and lens must accurately follow stars at the rate of Earth's rotation. The device that enables us to do that is called a *star tracker*. I covered portable star trackers in a recent First Exposure (*S&T:* Feb. 2022, p. 54), but you can also use a motorized equatorial

▲ An inexpensive intervalometer/remote cable release enables you to control the number of shots you take and their duration. With such a device, you can program your DSLR to execute time-lapse sequences automatically.

telescope mount. Having your camera and lens ride along with your telescope on its mount is called *piggyback astrophotography*, but it's the same thing as using a star tracker, usually just bigger.

Galaxies and nebulae can require cumulative exposures of tens of minutes — sometimes even hours! Sitting next to your camera to trigger the shutter for each subframe can quickly become tedious. Thankfully, there's a device called an *intervalometer.* It's an inexpensive accessory that plugs into your camera and allows you automatically shoot a sequence of frames after you've preset the number of shots and their duration. If you control your camera via computer software, an intervalometer feature is normally part of the package.

Taking images of the night sky is both challenging and deeply rewarding — and you'll learn something new each time you attempt it. We've only scratched the surface of imaging terminology; indeed many of the topics we've discussed could be (and *will* be) entire articles unto themselves. But starting with a firm foundation as you set out to capture the wonders of the night sky should make that learning process more enjoyable.

Happy imaging!

■ In five decades of observing and 30 years of imaging around the world, **ADE ASHFORD** is still discovering new and exciting celestial vistas to enjoy.

Pie in the Sky

ASTEROIDS: *How Love, Fear, And Greed Will Determine Our Future In Space*

Martin Elvis
Yale University Press, 2021
295 pages, ISBN 978-0-300-23192-2
US$30, hardcover

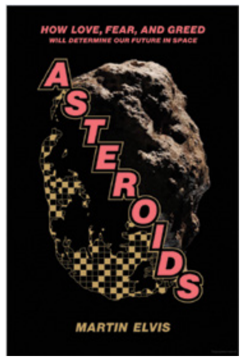
"UNTIL RECENTLY, 'space' and 'greed' didn't often turn up in the same sentence," writes Martin Elvis, an astrophysicist at the Center for Astrophysics, Harvard & Smithsonian, in *Asteroids*. "Space is too noble an enterprise to connect with filthy lucre." That's changing, and fast, Elvis says in this provocative look at the future of asteroid mining and other space industries. In recent years, myriad start-ups have arisen that aim to make a profit beyond Earth.

That's a good thing, Elvis argues. With market forces in play, space technologies will improve, and costs to go into orbit and beyond should come down significantly. This will reap benefits in all three areas Elvis focuses on in this book: love, fear, and greed — his shorthand for science, planet protection, and commercialism.

Love. Asteroids can teach us about the origins of our solar system and even of life itself. Could they have brought the water that life as we know it requires? Ceres, the dwarf planet, might be 30% water by mass. If none of that water was lost to space during a collision with our world, Elvis notes, only about five Ceres-like bodies crashing into us would have filled our oceans.

These small, rocky bodies might also have introduced the organic molecules our organisms need. The Murchison meteorite, which fell in Australia in 1969, is so rich in organics that a newly cut slice of it smells like asphalt or tar, Elvis says. Did the organics in such bodies season the "stone soup" within early oceans that enabled life to develop? Astrobiologists Christopher Chyba and Carl Sagan suggested this idea in a 1992 *Nature* paper and, Elvis says, "it's still looking like a good bet."

Fear. Most astronomers agree it's only a matter of time before a rock akin in size to the one that wiped out the non-avian dinosaurs 66 million years ago threatens Earth. Will we be ready? So far, we've located about 90% of the biggest near-Earth objects, but finding the final 10% won't be easy, Elvis says. They could be lurking behind the Sun, in orbits that only slowly bring them toward our planet. If we do detect a monster in time, we might be able to change its orbit — and have it miss us — using one of four methods under consideration, what Elvis calls hammers, nukes, tractors, and billiards.



Greed. Commercial space pursuits could help us on both the love and fear fronts, Elvis asserts. He delves deepest into asteroid mining. The resources are staggering: The iron content alone of the main-belt asteroids exceeds iron reserves down here by more than 10 million times. Their water is equally valuable. To lift a 1-kg liter of water from Earth's surface into low orbit costs about $20,000, he says. Depending on how much H_2O is needed in space, getting it from asteroids could prove far more economical. A chief use would be for rocket fuel; another is life support ("something astronauts are quite keen on," Elvis notes wryly).

In 2013, Elvis estimated the number of precious-metal, ore-bearing asteroids we know of at 10. Within a decade, he says, that number could reach a couple thousand. Each one of them could be worth $1 billion or more.

Whether anyone can actually make a profit off such activities remains unknown. But one thing's certain, Elvis says: Once a single profitable asteroid-mining venture succeeds, it will trigger an "asteroid rush," with all the legal and other complexities that entails.

Other commercial enterprises in space are progressing faster. Megaconstellation-building and space tourism are well under way, and for-profit space labs are in the offing. One company hopes to use microgravity to 3D-print living human organs to ease transplant needs. Others might create a special type of glass in orbit that Elvis says could be 100 times better for optical fibers now used for high-data-rate internet connections across oceans.

Elvis does pause to consider the ethical implications of space industry. A future base on the Moon's nearside might be so brightly lit that we could see it from Earth. "Is that inspiring?" Elvis asks. "Or is it sacrilege?" He wonders whether we should set aside certain exceptional locales, such as Mars's Valles Marineris, as wilderness areas.

No one could possibly think of all the ramifications of mining the asteroids and other profit-making space pursuits ahead of time, but Elvis makes a valiant effort in this book. His humor and insights, together with the fascinating facts he constantly marshals, make the many as-yet unanswerable questions he leaves the reader with go down easy.

■ **PETER TYSON** owns an asteroid. Well, a piece of a meteorite, anyway — from the Campo del Cielo iron bolide that fell in Argentina about 4,500 years ago.

Drawing in the Dark

Get inspired to sketch your favorite objects at the eyepiece.

Okay, raise your hands: On reading the title did you just think, "Oh, I can't even draw a straight line!"? Keep them up, let me count everyone. Um, let's see — yes, just as I suspected, quite a few. If you remember only one thing from reading this article, I hope it's that *straight lines are difficult to draw for almost everyone*. Truly.

Also, I can think of only three celestial objects with a straight line as part of their telescopic appearance. Two are extremely difficult — the jet in M87 and the jet in 3C 273 — and they require a large scope and nearly perfect skies to see. On the other hand, Rupes Recta (the Straight Wall) on the Moon is easy when the lighting is just right. So, if you're interested in *sketching* what you see through your telescope, not being able to draw straight lines won't hold you back. But is astronomical sketching within your reach? Let's find out.

The "Why"

Because there's no one best way to go about astronomical sketching, I'll describe how I do it as well as why I do it. The *why* — motivation — is as important as the *how* — technique. And if you think sketching sounds like something you want to do, I hope my process will inspire you to develop your own. Even though there are huge benefits to sketching, it's not for everyone. But you might find it useful to see how much — or how little — can go into sketching a celestial object and the extent to which it sharpens your observing skills.

I'm wired to sketch. Soon after I built the first version of my 8-inch Newtonian (see *S&T:* Nov. 2021, p. 58), I started sketching what I saw through the eyepiece. That's not my why, though.

Long ago I read about the importance of documenting every telescopic observation. Not for scientific reasons — those days are long gone, for the most part — but to become a better observer. Writing notes and making sketches would gradually increase my observing skills, and just as important, I'd have a record of my life as an amateur astronomer — an astronomical diary. I found that utterly compelling then, and I still do now. Your "why" may be different, but over time your notebooks could become some of your most cherished possessions.

▲ **GEM IN THE SWORD** It's hard to believe that this digital rendering of the Orion Nebula was made directly from a pencil drawing. Although this nebula can be one of the more difficult objects to sketch, the vast majority of celestial objects are much less complex. This rendering is a combination of many overlapping fields of view, based on eyepiece sketches made with my 28-inch f/4 Newtonian. I used a variety of magnifications, but no nebula filters. North is to the left.

White or Black Paper? Or Maybe Digital?

Although I sketch with a mechanical pencil on white paper, choosing white pencil or acrylic on black paper is also a popular method. Digital drawing apps are beginning to be useful, too. If you don't already have a preference, test different mediums first — and practice with them indoors where it's warm and brightly lit.

For instance, while practicing inside you'll have both eyes open, you'll be comfortably seated, and you'll have a well-lit photograph of an astronomical object in front of you. Seems straightforward enough — but let's compare it with sketching at your telescope out in the dark. You may be comfortably seated, but you may instead be standing on a ladder, while a dim red flashlight — perhaps held between your teeth — weakly illuminates your sketchpad. The wind may be trying to blow away your paper, dew may be getting it damp, or your flashlight batteries may be dying. Oh, and the object you're sketching is barely discernible with averted vision. If your scope doesn't track, you also have to keep nudging it to keep your object in the field of view.

Sheesh, is this even possible?

As daunting as all that may seem, the rewards are worth the effort for those who persevere. Like any new skill, sketching at the eyepiece takes a while to feel familiar, but over time it will become easier. I don't want to understate the difficulties, though, because the learning curve will be steep even if you have an artistic background.

But here's the thing — and it's important: *This isn't about art, and it isn't about comparing your sketches to anyone else's.* This is a personal record of what you see through your telescope, and you don't have to show it to anyone. If you remember two things from this article, this should be the second one.

The How: The Basics of Pencil Sketching at the Eyepiece

To add sketching to your observing palette, begin with simply shaped objects to get used to the process. Here's a quick indoor practice session. Before we start, get a blank sheet of paper and any type of pencil you have on hand. Ready?

- Hold the pencil so the lead is almost parallel to the paper.
- With a soft back-and-forth motion, use the lead of the pencil to make a roughly circular or oval patch about a centimeter in diameter. Start with light, mostly parallel pencil marks, and gradually make the center third darker.
- Take your time and do your best to make this circular graphite patch relatively, but not perfectly, even.

Select Targets for Beginning Sketchers

M84, **M86**, and **M87** • Elliptical galaxies are excellent objects with which to start.

NGC 4565 • This is much like an elliptical galaxy, except it's stretched out and has a dark lane down the middle, which is good practice for using an eraser.

M57 • The Ring Nebula has an elliptical perimeter and a circular interior, with slightly darker ends.

M29 • Not the most beautiful open cluster in the sky, but it's a good one to start with. The few bright stars have a distinctive pattern even under a heavily light-polluted sky.

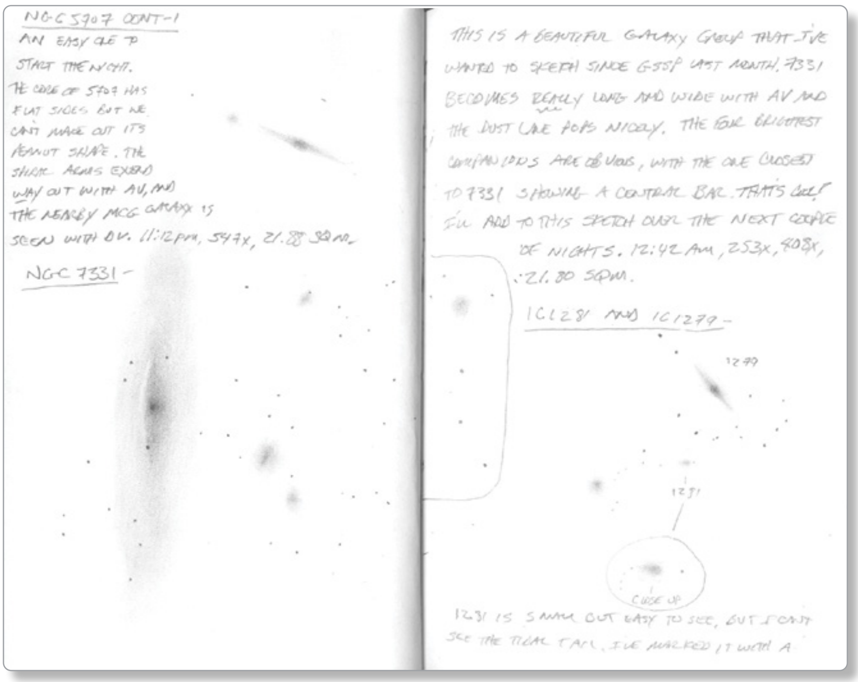
M17 • The Swan Nebula has a lot of nebular detail, so depending on how much you can see, you might want to make a template first. This could be a challenge.

NGC 257 • The Owl Cluster is an open cluster with a distinctive shape. Fun to sketch!

M31 • This is a good object for small-aperture, wide-field telescopes, plus with nearby M32 and M110 this is the finest group of three bright galaxies.

NGC 2169 • This open cluster practically begs to be sketched — it's called the 37 Cluster for good reason.

M42 and **M43** • A small-aperture, wide-field telescope under a light-polluted sky will still show a surprising amount of detail in these nebulae. Start with a template.



▲ **SKETCHER'S NOTEPAD** A spread from my observing notebook showing what the vast majority of my eyepiece sketches look like. They never get to the finished drawing or rendering stage, but I like them the way they are — soaked in starlight and dew. Also, I scan every page, so I have a digital backup, which also makes them easy to search.

ALL PHOTOS AND SKETCHES BY HOWARD BANICH UNLESS OTHERWISE NOTED; SKETCH TEXTURE: HAPPYKANPPY / SHUTTERSTOCK.COM; HAND-DRAWN STROKE: MADDYZ / SHUTTERSTOCK.COM

- With your finger (I suggest the little finger of your drawing hand), softly rub the patch in a circular motion until it's mostly, but not perfectly, smooth.
- Erase the bits that look out of place, add pencil lead where it looks like more is needed, and *smudge* more with your finger. Repeat as needed.
- Once you're happy with your smudge, use the tip of the pencil to add a small, dark dot as close to the center of the smudge as you can.

Congratulations, you've just sketched your first elliptical galaxy! Stretch it out and you've got an edge-on galaxy or add wings to make a spiral galaxy. Master these six steps, and you're on your way to sketching almost everything you can see through your telescope.

When I'm at the eyepiece I keep it simple by using only a sketching notebook or clipboard and a mechanical pencil with a good eraser. My notebook opens up to 11 inches by 8.5 inches — easy to hold in one hand with a pencil in the other. There's nothing special about either item, but I like using 0.7-mm HB lead in the pencil. Yeah, the initials are fun, but I chose it because it's a medium-density graphite that's easy to control.

For the most part, once I've made my sketch, I'll stop there. But for my favorite objects I'll make a finished *drawing*, and sometimes I'll go one step further and make that into a digital *rendering*. Digital renderings, made with an image-processing program on my computer, are closest to showing what I actually saw in the eyepiece. More on this later.

Perhaps you've seen observing-report templates that include sketching circles. They're a great way to get started, and many people use them. However, their drawback is that they determine the scale of your sketch — everything from the Crab Nebula (small) to the Andromeda Galaxy (very large) has to be scaled to fit within the same size circle. Most things will, but not the biggest and often most interesting objects.

Sketching Large and Complex Objects

Drawing big targets takes some upfront planning to set the scale because *the drawing has to be large enough to properly show the smallest details*. That's an important tip I learned the hard way, so let's make this the third thing to remember. When I sketched the Orion Nebula for the first time, I spent most of a rare clear winter night making a rough, freehand sketch in my notebook. But I was really frustrated with the result.

What went wrong? First, M42 is way too complex for me to render freehand. Spreading the sketch over two pages was a terrible idea — and the scale was way off. The Trapezium area ended up too small to show anywhere near all the detail I could see. Plus, the overall proportions were skewed, and I was irritated that two hours of effort didn't turn out better. It did get me thinking, though. I needed a template.

A single template for everything would be way too large to use at the eyepiece of my scope, so I made the project easier by

Glossary

Sketching: A quickly made drawing meant to capture the essence of an object.

Drawing: A finished version of a sketch meant to show more accurately what the object looked like.

Rendering: An image meant to be as realistic as possible.

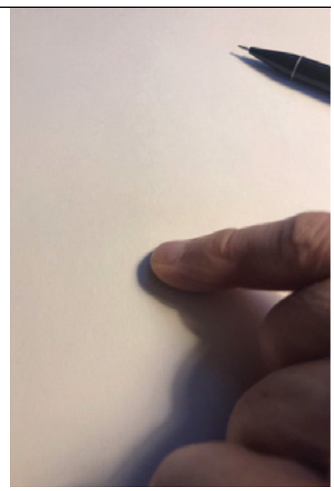
Smudging: Smearing pencil lead on paper with a smudging post or finger.

Cleaning bag: A small cloth bag filled with eraser shavings; used for lightly erasing large areas.

Eraser pencil: A long eraser in a plastic holder. The tip can be cut to a sharp point for erasing thin lines.

Tracing paper: Very thin and nearly transparent paper. It also has a fine texture and is excellent for smudging.

Vellum: A thicker, higher-quality relative of tracing paper. Best saved for making a finished drawing.



▶ **DRAW AND SMUDGE** Note how I hold the pencil nearly horizontal to the paper, and how I move it back and forth instead of round and round (second photo). As best you can, draw all the pencil marks in the same direction as shown. As the circular area becomes more consistently dark, start making the central third even darker. Do your best but don't try to be perfect — think of this as a practice doodle where imperfections are okay. Notice how rough the sketch in the second photo looks. When you get to this point, gently smudge it with a finger to blend the pencil lines together.

PAPER BACKGROUND: CARABUS / SHUTTERSTOCK.COM breaking it into two parts. I decided to make one template for M42 and M43, and a separate one for the Trapezium region. (See page 32 in the December 2017 issue for details.)

I also found that thinking of a big object as a bunch of small objects that overlap makes sketching easier to conceptualize and to manage. Like any complex task, breaking down the process into smaller bits is a good way to succeed. For me, that cracked the nut on how to tackle large and complex objects.

Templates

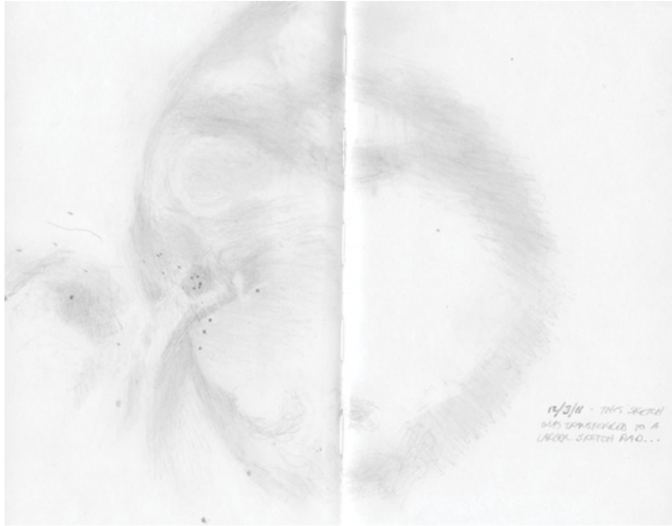
Until 2011 I sketched everything freehand, which worked well because at the time I mostly sketched the simplest deep-sky objects, plus a planet or two whenever the seeing was sharp. Planets are easy, because accepted practice is to either print a template for Jupiter and Saturn (**https://is.gd/planet_templates**) or use a 2-inch-diameter eyepiece cap to draw the outline of the planets large enough to show a disk.

How about a deep-sky object template? I make my own by printing a photo of the object I'm interested in, place a sheet of *tracing paper* over it, and lightly trace the outlines of the object and the brighter stars. Bingo — instant template. Then I place a solid sheet of white paper behind the tracing paper so the traced outlines are visible, and then tape them both to a clipboard. Now I can confidently depict details in their correct places, orientations, and proportions while at the eyepiece.

Technique Tips

Overall, keep things as simple as possible. That's why I use a mechanical pencil with a built-in eraser. The lead never needs sharpening, and the eraser is always handy. A must-have is a red flashlight with adjustable brightness. Using the least amount of light to illuminate your sketching medium will help preserve your night vision. I also recommend closing your observing eye (wearing an eyepatch might help), while sketching to keep your observing eye at maximum sensitivity.

Remember, you're not trying to make a finished drawing while at the eyepiece. Save the smudgers and the pencils of differing hardness for when you're indoors. It's difficult



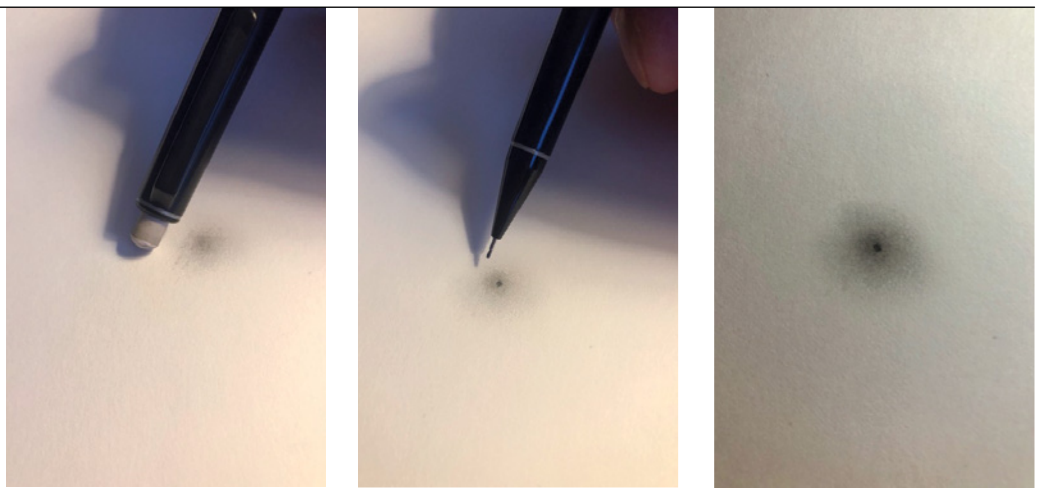
▲ **LEARNING FROM MISTAKES** This is how not to draw the Great Orion Nebula. The pages of my notebook are 11 × 5.5 inches opened up like this, a nice size for sketching — but goodness, not over the seam! This was my first attempt at drawing such a large object, and within a couple of weeks I had come up with my tracing paper and clipboard template process. This is a far cry from the digital rendering shown on page 58, but this effort led directly to it. North is to the left.

enough to produce a sketch at the eyepiece without a bunch of out-of-place lines and blobs that you can't see under the dim red light of your flashlight. If you try to make fine adjustments in the dark, you'll likely find you have to run your flashlight too bright, which will make it harder to see all the detail present in your scope's eyepiece. Even if you find you're super-good at this, keeping things simple at the eyepiece makes the process more enjoyable.

But smudging is crucial for rendering delicate details while at the eyepiece, so what to do? Use that finger — with a little practice it may become one of your favorite drawing instruments. A bonus is that tracing paper and *vellum* are both great for smudging.

It bears repeating: Draw at a scale that allows the smallest detail to be clearly shown. That's why my sketching clipboards

▶ **SKETCH AN ELLIPTICAL** Your eraser is as important as the pencil lead. Don't be shy when sketching; the eraser will get rid of any excess lines and smudges. If you erase too much, add more pencil — repeat as needed. After a bit more finger-smudging, you should have a mostly round smudge with a darker center. Add a black dot with the end of the pencil, and you've just sketched your first elliptical galaxy! To see a short video of this process, go to **https://is.gd/sketching_primer**.



▲ **KEEP YOUR PAPER IN PLACE** I used three clipboards for sketching the Cygnus Loop at the eyepiece. Since I made four eyepiece sketches, one clipboard did double duty. The blue tape holding down the corners of the tracing paper templates was essential to keeping the paper flat while sketching for whenever a breeze came up.

▲ **OPAQUE PROJECTOR IN ACTION** I projected a photo of the Cygnus Loop onto a large piece of paper taped to a window. After lightly tracing the outline of each Veil with a pencil, I completed the template of the Loop. The photo that's being projected is a negative image that I found online and printed at 5 inches by 7 inches.

are 15 inches by 16 inches. While comfortable for me to hold at the scope, you may find a different size works better.

Finished Pencil Drawing

I'll usually make a finished pencil drawing directly from my eyepiece sketch, but the Cygnus Loop required an extra step (see *S&T:* Sept. 2021, p. 28). I needed to place the separate eyepiece sketches of all five Veils (distinct parts of the Loop) at their correct relative sizes and positions, so I created a full-size template of the Loop on a 32-inch-square piece of vellum paper at the proper scale using an art projector. This allowed me to accurately transfer all the detail I'd recorded in my eyepiece sketches to the finished pencil drawing. An art projector displays a printed picture on a wall at more or less any scale. After finding a negative photo of the full Cygnus Loop online, I printed it at 5 inches by 7 inches and placed it under the projector as shown in the photo above.

After adjusting the projector to get the proper size, I lightly sketched the outline of the Loop on the vellum to complete the template. Then I settled in to draw all the details from my separate eyepiece sketches onto the template. Watching the drawing come alive with everything I'd seen through my scope was a wonderful experience.

The finished drawing was made with a mechanical pencil with 0.7-mm HB lead — the same one I use at the eyepiece — a *cleaning bag*, and an *eraser pencil*. That, and my little finger for smudging.

The Benefits of Sketching at the Eyepiece

1. The process of sketching forces your attention on an object more intensely than any other method. Drawing something — anything — requires your eye-brain system to wake up and *really* see every detail.
2. The more sketching at the eyepiece you do, the better you get at it, yes — but the real payoff is that you see more. This is what makes you a better observer, and over time you will come to see way more than you thought possible.
3. It's gratifying to go through your notebook a year after starting to see how your sketches have improved, and how much more you've learned to see.

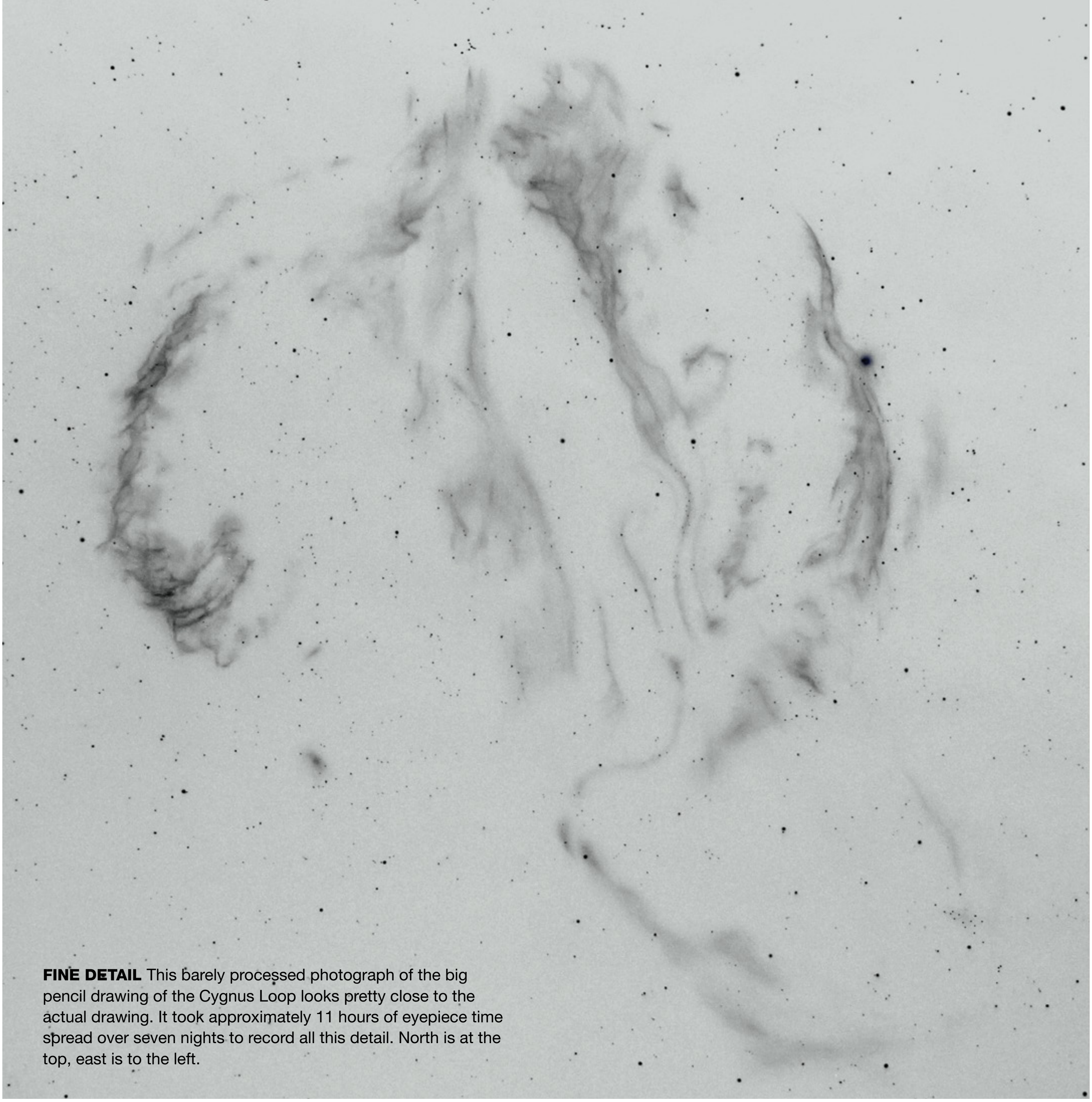
Digital Rendering

Making a digital version of the finished drawing is usually as simple as putting it in a flatbed scanner. But for drawings that are too large, photography is the answer. Sounds easy, right?

Yes, but no. The drawing must be nearly perfectly illuminated so there's no brightness gradient. This requires setting up a temporary studio in order to get the lighting just right. After what always seems like too much effort, it's then time for some computerized image processing. Even if you have no interest in digitizing your drawings, it's still a good idea to scan or photograph your work — a digital backup will be invaluable if the original ever gets damaged or lost. Plus, digital renditions are easy to share with others.

My goal with image processing is to turn my pencil drawing into a rendering that looks as much like what I saw in the eyepiece as I can manage. I find this step hugely satisfying, and it's what you see in my observing articles. I use the free

SKETCH TEXTURE: HAPPYKANPPY / SHUTTERSTOCK.COM; HAND-DRAWN STROKE: MADDYZ / SHUTTERSTOCK.COM



FINE DETAIL This barely processed photograph of the big pencil drawing of the Cygnus Loop looks pretty close to the actual drawing. It took approximately 11 hours of eyepiece time spread over seven nights to record all this detail. North is at the top, east is to the left.

image-processing program GIMP (**gimp.org**) to invert the photo of the finished drawing from a negative to a positive and adjust the brightness, contrast, and several other parameters. At this stage I add colors as I see them through eyepiece, but that's a whole other article!

Compared to what astrophotographers go through, this is a piece of cake. Although it may seem a long way from looking in the eyepiece, the result is as realistic as I'm able to make it.

Sketchy Thoughts

I realize that this process may come across as a hopelessly subjective hairball. Why not just take a photo? The practical answer is that imaging is even more involved, not to mention way more expensive. The real answer, though, is that a photo is incapable of showing what I *see*. For me, it's worth the extra effort to go through each step outlined above for a few special objects. However, making an eyepiece sketch of nearly everything I observe is my real enjoyment and is the bedrock of my observing skill.

Here's a promise: If you give sketching a determined try for one year, you'll see more than you thought possible and become a better observer in the process. Guaranteed.

But, will you finally be able to draw a straight line? Fortunately, it doesn't matter.

■ Contributing Editor **HOWARD BANICH** can draw *nearly* straight lines, but really straight ones are still aggravatingly difficult. He can be reached at **hbanich@gmail.com**.

Want to know the truth about color in astrophotography? Well, it isn't black and white, that's for sure. The fact is, color is subjective. We all perceive color slightly differently — images evoke different perceptions depending on the viewer, because seeing a photo involves the entire eye-to-brain visual system. A quick glance at the various color choices applied to photos of any particular deep-sky object makes it clear that there is no single "correct" way to present color. Some imagers prefer bold, saturated colors, while others opt for a more muted palette.

Beauty is literally in the eye of the beholder. For those of us who image the night sky, the first and most important judge of every image is its creator. And while there's plenty of room for flexibility, your color choices shouldn't be random. Variations in hue and saturation throughout an image can provide important clues to the chemistry and physical structure of your subject. Those choices require a few guiding principles.

Color from Black and White

In today's era of digital photography, virtually every sensor in every digital camera is monochrome, meaning it produces images rendered in shades of gray, ranging from pure black to pure white. These grayscale images contain no color. This is true even for the raw images from consumer digital cameras, including the one in your cell phone. Since these detectors are sensitive to visible light (and more), they require a method to isolate specific wavelengths from different parts of the spectrum — for example, red, green, and blue — that are then combined to make a color picture.

The detectors in your cell phones, DSLRs, and other color cameras contain a built-in array of microscopic red, green, or blue color filters over the pixels. These filters are arranged in a repeating pattern of R, G, and B filters like a checkerboard, dividing up the detector into the three primary colors (though some include a fourth, clear filter). The grayscale

▼ **WHAT COLOR IS IT?** Images of deep-sky objects can tell us different things depending on how they were acquired. These pictures of emission nebula IC 5070 in Cygnus were shot through both broadband color (left) and narrowband filters (right). The natural-color image shows the region dominated by reddish hydrogen-alpha nebulosity, while the narrowband image highlights the distribution of ionized oxygen (O III) and sulfur (S II).

PALETTES OF THE DEEP SKY

Different filters help reveal the chemistry of the universe.

◀▲ **THREE INTO ONE** Color photographs captured with digital cameras comprise monochrome images recorded through color filters. This picture of M31, the Andromeda Galaxy, was made from a series of shots recorded through red, green, and blue filters (above) to produce the colorful result seen at far left.

images from these cameras are then decoded to produce a color image. This array is referred to as a Bayer filter array after its inventor, Bryce Bayer, and the process of reinterpreting the image into color is known as *debayering*. Debayering is performed automatically in most consumer cameras. Astronomical image-processing software can also debayer DSLR and other color-camera images as long as they were originally recorded in RAW format. (Cameras automatically debayer images saved as JPEG or other formats.) Using RAW allows more processing options when determining color balance in deep-sky images, among other advantages.

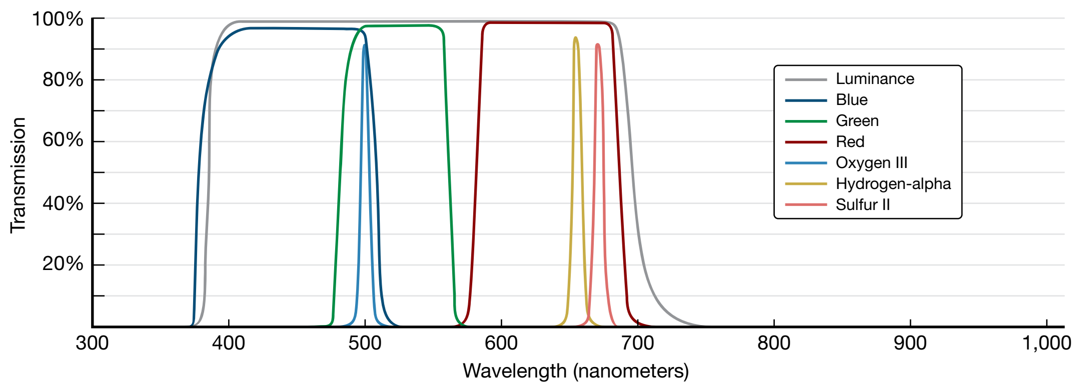
Cameras with monochrome sensors that don't include a Bayer array achieve color separation with a filter wheel that allows you to swap multiple filters into the light path one at a time to record each color individually. These sets of images are then assigned to the red, green, and blue channels in software to make a tri-color image. In the most straightforward example, a natural-color picture is produced by assigning light recorded through red, green, and blue filters to the respective channels in your favorite image-processing program.

With deep-sky targets, we can't verify color accuracy with our own eyes, not even through a telescope. But we can aim for a neutral background and a range of star colors that are as unbiased as possible. Some imagers use careful measurements of the recorded data and make color corrections based on a Sun-like field star in order to achieve accurate color. But in general, if you take care to follow one of those two guiding principles, the colors of deep-sky objects should appear as expected based on their physical characteristics. For example, many nearby spiral galaxies sport yellow cores, pinkish patches of emission nebulosity, blue star clusters, and brownish dust lanes. Reflection nebulae display mainly blue nebulosity encrusted with colorful stars. And bright star clusters often appear sprinkled with blue, yellow, and orangish stars.

Specialized Filters

As noted earlier, camera sensors detect a much greater swath of the electromagnetic spectrum than our eyes do — from about 350 to 1,100 nanometers, compared to the human vision range of 380 to 800 nm. Filters block some wavelengths while letting others pass through to the sensor. Most filters used for deep-sky astrophotography block ultraviolet and near-infrared wavelengths, though both extremes are useful for planetary imaging. Earth's atmosphere blocks the majority of ultraviolet wavelengths. It's also desirable to block near-infrared light, since it adds a red color cast in images and, in some

▶ **SPECTRAL RANGE** Colors depicted in the majority of amateur astrophotos originate in the visible spectrum, but color can be used to represent different things. A natural-color photo arises from images recorded through red, green, and blue filters. Many false-color representations of nebulae are recorded through O III, Hα, and S II filters, which highlight ionized gases that emit light at specific regions within the visible spectrum.



UNLESS OTHERWISE NOTED, ALL IMAGES PROVIDED BY AUTHOR; GRAPH: GREGG DINDERMAN / S&T

optical systems, focuses at a slightly different position than visible light, resulting in puffy, bloated stars.

Broadband color and narrowband filters are the main ones used for deep-sky astrophotography, and each comes in a few different flavors. Color filters let through light over a wide range of wavelengths. R, G, and B filters pass a range of about 100 nm each, covering the majority of the visible spectrum from about 400 nm to 700 nm. Because of this, color filters, including those in a Bayer filter array, yield the most natural-looking colors. Broadband filters are excellent for imaging any type of deep-sky target, including galaxies, star clusters, and nebulae.

◀ **HUES OF BLUE AND GOLD** Deep-sky targets like the Double Cluster (NGC 869 and NGC 884), and reflection nebulae like the Pleiades (M45), look best with a natural-color palette recorded through red, green, and blue broadband filters.

Some broadband filters also block certain wavelengths associated with common light-pollution sources, like mercury and sodium-vapor streetlights, which once dominated city lighting but are being replaced by LED lighting. These light-pollution suppression filters are useful under moderately light-polluted skies, though the resulting images may have a slight color cast due to the filter blocking some wavelengths.

Narrowband filters block all light except for specific wavelengths. For example, a hydrogen-alpha (Hα) filter blocks all wavelengths except for a narrow range centered at 656.28 nm, where ionized hydrogen atoms emit light. Hydrogen is the most common element in the universe and is the primary material from which stars are formed. These star-forming regions appear as pinkish clouds of nebulosity riddling the Milky Way and other galaxies. Similar narrowband filters are used to record the emissions from different ionized gases — oxygen (O III), sulfur (S II), and nitrogen (N II). These four are the most abundant gases in the universe that originate from the death of stars in planetary nebulae and supernovae, seeding future star formation. Because narrowband filters only pass a tiny sliver of the visible spectrum, they also block most sources of light pollution and can even attenuate moonlight. This makes them especially useful for imaging in urban conditions, where a broadband approach would be very challenging. Narrowband imaging is best suited to photographing expansive fields of nebulae within the Milky Way.

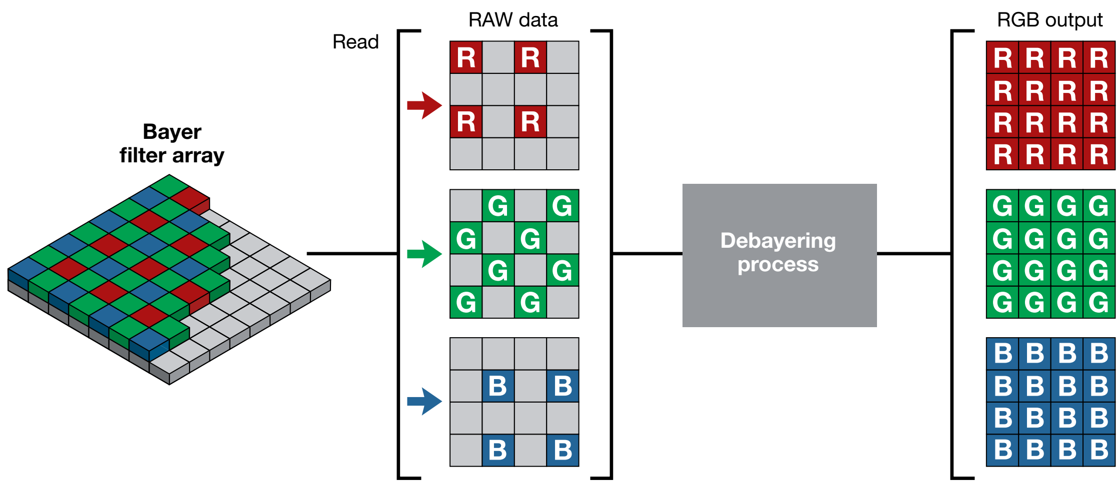
Narrowband filters are most effective when paired with a monochrome sensor, but users with color cameras can still get involved in narrowband imaging. Several manufacturers, including OPT Telescopes (**optcorp.com**), Optolong Filters (**optolong.com**), and others sell multi-bandpass narrowband filters. These block most incoming light except those associated with Hα, O III, and sometimes S II. Using these types of filters, most of the hydrogen signal will be captured in the red channel of your color-camera image, while the oxygen signal appears roughly equally on the green and blue pixels.

Assigning Color Channels

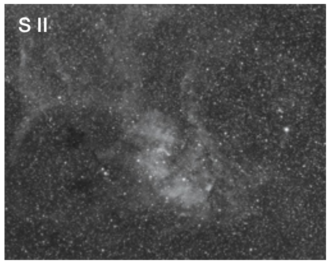
So how do we make a color picture from data recorded through individual filters? You can produce natural-color images with broadband RGB filters and by assigning each color to its respective channel.

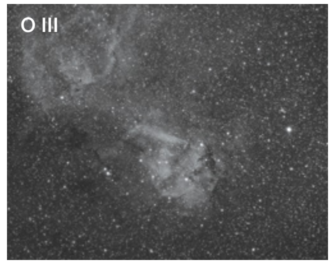
A greater range of color choices is available when narrowband filters are either included with RGB filters during acquisition or employed exclusively. Some amateurs mix in narrowband data with broadband images to produce

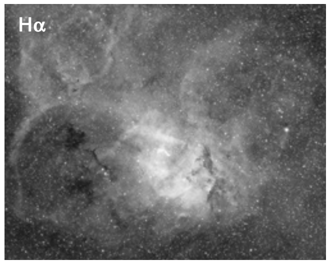
▶ **TINY FILTERS** Consumer cameras — from DSLRs to the tiny detector in your smartphone — incorporate a grid of color filters over a monochrome sensor. The resulting image is then split into three separate images, where interpolation fills in the gaps between pixels and the result is combined into a color picture.



BAYER FILTER GRID: LEAH TISCIONE / S&T







◀▲ **ISOLATED WAVELENGTHS** Images recorded through narrowband filters that pass only specific wavelengths of light found in nebulae are combined in a variety of false-color palettes. In this image of Sh2-132 in Cepheus, data captured through S II, Hα, and O III images (above) are blended into a false-color result seen at far left.

"enhanced color" results — these pictures blend narrowband data with the color channels of the corresponding wavelength in the visible spectrum. For example, Hα is mixed with the red channel of an RGB image to emphasize emission nebulosity. Likewise, O III is added to both the blue and green channels of a natural-color image to enhance the elements' contributions, which is particularly helpful when targeting planetary nebulae and supernova remnants. This technique retains a natural color balance while enhancing the visibility of dim nebulae.

Imaging exclusively with narrowband filters offers the widest range of options when creating a color image. A natural-looking color palette can't be generated from narrowband data alone because the filters only pass a tiny fraction of the visible spectrum. This affects star colors in particular. Additionally, the three primary narrowband wavelengths don't fall neatly into corresponding regions of the visible spectrum to make a natural-color image. Doubly ionized oxygen (O III) emits light at two wavelengths near the crossover between blue and green light (500.7 and 495.9 nm), while Hα, N II, and S II appear in the red part of the spectrum within a span of about 15 nanometers at 656.28, 658.4, and 671.6 nm, respectively. For these reasons, photos made solely from narrowband data are referred to as "false-color" images.

Professional astronomers working with the Hubble Space Telescope and other observatories established the narrowband palettes we typically use today. The most common narrowband color combination is referred to as the *Hubble Palette* since it was popularized in many of the Space Telescope's most iconic images beginning in the early 1990's. Hubble astronomers use a descending-wavelength palette by assigning S II, Hα, and O III to the red, green, and blue channels, respectively. At about the same time, astronomers using the Canada-France-Hawaii Telescope (CFHT) chose to combine narrowband data by assigning Hα to the red channel, O III to green, and S II to blue. Each of these approaches presents a very different look, as you can see on page 40.

Another popular narrowband technique is to shoot through only Hα and O III filters, and combine the results by treating Hα as red and assigning O III to both green and blue. This is particularly useful when the target object contains little or no S II component.

Still other astrophotographers aim to get the best of both worlds by shooting their targets with both narrowband and broadband filters. This allows the nebulae to be processed one way, while achieving natural hues in the field stars.

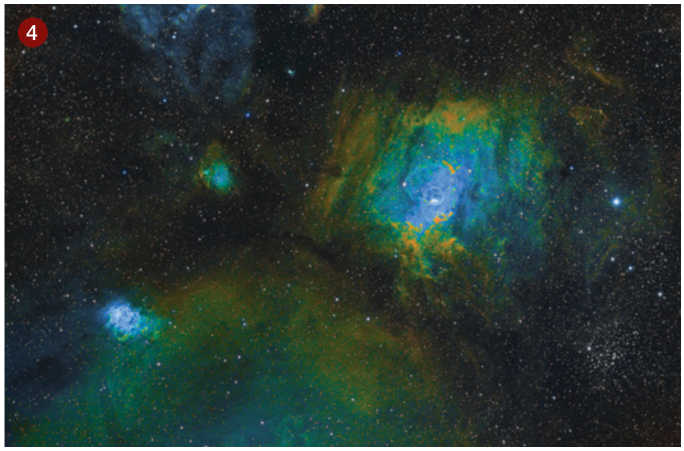
You don't need to limit yourself to a single result either. I often make multiple versions of an image with the same narrowband dataset.

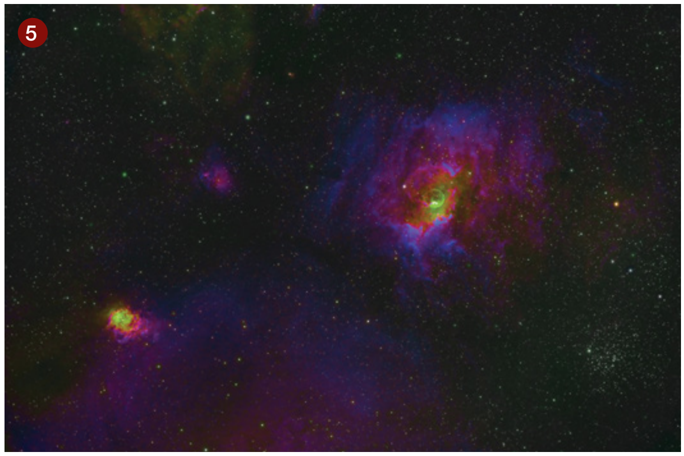
Processing Tips

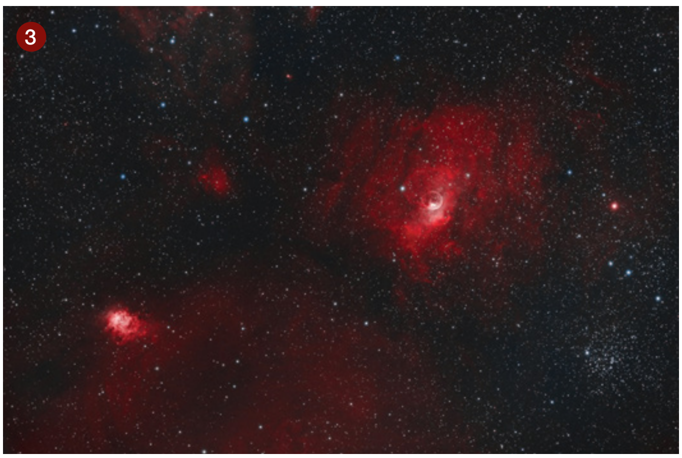
We perceive most of the detail in the lightness component (brightness, contrast, graininess, smoothness) of a color image, while the chrominance component provides color information. I try to account for this fact when I process my color pictures by separating the workflow into steps that affect lightness separately from those that focus on color. With this foundation, I use a different approach for broadband images compared to narrowband, regardless of the type of camera used.

When I process natural-color astrophotos, my approach is to complete almost all color corrections before applying any non-linear stretching or detail enhancement. I aim to achieve a neutral background and stars that display natural-looking hues (red, gold, blue, and white). One important step toward achieving this result is to remove any uneven field illumination (such as vignetting and light-pollution gradients) after combining the images into a color composite.

For narrowband images, I also remove gradients fairly early in the workflow. However, I defer all other color adjustments until I've fully processed the lightness component of the image, including optimizing the sharpness, smoothness, brightness, and contrast. After that, I adjust the color by aiming for a pleasing combination of tones that reveal the chemistry and structure of my subject.







◀▲ **MULTIPLE CHOICE** You can combine images of nebulae using broadband color and narrowband filters in several ways. This colorful series shows NGC 7635, the Bubble Nebula, in Cassiopeia through various filter combinations. 1 Broadband RGB. 2 Enhanced color by adding Hα to the RGB image. 3 Bi-color image using Hα as the red channel and O III as both the green and blue channels. 4 Narrowband image combined in the Hubble palette (red is S II, green is Hα, and blue represents O III). 5 Narrowband image combined in the CFHT palette (Hα is assigned to the red channel, O III to green, and blue represents the S II component).

Narrowband is also a bit different than broadband imaging in that it's dominated by Hα signal. If we simply combined narrowband channels based solely on the signal recorded in three exposures of the same length, the result would be primarily tinted the color that Hα is assigned. For example, a Hubble palette image would look mostly green. In order to compensate for this imbalance and achieve a wide range of colors in a narrowband image, the three component images need to be stretched so that each color channel contributes fairly equally to the final result.

While you process your images, remember that while perception is subjective, measurement is not. It's important to use your eyes *and* objective measurements of pixel values to help achieve the result you desire. Your eyes, your screen, and even the ambient light conditions will influence what you see but do not alter the image data. I often rely on the histogram displays of my images to evaluate whether or not the background is neutral and which colors dominate the midtones.

When it comes to achieving satisfying color images, the same principles apply regardless of which type of camera or filter set you use. Just remember to think about color at each stage of the imaging process, from acquisition to the final presentation of your work.

■ Contributing Editor **RON BRECHER** is always excited to photograph the night sky from his backyard observatory in Guelph, Ontario.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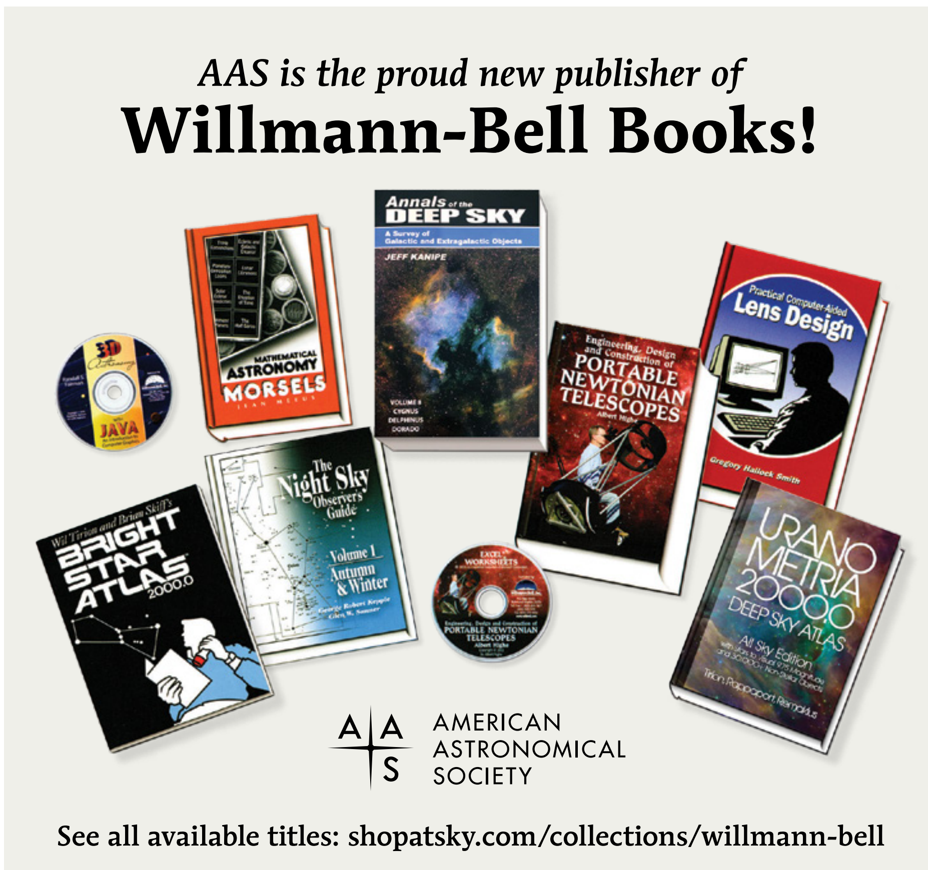
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Sky-Watcher's Evoguide 50DX

This new version of the Evoguide 50 has multiple uses for today's astrophotographers and observers.

◀ The Sky-Watcher Evoguide 50DX package includes everything seen here. The two-ring mounting bracket attaches to either the green Vixen-style dovetail and riser block (as pictured) or the "finder" stalk at left with a dovetail foot that fits an increasingly common quick-release base found on today's telescopes. The tight-fitting, metal lens cap seen in the foreground is a welcome feature of the scope.

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Sky-Watcher Evoguide 50DX

U.S. Price: $335

Skywatcherusa.com

What We Like

Excellent optics

Solid construction

Highly versatile beyond its calling as a guidescope

What We Don't Like

Backlash in the focusing ring

WHILE THE NAME RIGHTLY implies that the Sky-Watcher Evoguide 50DX was designed as a guidescope, it's more versatile than that. Fitted with eyepieces, it can serve as a high-quality finder and even a small telescope (more about that later). And with the optional Evoguide 50ED Field Flattener ($105), it's a decent wide-field astrograph that performs well with sensors as large as APS format.

The Evoguide we borrowed from Sky-Watcher for this review still carries the 50ED name badge on the side of the tube, and the company says the optical tube has not changed since its introduction as the 50ED several years ago. The 50DX now includes a nice two-ring mounting bracket with soft-tipped locking thumbscrews. This bracket attaches to either a "finder" stalk with a dovetail foot that fits most quick-release finder shoes or attaches to a small riser block and 150-mm (6-inch) long Vixen-style dovetail bar (both are included). There's also a small locking ring designed to slip over 1¼-inch eyepiece barrels and guide camera nosepieces to set the approximate focus position as they slide into the Evoguide's focuser.

A label attached to the Evoguide's fixed dew shield says the two-element objective (with one element made of extra-low-dispersion glass) has an aperture of 50 mm, but on the optical bench I measured the full aperture that brings starlight to a focus on axis as being 51 mm. That's a small, but nevertheless welcome, difference. Slightly more significant is the issue of the objective's focal length. The label states it's 242 mm, while the manual calls it 250 mm. I measured it as 253 mm, which is the value confirmed by the scope's image scale when shooting without the field flattener. This makes the scope's native focal ratio f/4.96. The field flattener slightly increases the effective focal length to 266 mm and f/5.22.

The Evoguide's helical focuser, which does not rotate the drawtube when the focus ring is turned, has a modest 18 mm range of travel. With the focuser fully retracted, the scope's overall length is just 22 cm (a touch over 8½ inches), and the focal point lies 65 mm outside the mounting surface of the drawtube's male M42 threads (often called T threads in the camera world). While the manual doesn't mention it, this is enough back focus to attach a DSLR camera to the scope with a standard T ring. But be warned, while such a setup will give you full access to Evoguide's field of decent star images (an imaging circle I judge to be about 10 mm in diameter), this is still far short of the coverage needed for even DSLRs with APS-size sensors, let alone a full-frame camera.

In addition to the M42 threads, the focuser's drawtube is bored to accept 1¼-inch eyepieces and accessories, which are held in place with three thumbscrews. There's a 39-mm long extension tube included with the Evoguide that threads onto the drawtube and also has M42 male threads and a 1¼-inch bore with three thumbscrews. As such, I could always find a combination that let me focus every eyepiece and small astronomical imaging and/or guide camera I tried with the little scope. Although some eyepieces reached focus only when partially inserted into the drawtube, there still isn't enough back focus to guarantee that the Evoguide will work with all star diagonals. But it does work with some.

As a Guidescope

Since the Evoguide was designed as a guidescope, let's look at that application first. Having been on the roller-coaster ride through the Golden Age of emulsion-based astrophotography at the end of the 20th century, I've witnessed a lot of changes as photography has gone digital. With the exception of the comparatively high cost of getting a foothold in astrophotography today, I consider all of these changes to have been for the better. And one shining example involves guiding a telescope.

Long gone are the single, multi-hour exposures needed to create the best deep-sky photos on film. Today, many stunning deep-sky images are made from stacks of digital exposures that are so brief they often don't require guiding the imaging telescope. But there are still advantages of using a guidescope for these short exposures. One good reason is *dithering* — the technique of moving the image around on the digital sensor by small, random amounts between each exposure. As such, when the exposures are aligned and stacked during processing, image artifacts due to the sensor are greatly suppressed or eliminated entirely. All the autoguiding software that I'm familiar with these days has routines for dithering exposures.

I did my autoguiding tests with an Orion StarShoot Mini 6.3mp Camera. This camera slips into the Evoguide's 1¼-inch focuser, and I ran tests with and without the Evoguide's field flattener and found no differences in the results. Aiming at dozens of random locations in the sky, there was never a time when I couldn't find a suitably bright guide star with exposures of a second or two. And the setup was consistently able to guide at the arcsecond level, which is on par with the performance I've achieved in the past using much larger guidescopes. I can't think of a reason why I'd ever want anything larger than the Evoguide going forward.

▲ The optional two-element Evoguide 50ED Field Flattener is really a must-have accessory for anyone planning to do astrophotography with a digital sensor that requires an imaging circle of more than about 10 millimeters. The flattener produces a 28-mm image circle with very good star images (large enough for sensors up to APS format). It also has male M42 threads and is bored to accept 1¼-inch accessories. It comes with a pair of metal, screw-on dustcaps.

As a Finder and Telescope

The Evoguide can also serve as a great finder, though it may be a challenge today finding a wide-field eyepiece fitted with a suitable reticle. Most commercial eyepieces that have reticles are intended for visual guiding and as such have a short focal length and a small field of view. A typical example is the illuminated 12.5-mm Celestron model I have. Fitted to the Evoguide, it yields 20× and a 1.9° field of view, which is rather small for a finder. Nevertheless, if you're good at eyeballing the center of the field, the Evoguide works nicely with just about any wide-field eyepiece.

▲ *Left:* The non-rotating drawtube on the helical focuser and matching 39-mm-long extension tube both have male M42 threads (also called T threads) and are bored to accept 1¼-inch eyepieces and accessories, which are firmly held in place with three thumbscrews. *Right:* Another nice feature of the Evoguide is the locking, soft-tipped thumbscrews that can hold the scope firmly in its mounting rings without marring the scope's painted tube.

▲ The small locking ring included with the Evoguide 50DX fits around 1¼-inch barrels to preset the focus point of equipment inserted into the focuser. It's shown here on a small guide camera that's not fully inserted into the field flattener for the sake of illustration.

I particularly liked the view with a Tele Vue 24-mm Panoptic eyepiece, which provided 10.5× and a 6.1° field — about the maximum possible with a 1¼-inch eyepiece fitted to the Evoguide.

Most of us won't look at the Evoguide and think "telescope," but looks are deceiving. When I first got into astronomy, there were several manufacturers selling high-quality 50-mm refractors, including such venerable companies as Unitron and Swift Instruments (with the latter's 50-mm model reportedly made in Japan by Takahashi). These scopes had the classic look of a long-focus refractor. But the reason was practical more than for aesthetics since their doublet crown-and-flint objectives required a relatively long focal ratio to achieve sufficient color correction. Furthermore, typical eyepieces back then did not perform well with fast focal ratios. Neither of these issues is a problem today. With eyepieces that gave matching magnifications, the Evoguide and my Swift 50-mm scope (yup, I own one) made for an interesting matchup. And if I had to pick a winner, the prize would go to the Evoguide, since its fully multi-coated objective provided slightly brighter and definitely more contrasty views. Bottom line: The Evoguide serves well as a very nice and reasonably capable 50-mm telescope.

Astrograph Mode

As mentioned earlier, the Evoguide by itself produces decent star images across an image circle only about 10 mm in diameter, corresponding to a 2¼° field of view. But adding the optional Evoguide 50ED Field Flattener increases the usable image circle to about 28 mm and a 6+° field. As the images on the facing page show, the flattener performs well with cameras with APS-format sensors. I did my testing with a ZWO ASI071MC Pro camera, which has a one-shot-color sensor measuring 23.6 by 15.6 mm.

While the Evoguide's performance with the field flattener falls a little short of systems built from the ground up as dedicated astrographs (see, for example, Alan Dyer's review of the William Optics RedCat 51LX APO astrograph in our March 2021 issue, page 66), it's considerably less expensive. And the Evoguide and flattener greatly out-performed images I shot with the same ZWO camera attached to a Zeiss-made Hasselblad 250-mm f/4 camera lens stopped to f/5.6. And for the price I paid for that lens in today's dollars, I could own several of the Evoguide astrograph setups.

The main caveat that goes with using the Evoguide's flattener is its rather short 17.5-mm back-focus requirement for optimum performance. Many of today's cameras, like the ZWO model I used, easily work with the flattener, but there's not enough back focus for any camera I know of that also has a filter wheel in the light path. But that's not the end of the story. Starizona (**starizona.com**) offers a special flattener called the EvoFF v2 ($99) that has 55 mm of back focus and will work with many camera/filter wheel combinations.

The Evoguide's helical focuser has a very fine thread pitch — it takes more than 18 turns of the focus ring to span its 18-mm range. This makes it very easy to achieve precise focus for imaging,

▼▶ The Evoguide is a highly versatile scope that, despite not being mentioned in the owner's manual, will work with DSLR cameras (left) as long as you're willing to accept good star images across only a 10-mm circle covering a 2¼° field at the center of the frame. Fitted with eyepieces (center), the Evoguide becomes a high-quality finder and small telescope. And, of course, it makes a great guidescope (right). It's shown here with the field flattener, but the author found no advantage to using it with the small sensors in typical guide cameras.

but there's more than a half turn of backlash in the focusing ring before the drawtube reverses direction. As such, I would always start with the camera outward of its focus point and approach focus by slowing turning the ring to pull the camera forward.

Despite the half turn of backlash sounding like a lot, I wasn't bothered by it when focusing cameras attached to the little telescope. It was a bit more of an issue when using the scope visually, but then, too, so is the very slow movement of the focuser when turning the ring — it's not like the quick back-and-forth motion most of us are used to with typical telescope focusers.

▲ These 30-second exposures of the region around M42, the Orion Nebula, made with a camera having an APS-format sensor show the marked difference in field coverage when using the Evoguide without (left) and with (right) its matching Evoguide 50ED Field Flattener. More details are in the accompanying text.

All in all, the Evoguide is a very capable guidescope, high-quality finder, small telescope, and wide-field astrograph. If any of these applications fill your needs, then my recommendation is "go for it."

■ Senior Contributing Editor **DENNIS DI CICCO** lives under the ever-increasing dome of light pollution in the western suburbs of the Boston/Cambridge metro area.

Try CTG Engineering

Cardboard, tape, and glue can do some amazing things.

◀ Drew Sorenson built the rocker box for his travel scope out of cardboard. For the azimuth adjustment he simply skidded the box around on the ground.

THOSE OF YOU WHO have been reading this column for the last few years have a pretty good idea of my design philosophy: It doesn't have to be pretty so long as it works. The question is, how far can you take that philosophy before it quite literally falls apart at the seams? Much, much farther than you might think. Over the years I've been repeatedly amazed at what people have built and called a telescope. Probably the most audacious one I've ever heard of was the watermelon scope presented at Stellafane in 1991. That's right: the OTA was a watermelon. And it worked . . . at least for a little while.

In our April issue I wrote about a travel scope that I'd built, based on an elegant design by Dutch ATM Roel Weijenberg (*S&T:* Oct. 2016, p. 72). That led to a discussion of travel scopes with Drew Sorenson, whose pipe-fitting pier mounts I featured in our May 2020 issue. Drew mentioned that he had once taken just the mirrors and hardware with him on a trip to Mexico and had built the entire telescope on site — out of cardboard boxes.

This I had to see! Fortunately, Drew had a photo (left).

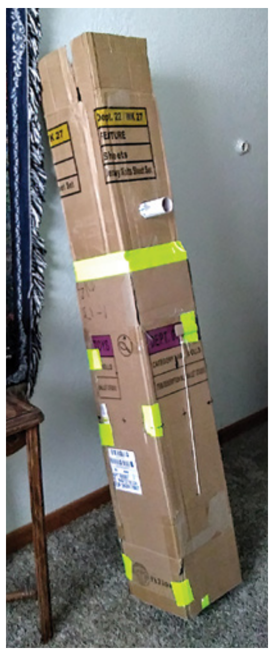
It's anything but elegant. Yet somehow it is elegant, in a primal sort of way. I don't even need to describe how he built it or how it works; you can see that just by looking at it. Drew reports that it showed the night sky quite well, and the view impressed his family and their neighbors as well as any factory-built scope would have. A line of people queued up to look through it every night.

That wasn't Drew's only travel scope. He built another one for a later trip to Texas to visit more family. This time he took only the mirrors and fabricated everything else out of cardboard, including a curved secondary mount. The box he was using for material was too small to make the entire OTA in one piece, so he spliced two pieces together in the middle. The focuser was a simple push-pull cardboard tube. Drew didn't bother to construct a rocker box for this one; he just propped the scope against a chair and scooted the bottom around for aim.

Both scopes functioned well enough to provide great views for the duration of his visits, and Drew had no worries about the OTA surviving the trip. He simply recycled the pieces when he was done with them.

Oregon ATM David Davis had a similar need one year at the Oregon Star Party. He had just finished a 16-inch f/3 ultra-thin (⅜-inch thick!) mirror he affectionately called "Fuzzy," and he needed an OTA to show what it could do. While looking around his shop for inspiration, his gaze fell on a sheet of pink insulation foam. Using a handheld power saw, he cut the foam into strips with angled edges, taped them together with blue gaffer's tape, and stuck them in a wooden flower planter. He nudged them into an acceptable circle, then filled the edge gaps with spray foam, which also stiffened up the OTA quite well.

He attached a focuser to a thin board, which he then bolted through the foam and did the same for a Telrad finder. The rocker



◀ Drew's 4-inch f/10 travel scope was just a cardboard OTA. He leaned it against a chair for aiming.

DREW SORENSON (2)

▲ The cardboard secondary mount had a nice, smooth curve to it when bent along the direction of the corrugations.

box and ground board were the work of a couple hours, and David had a telescope. It was the hit of the star party, garnering just as much admiration for the innovative telescope design as for the mirror David had built it to house.

The moral of these stories is obvious: It doesn't matter what the scope looks like so long as it works. If you want to make your scope out of Popsicle sticks and glue, there's no reason why you shouldn't. And if you're travelling with it, you can probably source most of what you need at your destination.

In short, all cats are gray in the dark, and any telescope that provides a decent view is doing everything it needs to do.

■ Contributing Editor **JERRY OLTION** has made a telescope out of a bean can.

◀ David Davis built this demonstrator for his ultra-thin mirror out of pink insulation foam.

CURVED CARDBOARD SPIDER: DREW SORENSON; PINK FOAM OTA: BARB BAJEC

▷ REFLECTIONS IN ORION

Gregg Ruppel

Dark dust clouds appear to twine their way through the colorful swaths of nebulosity known as M78 in Orion. The two stars embedded in the larger patch of bluish dust (below center) are the primary source of illumination within this enigmatic object.

DETAILS: *Astrosysteme Austria ASA10N Newtonian astrograph and SBIG STL 11000M camera. Total exposure: 16.8 hours through Astrodon LRGB Gen2 filters.*

▽ SILENT APPROACH

Sérgio Conceição

Brilliant Venus outshines the stars of Scorpius seen to the left of a windmill in Alentejo, Portugal, during the evening twilight of October 7, 2021.

DETAILS: *Canon EOS R6 camera and Canon RF 15-to-35-mm zoom lens. Total exposure: 1.3 seconds at f/4.5, ISO 2000.*

DEEP WITHIN THE HEART

Wanda Conde

Stellar winds from several hot, young stars within open cluster Melotte 15 (top right) carve intricate shapes into the dust at the center of the Heart Nebula, IC 1805, in Cassiopeia.

DETAILS: *Celestron EdgeHD 8-inch Schmidt-Cassegrain and ZWO ASI1600MM Pro camera. Total exposure: 14.6 hours through Astrodon narrowband filters.*

△ **A LITTLE ROSETTE**

Patrick Cosgrove

A single main-sequence star at the heart of Sharpless 2-170 in Cassiopeia powers the pinkish glow of this faint emission nebula.

DETAILS: *Astro-Physics 130-mm StarFire GTX Gran Turismo and ZWO ASI2600MM Pro camera. Total exposure: 7 hours through ZWO LRGB and Astronomik narrowband filters.*

△ **GALACTIC DUET**

Drew Evans

After a series of close encounters, M81 (left) and M82 (right) in Ursa Major have profoundly affected each other, resulting in vigorous star formation in the latter.

DETAILS: *Explore Scientific FCD100 Series 127-mm Triplet ED refractor with ZWO ASI2600MC and ASI2600MM Pro cameras. Total exposure: 29½ hours through LRGB and Hα filters.*

THE STRAIGHT WALL

Christian Viladrich

Rupes Recta (center) is a linear rille near the southeastern edge of Mare Nubium (left) that stretches more than 100 km (62 miles).

DETAILS: *Astrosib RC500 Ritchey-Chrétien telescope with ZWO ASI1600MM Pro camera. A stack of 900 frames recorded through a red filter.*

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A City Goes Dark

How I convinced a Dutch municipality to switch off all its lights.

NOT LONG AGO, in the desert of Dubai, I looked through a telescope and saw billion-year-old stars. So distant, so ancient; for some of them, we don't even know if they still exist. Such a sight humbles you.

A few weeks later, back in my home city, I realized we have this amazing performance always above us. But we don't see it because of light pollution. Then I had an idea: What if for one night we turn off all the lights in a city, so we can observe the stars together? This was the beginning of the idea for Seeing Stars (**https://is.gd/seeingstars**).

During the pandemic, we have often felt isolated in our own bubbles, disconnected from other people and not allowed to gather for festivities. Looking at the starry night sky together gives us a feeling of unity. It's a COVID-proof way of celebrating, and something we can do in our own backyards.

The idea remained in my head for a year, and I caught myself talking about it with friends and journalists. I became a voluntary captive of my own idea, and I needed to free it to free myself.

So one morning I called the director of the Dutch tourism board, Jos Vranken. "Jos," I said, "I have an idea. I need a mayor who is willing to switch off all lights in a city." A five-second silence ensued. "I'll call you tomorrow," Vranken said.

A few weeks later we traveled to the city of Franeker in the Netherlands' northwest and met with its mayor, Marga Waanders. To our surprise, she instantly said yes to my concept. Franeker has a rich astronomical history, including boasting the world's oldest working planetarium, built in 1781 by amateur astronomer Eise Eisinga in his own home. My idea reflected this heritage. Also, as Waanders realized,

▲The stars come out over Franeker after all nonessential lighting is turned off *(right)*. The Dutch city of Leiden plans a similar event as part of its Leiden European Year of Science 2022 festival.

the magic of a dark sky would create a sense of community and boost local tourism. "I am so proud to switch off all the lights in our city, to see the stars and feel connected with each other," Waanders declared at the opening.

Enjoying the stars from city streets may sound like a fairy tale, but Franeker achieved this during the month of June 2021. Before the event, we talked with citizens, entrepreneurs, and local government, discussing issues such as ensuring public safety; in its way, it was a true form of community art. Then, one night, as we stood in the cold and windy street, the lights went off, and we watched as parts of the Milky Way appeared over the city center.

Beholding the stars, whose light speeds toward us at 300,000 kilometers per second, does something to you as a human. After the event, people shared their experiences. For some, turning off all the lights had been discomfiting. Others had felt enlightened, and had mused about the future of space travel. Everyone, though, regardless of their reaction, had stared up for a time in awed silence.

To help spread my idea, I spoke with Kathleen Ferrier, Chairperson of the Netherlands Commission for UNESCO. She reacted enthusiastically, saying that "Everybody should have the right to see the stars." We agree, which is why we encourage cities worldwide to follow in our footsteps. Already we have seen interest from Leiden, Sydney, Venice, Stockholm, and Reykjavík.

Visionaries often talk about smart cities filled with sensors and AI. But for me a true smart city is about real connections — with each other, with the environment, and with oneself. Being able to observe the stars in one's own municipality is an intrinsic part of that future ideal city. Let's bring this primeval light back into our lives.

■ **DAAN ROOSEGAARDE** is a Dutch artist and innovator who, in 2007, founded the Rotterdam-based social-design lab Studio Roosegaarde (**studioroosegaarde.net**).