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THE ESSENTIAL GUIDE TO ASTRONOMY

February 2022 VOL. 143, NO. 2

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ROLF WAHL OLSEN

ON THE COVER

The beloved stars of the Pleiades are a great target right now.
PHOTO: MASIL IMAGING TEAM

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Investing in People

IN NOVEMBER, the National Academy of Sciences released its long-awaited Astro2020 Decadal Survey (**https://is.gd/decadalsurvey**). This once-a-decade report offers recommendations to NASA and other funding agencies for missions and other priorities in astronomy and astrophysics through the 2020s and beyond.

On top of the usual support of next-generation instruments and missions — and there are some beauties — the report also focuses intensively on improving diversity in professional astronomy. Racial and ethnic diversity in astronomy faculties at colleges and universities remains "abysmal," the study notes. Blacks and Hispanics comprise just 1% and 3% of astronomy faculty, respectively. Native Americans are also underrepresented, with fewer receiving bachelor's degrees in astronomy than for any other physical science.

Among many other points, the document urges funding agencies like NASA to factor in the diversity of project teams when evaluating funding awards to investigators, collaborations, and organizations that manage facilities.

Recent studies indicate that this would be a smart move. In a 2020 study, for instance, Stanford University researchers analyzing more than 1 million U.S. PhD recipients from 1977 to 2015 determined that underrepresented students, including women and non-white scholars, innovate at higher rates than majority students (**https://is.gd/stanfordparadox**).

▲ Derrick Pitts with George Takei (Star Trek's Sulu) at a Franklin Institute event

THE FRANKLIN INSTITUTE

"If those groups innovate more, how do we explain their lack of prominence and promotion in the scientific enterprise?" asks Stephon Alexander, a Black professor of astronomy at Brown University, in his book *Fear of a Black Universe* (see our review on page 39).

Increasing opportunities for participation in astronomy among *the general public* — particularly in underrepresented groups — is what drives Derrick Pitts (see our profile on page 26). Chief astronomer at Philadelphia's Franklin Institute and director of its Fels Planetarium, Pitts has devoted his career to astronomy outreach in the inner city. His new, NASA-funded Mission to Mars program will expand his successful outreach model to the national level.

As the U.S. celebrates Black History Month in February, we at *Sky & Telescope* support our colleagues at the AAS's Committee on the Status of Minorities in Astronomy in its mission "to enhance the participation of underrepresented minorities in astronomy at all levels of experience." That means from top professional teams and faculties right down to the person on the street.

Peter

Editor in Chief

SKY&TELESCOPE
The Essential Guide to Astronomy

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Another Mobile Scope Shelter

I enjoyed reading Jerry Oltion's article "A Mobile Scope Shelter" (*S&T:* Oct. 2021, p. 72). The image above is of mine, which protects a 24-inch (60-cm) Newtonian.

Through the years, I have had many observatories. My first one was a temporary snow observatory. It was featured in the January 1974 issue of *S&T* on page 29. It was followed by three permanent ones: 1976 to 1985, 1989 to 2013, and 2013 to today (it houses a Celestron C14 Schmidt-Cassegrain for photometry and a Celestron C11 Schmidt-Cassegrain for spectroscopy).

Last spring, maCommunauté, a local French-Canadian YouTube channel, invited me to show off both my observatory and mobile shelter in their video (**https://is.gd/Les_Etoiles**) and talk about astronomy.

Damien Lemay • Rimouski, Quebec

▲ Damien Lemay stands beside the shelter for his 24-inch (60-cm) Newtonian.

The Venusian Atmosphere

In "Venus: Inevitability or Catastrophe?" (*S&T:* Oct. 2021, p. 12), Paul Byrne states that the number of impact craters on Venus is about the same as on Earth. The article seems to imply that scientists expected this but were surprised that they all appeared to have formed around the same time. I found the number of impacts more surprising than their age.

With Venus's atmosphere being 90 times as dense as Earth's, I would expect a much smaller number of impactors for two reasons: A much larger percent of incoming objects should skip off the denser atmosphere, and a significantly larger number of objects would burn up (actually break up). What am I missing?

Bruce Barron
Peoria, Arizona

Paul Byrne replies: *There are no craters smaller than 3 km (1.86 miles) in diameter on Venus, and a dearth of those less than 25 km across, for precisely the reason you state. The atmosphere shields the surface from impactors that would otherwise make holes that size. But the real surprise for Venus was that there aren't any huge impact craters, i.e., those hundreds to thousands of kilometers across. Surely there once was, since we see similar impacts on Mercury, the Moon, and Mars. But something has removed that record on Venus, and we think that process is volcanic resurfacing. We also don't know enough about the craters Venus does have to say that they all formed around the same time. We can just say that there don't appear to be any terrains that are billions of years old.*

I enjoyed reading "Venus: Inevitability or Catastrophe?" in the October 2021 issue. One obvious difference between Earth and Venus is the length of their day. I just read a possibly relevant article in the August 6th, 2021, issue of *Science*, in which Elizabeth Pennisi describes a theory that says "Longer Days on Early Earth Set [the] Stage for Complex Life." Our planet used to rotate much faster, so the day was much shorter, but the Moon's gravity slowed Earth's rotation. According to that article, the level of oxygen in Earth's atmosphere rose with the length of the day.

Pennisi's article led me to wonder if the long day on Venus could have had an effect on the planet's temperature, since heat would build up on one side for much of the planet's year. While there would be a similar phase of cooling, such a long heating period could cause changes that may slow nighttime heat dissipation. Even a small asymmetry could result in runaway heating. Has anyone with a better grounding in planetary science than my own considered this?

Seth Steinberg
Port Angeles, Washington

Paul Byrne replies: *The short answer is, we don't know for how long Venus's day has been, well, very long. The planet might once have rotated faster, or it might also have been a slow rotator. There are climate models that suggest the development of a thick atmosphere helped slow the planet's spin rate from a much faster initial state. Figuring out the role of the atmosphere in the planet's climate and the extent to which a physically massive atmosphere could have caused, rather than could be the result of, a runaway greenhouse state is something we still don't have the answer to.*

Children and the Community

I just read "Fanning Sparks" (*S&T:* Sept. 2021, p. 84), in which Max Corneau laments the lack of connection between talented students and amateur astronomy clubs. I was a space-loving, STEM-oriented, child-of-Apollo-and-Star-Trek youth who went on to study aerospace engineering in the early 1980s, but I didn't know there was such a thing as astronomy clubs until about 1996!

I wonder if anyone has created any astronomy groups specifically for children and youth. Kids go where their friends are. While they might make friends with adults in an amateur astronomy club, they are more likely to attend a group with friends their own age that they already know. We could start with models that work, or have worked in the past, like scouting. Sky Scouts! Local amateurs could lead weekly or biweekly meetings with astronomy lessons and projects for various ages and levels. Kids could earn badges for different skills and advance ranks based on experience and projects completed. It would be a lot of work, but I can hardly imagine that someone somewhere isn't already doing this. If someone is, it's time to scale it up and export it!

David Douthett
Charles Town, West Virginia

I deeply empathize with Max Corneau's sentiments. For decades, I have devoted my professional life to providing opportunities for high-achieving students to study alongside professional scientists and engineers from all disciplines. As part of that work, each year around 25 students from Canberra, Australia, keen on astronomy complete projects through McNamara-Saunders Astronomical Teaching Telescopes (MSATT), a small teaching program and facility I built at Mount Stromlo Observatory (**msatt.teamapp.com**). Each student partners with a professional or advanced amateur astronomer or engineer for eight months to complete their project and produce a fully referenced report on their findings. Anyone interested in the model can contact me at **geoffrey.mcnamara@ed.act.edu.au**.

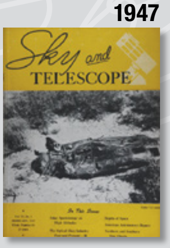
Geoff McNamara
Canberra, Australia

FOR THE RECORD

- In "Capturing Stellar 'Voids'" (*S&T:* Dec. 2021, p. 60), IC 434 was mistakenly listed as IC 404.
- The official name of the dark nebula between NGC 7000 and IC 5070 and IC 5067 is LDN 935 (*S&T:* Dec. 2021, p. 63).
- The bright star-like object identified in the image on page 29 of the September 2021 issue as the Southeastern Knot is the variable star UX Cygni.

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


◖ February 1947

Airborne Observatories "The aerial guns of the Army's B-29 bombers are being replaced by Geiger counters, cloud chambers, and other scientific equipment at the Naval Ordnance Test Station at Inyokern, Cal., thus converting the planes into airborne cosmic-ray laboratories. Under the direction of Dr. Carl D. Anderson, California Institute of Technology, discoverer of the positron, the planes will collect data from altitudes up to 40,000 feet, according to Science Service."

Planes and balloons had made single flights for astronomy before, but the idea of dedicated airborne observatories was taking hold.

◖ February 1972

Prehistoric Impact "About five degrees north of the Arctic Circle, near longitude 110° east in the Khatanga river basin, there is a round depression about 45 miles in diameter. The Popigay and other lesser rivers flow through the depression, which has usually been regarded as the result of a collapse some 100 million years ago . . . But Soviet scientists who explored this feature during the summer of 1970 believe it was formed by the impact of a large extraterrestrial object about 30 million years ago.

"If so, the Popigay depression is an astrobleme. This term, introduced by the American geologist R. S. Dietz in 1960 to signify an ancient meteorite-impact structure, is from Greek roots meaning 'star wound.'"

◖ February 1997

Lunar Water "On December 3rd a scientific press conference was held in an unlikely setting — a Pentagon briefing room — to announce something equally unlikely. At issue was the Clementine spacecraft's 1994 study of the Moon. 'We think we have found ice,' intoned Paul D. Spudis (Lunar and Planetary Institute). 'We are not positive, but we see signals consistent with ice and we think it's there.' . . .

"Clementine was designed for imaging and altimetry, not prospecting for water. But early in its [lunar run colleague Stewart] Nozette hatched another scheme. He proposed using the craft's transmitter to 'shine' radio waves into the perpetually darkened floors of craters at the Moon's poles. The reflected energy, if detected on Earth, might settle the debate over whether patches of ice lie hidden there. . . .

"'We lucked out immensely,' Nozette says. Not only did the echo prove stronger than expected, but the all-important polarization ratio also showed a modest peak precisely when the shadowed areas were within the radio beam."

Despite this optimism, Clementine hadn't proved the case for water on the Moon. That came in 2008, when the impact probe from India's Chandrayaan-1 orbiter detected water ice in the crater Shackleton. In 2020, scientists using NASA's airborne SOFIA telescope announced they'd found spectral features of water in sunlit areas.

FAST RADIO BURSTS

China's FAST Sees Thousands of Bursts from Single Spot

CHINA'S FIVE-HUNDRED-METER Aperture Spherical radio Telescope (FAST) caught more than a thousand radio flares coming from a cosmic source about 3 billion light-years away.

First detected in 2007, *fast radio bursts* (FRBs) last just a fraction of a second but carry tremendous amounts of energy. Most appear to be one-offs, but some are known to repeat.

The source featured in the October 14th *Nature*, designated FRB 121102, is a well-studied repeater. It cycles in activity, usually alternating 67-day silent periods with 90-day flurries of bursts. Between August and October 2019, FAST caught 1,652 bursts.

The researchers soon realized that the object's bursts came in two flavors: High-energy ones behaved like those from other repeating FRBs, but the low-energy bursts did not.

"It suggests there are probably two processes at play," says Pragya Chawla (University of Amsterdam), who was not involved in the study.

Observations of a Milky Way magnetar have shown that some FRBs originate around these exotic objects (*S&T:* Sept. 2020, p. 9) — but maybe not all of them do. Co-lead investigator Pei Wang (National Astronomical Observatories of the Chinese Academy of Sciences) argues that FRB 121102 provides evidence against some versions of the magnetar scenario. The bursts would require too much of the magnetar's energy, he explains.

▲ Highly magnetized neutron stars, known as magnetars, might produce FRBs within their magnetospheres.

But study coauthor Bing Zhang (University of Nevada, Las Vegas) says other versions of the magnetar scenario are still in play. While shock waves traveling outward from the magnetar are inefficient at producing FRBs, closer processes within the *magnetosphere*, where the magnetar's magnetic field dominates, are much more efficient. Zhang says that under the latter scenario, the total energy emitted "is absolutely fine."

The team hopes to observe bursts closer to home in the near future to get a better handle on FRB origins. "If we can detect, say, a thousand bursts from a nearby source, then we can learn more," Zhang says. He teases that they've already spotted something intriguing: "All I can say is, just please stay tuned, there should be more excitement."

■ BENJAMIN SKUSE

SOLAR SYSTEM

Plutonian Mounts Aren't Ice Volcanoes

TWO ICONIC caldera-like features, Wright Mons and its companion Piccard Mons, aren't what they seem, according to a careful study of data from the New Horizons mission.

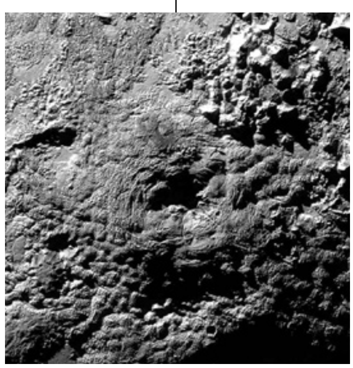
Both appear to have central pits, and mission scientists initially thought they might be cryovolcanic summits. But appearances can be deceiving. Wright and Piccard's holes might just be places not overrun by vast outpourings of icy goo from surrounding vents, Kelsi Singer (Southwest Research Institute) suggested at the annual Division for Planetary Sciences meeting.

Singer and colleagues used New Horizons data to take a closer look at the terrain around Wright. Despite broad swells and nubbly texture, the researchers found hardly any elevation changes. Even the floor of Wright's maw is about level with the surrounding surface. That suggests that what looks like a ring-shaped massif is instead part of a gradual, irregular pileup of cryolava that — for whatever reason — didn't fill in this part of the terrain.

Singer now thinks that icy lava oozed up from below through still-unidentified openings. The near-total absence of craters in the terrain suggests it might be only 1 billion years old. But that raises the question: What heat source would have melted Pluto's water ice? The dwarf planet should have cooled off long ago, and because it and its largest moon, Charon, always point the same face at each other, there's no tidal pull to knead the world's interior.

"There is still a lot to be figured out about how this kind of effusion onto the surface could work at all," Singer says.

■ CAMILLE M. CARLISLE



◀ The depression at the center of Wright Mons (ring-shape feature at center) is level with the surrounding icy surface.

MAGNETAR BURST: NASA'S GODDARD SPACE FLIGHT CENTER / S. WIESSINGER; WRIGHT MONS: NASA / JHUAPL / SWRI

MOON

Lunar Samples Confirm Late Volcanism on the Moon

ANALYSIS OF LUNAR MATERIAL, delivered to Earth from the lunar nearside by China's Chang'e 5 mission, confirms that the samples are the youngest collected to date. But their composition surprised scientists.

A team led by Xiaochao Che (Chinese Academy of Geological Sciences) analyzed the content in two 3–4 millimeter-size basalt fragments, determining that they are 1.96 billion years old — a billion years younger than material returned by the Apollo and Soviet-era Luna missions. The team published the results in the October 8th *Science*.

Collecting young lunar fragments was one of the main objectives for the Chang'e-5 mission, which sent a lander to the Moon in December 2020. The craft grabbed 1.7 kilograms (3.7 pounds) of lunar regolith from the vast volcanic plain of Oceanus Procellarum and flew back to Earth within the month. With the help of observations

▲ This is a rectified version of the landing site panorama taken by cameras aboard China's Chang'e 5 lander in Oceanus Procellarum.

from lunar orbit, scientists had determined this mare was relatively young; its paucity of craters suggested recent lava flows. The samples' ages confirm that volcanism occurred later there than in other areas of the Moon.

The samples' composition poses new questions, however. Scientists had suspected that an abundance of heat-producing elements in the lunar mantle underneath this mare might have kept the magma flowing longer. Some of these elements would have been radioactive (namely uranium, thorium, and potassium). Yet Che's team finds only usual amounts of these radioactive elements; the concentrations are similar to those in the basalts returned by Apollo and Luna missions.

Scientists also expected the rocks from this site to contain lots of heat-producing materials known as KREEP (short for potassium, rare Earth elements, and phosphorus). Instead, the team found only small amounts.

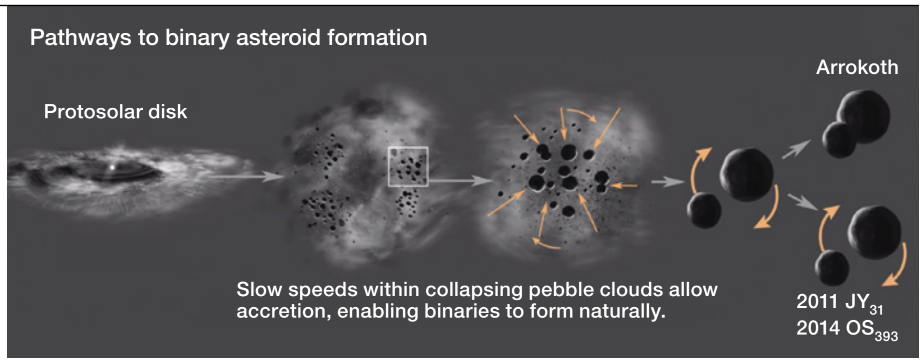
"The unexpected composition challenges our traditional thinking," says Long Xiao (China University of Geosciences), who was not involved in the study. If not heat-producing elements, though, what kept the material under Oceanus Procellarum hot?

Besides raising new questions, the radiometric dating also provides "ground truth" for comparison with crater counts, the method used to date other inner solar system surfaces.

■ ANDREW JONES

SOLAR SYSTEM

New Horizons Finds "Twins" in the Kuiper Belt



NASA'S NEW HORIZONS spacecraft has spotted two asteroid pairs in the outer solar system, reported Hal Weaver (Johns Hopkins University Applied Physics Laboratory) at the annual Division for Planetary Sciences meeting.

The probe's Long Range Reconnaissance Imager took pictures of 2011 JY_{31} and 2014 OS_{393} from a distance of 0.15 a.u. and 0.09 a.u., respectively.

The images of both targets appeared slightly elongated compared to a nearby star, so the team fit each shape with a two-body model. Even though the images couldn't resolve the individual objects, the models showed that two bodies better explained the observed elongation and brightness. For 2011 JY_{31}, the two objects orbit each other about 200 km (120 miles) apart, while for 2014 OS_{393}, the model indicates slightly smaller bodies 150 km apart.

The pairs were two of four "cold classical" Kuiper Belt targets, Weaver says. This family of objects hasn't changed much since it formed early on in solar system history. A third target wasn't a binary; a fourth remains undetermined.

New Horizons imaged one other object that's part of the "scattered disk" family, whose members have undergone an interaction that altered their original orbit. That one doesn't appear to be a binary, Weaver says.

The twin asteroids — like double-lobed Arrokoth, which New Horizons imaged in early 2019 — support a formation model in which gentle collisions among small "pebbles" make dense pebble-filled clouds, which then collapse into larger planetesimals.

Another flyby target isn't out of the question for New Horizons, but Kuiper Belt objects are few and far between. The probe's position in star-rich Sagittarius further complicates the hunt.

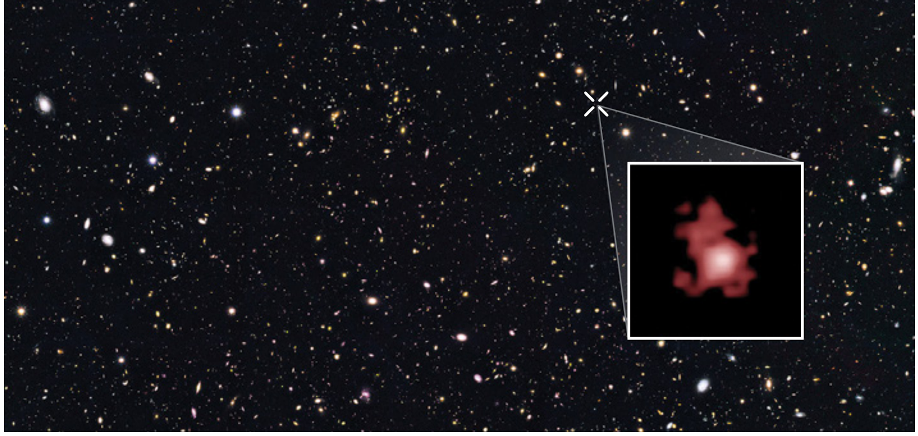
"It's a long-shot," Weaver says, "but this is humanity's only mission to the Kuiper Belt for the next couple decades, so we're trying to squeeze every last bit we can out of it."

■ DAVID DICKINSON

CHANG'E 5 LANDING: CNSA / CLEP / DON DAVIS; BINARY ASTEROID FORMATION: NASA / JHAPL / SWRI

SPACE & SOCIETY

Did Astronomers See a Distant, Dying Star, or an Earth-bound Satellite?



▲ This Hubble Space Telescope image shows the most distant galaxy known, GN-z11.

LAST YEAR, astronomers caught a surprising flash of light from the most distant galaxy known, GN-z11. The team proposed that they had seen the fading afterglow of a long *gamma-ray burst* (GRB), the violent destruction of, in this case, one of the universe's earliest stars (*S&T:* Apr. 2021, p. 8).

But now, other astronomers argue that the original team saw not a natural phenomenon but the chance passing of an artificial object in Earth orbit.

The flash occurred during one of more than 100 spectroscopic images that Linhua Jiang (Peking University, China) and colleagues took of GN-z11. Jiang's team checked whether some nearby object could have photobombed their observations. Only when they came up blank did they propose a GRB.

Oddly, the spectrum wasn't quite what one would expect for a GRB. Curiouser still were the odds: Based on the galaxy's star formation rate, it ought to host between 1 and 200 GRBs every million years. The chance of Jiang's team actually catching one of them during one of their exposures was at most 1 in 100 million.

Charles Steinhardt (Cosmic Dawn Center, Denmark) and colleagues proposed that the flash might have been an artificial satellite. Then, just a month later, Michał Michałowski (Adam Mickiewicz University, Poland) and his team announced that they had found the likely offender: the Breeze-M upper stage of a Russian Proton rocket. Both studies appeared October 4th in *Nature Astronomy's Matters Arising*.

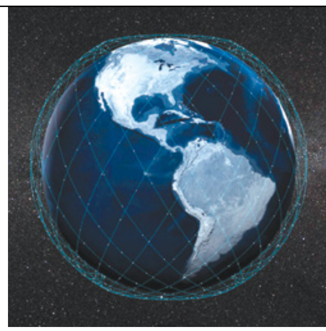
Jiang's team was actually aware of the Russian booster. They had used **Calsky.com**, a website popular with amateur astronomers, to calculate its trajectory and found that it passed outside the telescope's field of view. But that website has since shut down, and it remains unclear why their trajectory calculation differed from Michałowski's by several arcminutes. While Jiang and colleagues maintain the validity of their results, they also clarify that they made no conclusive claims. "We just reported this event and provided our most probable interpretation," Jiang says.

This isn't the first time satellites have posed as astronomical phenomena (*S&T:* June 1987, p. 604), and it won't be the last. Technological advances have enabled astronomers to watch supernovae unfold and tally near-Earth asteroids, but they'll have to tease out the real sources from artificial interference, a process that becomes especially difficult in the cases of transient events and spectroscopy — both exemplified by the GN-z11 flash.

■ MONICA YOUNG

SPACE & SOCIETY

Streetlights to Satellites: Taking Light Pollution to the United Nations



◀ Starlink satellites orbit the globe in this artist's concept.

RURAL REGIONS HAVE remained a bulwark for dark skies in a time when most of the world's population can't see the Milky Way. However, as the number of satellites in low-Earth orbit grows, moving lights will become visible from even the most remote areas.

To tackle light pollution from both ground and space, astronomers, dark-sky advocates, and satellite reps joined members of the United Nations Office for Outer Space Affairs for the second "Dark and Quiet Skies for Science and Society" conference in October.

The workshop report, forthcoming as of press time, will go to the Scientific and Technical Subcommittee of the Committee on the Peaceful Uses of Outer Space (COPUOS). If approved as a resolution, it will then go to the member states of COPUOS and perhaps even to the General Assembly.

Many presenters urged COPUOS to protect the night sky. Lawyer Charles Mudd even advocated that Earth's orbital space be considered an integral part of our planet's environment — and be regulated as such.

But while successful dark-sky efforts in Europe have been grounded in environmental protection, that approach may be less likely to work in the United States, suggests organizing committee member Richard Green (University of Arizona).

"If [satellite companies] have to create an environmental impact study, it's a big deal," Green says. "It takes years, and it's very expensive." Instead, there are other, albeit narrower approaches American policymakers might take.

For their part, industry representatives of SpaceX, Amazon, and OneWeb have been pushing for corporate responsibility (rather than regulation). But, Green notes, "it would be good to have regulatory incentives to make sure they stick to that good intention."

■ MONICA YOUNG

GN-Z11: NASA / ESA / P. OESCH (YALE UNIVERSITY); SATELLITES IN ORBIT: STARLINK

SPACE & SOCIETY

Pittsburgh Goes Dark; Could It Start a Trend?

CAN YOU SEE the Milky Way from your home? Diane Turnshek can, and she wants Pittsburgh to see it, too.

Turnshek (Carnegie Mellon University) helped draft the Pittsburgh City Council's new Dark Sky Ordinance, which covers the city's parks, facilities, and streetlights. The new ordinance would replace 35,000 old high-pressure sodium streetlights within the next three years. All of them will be dark-sky-friendly, with cut-off fixtures that direct light where it needs to go.

Crucially, the ordinance also replaces 4,297 newer LED streetlights, the bright, blue-white kind that were hastily installed in cities across the world in the 2010s. Turning night into day, these high-temperature LEDs are now a leading cause of the world's growing light pollution. Pittsburgh will replace these with lower-temperature LEDs, which have become cost competitive.

The new plans also include placing between 3,000 and 15,000 new LED streetlights, which the city found necessary during the analysis. These will also be dark sky–friendly: motion-sensored, shielded, and with both a lower wattage and cooler temperature.

Part of the preparatory work included making a nighttime map of Pittsburgh's 58 square miles. Turnshek and colleagues undertook this effort using drones and a Sony DSLR camera under a Cessna aircraft on clear, snowless, dry, and moonless winter nights. Astronauts on the International Space Station also took photos.

Pittsburgh's ordinance isn't specifically related to the needs of astronomers. Rather, its stated aims are to improve safety and security, reduce light pollution, save energy, and advance equity in all Pittsburgh neighborhoods.

"The new Pittsburgh ordinance is not quite as restrictive as Flagstaff or even Tucson," says John Barentine (now at Dark Sky Consulting), naming two cities where the needs of professional astronomical observatories *are* taken into account. "But for major U.S. cities, especially those on the East Coast, it is quite a bit better than others that are out there — I think this is the future of outdoor lighting policy in the U.S."

■ JAMIE CARTER

▲ The Phipps Conservatory and Botanical Garden, photographed from above via drone, is one of the organizations that has signed on to Pittsburgh's dark-sky ordinance.

MICHAEL LINCOLN AND DIANE TURNSHEK

IN BRIEF

Jupiter Whacked Again

Get your scorecards out — Jupiter took another interplanetary hit on October 15th, the 11th observed in modern times. A month after amateurs recorded a different flash (*S&T:* Jan. 2022, p. 10), a team led by Ko Arimatsu of Kyoto University captured this most recent flare at infrared and visible wavelengths. Another Japanese observer, who goes by the Twitter handle yotsuyubi21, and Victor PS Ang of Singapore confirmed the impact. Arimatsu and his group used a surveillance system, part of the Organized Autotelescopes for Serendipitous Event Survey (OASES), to record the burst, which lasted about four seconds. According to the Europlanet Society, every year an average of 6½ objects hit Jupiter in impacts big enough for amateurs to record. Aided by transient-alert software like DeTeCt (*S&T:* Jan. 2022, p. 52), we've seen a steady uptick in the number of observed impacts, proving that the more we look, the more we see. Neither of the two recent impacts made dark scars on Jupiter's cloudtops.

■ BOB KING

See images and video at https://is.gd/Jupiterimpact11.

Lucy Launches to the Trojans

NASA's Lucy mission launched on October 16th to explore Jupiter's Trojan asteroids (see page 12), which serve as pristine examples of the early solar system. The launch was flawless and the solar panels deployed as expected and are generating power, but one of the panels did not latch correctly. Nevertheless, the mission is continuing to a heliocentric orbit. After an Earth flyby in late 2024, Lucy will visit one main-belt asteroid (52246 Donaldjohanson) in 2025 and seven Trojan bodies between 2027 and 2033 (with an additional Earth flyby in 2031). The Trojans have likely been trapped in their current orbits for billions of years, so they are representative of material left over from the formation of the solar system. Lucy will investigate the geology and composition of the rocks to shed light on planet formation processes. The Lucy team is looking for motivated observers to follow occasions when target asteroids occult background stars. Such observations can help improve estimates of their shapes and orbits. Unistellar also has ongoing asteroid occultation campaigns.

■ DAVID DICKINSON

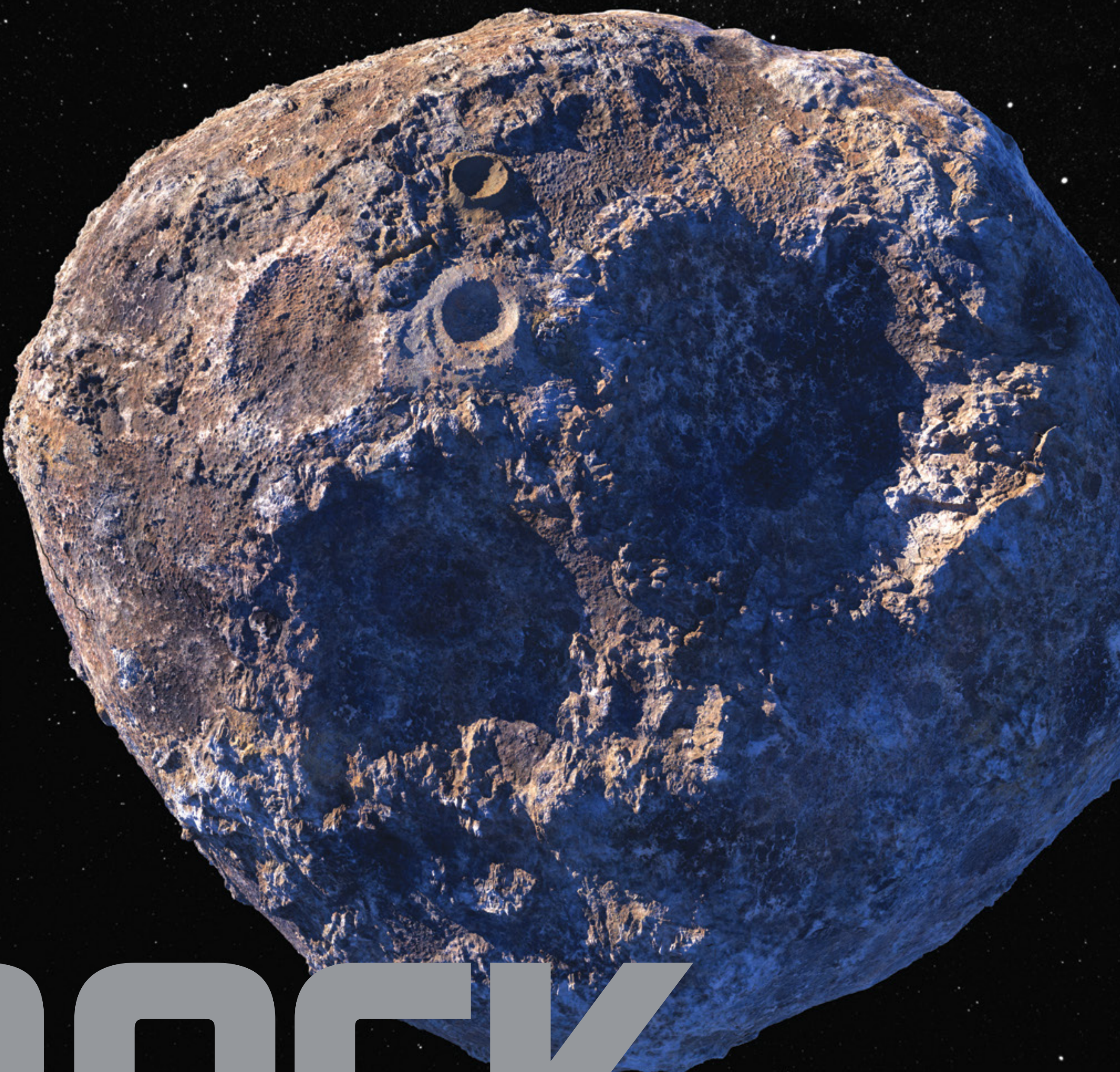
See upcoming events at https://is.gd/Lucyocc and http://is.gd/Unistellarocc.

Two Hits Made the Moon

Scientists have long thought that the Moon formed when a Mars-size protoplanet (dubbed "Theia") hit newborn Earth. Now a study in the October *Planetary Science Journal* suggests that the protoplanet hit Earth not once but twice. The first time, Theia only glanced off Earth. Then, some hundreds of thousands of years later, it came back to deliver the final, Moon-generating blow. Erik Asphaug (University of Arizona) and colleagues simulated the impact 1,000 times and found that a "hit-and-run return" scenario could help answer two longstanding questions around the Moon's origin. First, Theia had to come in at the right speed: too fast and it would have exploded, too slow and the Moon's orbit would look different. The one-two punch puts Theia's speed between these extremes. The first, glancing impact would have slowed it down for the second one. The hit-and-run-return scenario also addresses unexpected similarities between the Moon's and Earth's compositions, because two impacts would have enabled more mixing. While the simulations don't quite match the observed compositions, the team argues that more advanced models would yield even better results.

■ ASA STAHL

 by Emily Lakdawalla



ROCK ON

Planetary scientists are sending robotic emissaries to unmask the secrets of asteroids throughout the solar system.

Countless tiny worlds travel among the stately orbits of the solar system's planets. These worlds populate the asteroid belt, congregate in clumps along planets' orbits, and make excursions to just about every region, with occasionally striking results. Some formed where we find them now; others migrated from elsewhere. And although they might look like boring planetary debris, they are our best connections to the earliest history of the solar system.

Since 1990, a dozen missions have visited asteroids, comets, and Kuiper Belt worlds. In combination with observations from optical and radio astronomy, data from these missions have helped us understand both how the planets formed and how the giants herded the non-planets into their present-day locations (*S&T:* Mar. 2021, p. 22).

But the scientific theories we've devised based on these discoveries are only useful insofar as their predictions stand up to more observations. Two new missions will soon test the theories that grew from the last three decades of work, by exploring parts of the solar system we haven't visited yet: The Lucy mission will complete a flyby tour of at least seven asteroids caught along two parts of Jupiter's orbit, while Psyche will head to its eponymous asteroid, 16 Psyche, located in the main belt between Mars and Jupiter.

Both spacecraft are from NASA's Discovery program, each developed and launched quickly with a relatively small budget of "only" $450 million. Both feature enormous solar panels, some of the biggest ever sent beyond Earth. And both face several-year cruises and planet flybys before they reach their science targets. Together, Lucy and Psyche will test whether existing theories of planet formation and migration can explain their target asteroids' unique properties and current locations.

The Story So Far

In The Beginning, all was gas and dust. Then, gas began to condense onto dust grains, which helped the grains stick together upon collision. At the center of the swarm, the proto-Sun ignited and blasted out intense radiation, transmuting stable atoms into the radioactive isotope aluminum-26. This isotope was then trapped in condensing grains rich in calcium and aluminum. Scientists have analyzed such ceramic-like grains carried to Earth in meteorites and determined that these solar-system-forming events took place 4.568 billion years ago.

◀ **16 PSYCHE** This artist's illustration shows one option for how Psyche might look. Scientists think the asteroid is a blend of rock and metal, which might be mixed together (as shown here) or in discrete sections.

PETER RUBIN / NASA / JPL-CALTECH / ASU

The solar nebula's gas dragged on the tiny dust particles as they orbited the prenatal Sun, moving them into crossing paths. The resulting collisions were slow, the particles nudging together gently enough that they didn't fly apart. Planetesimals grew from such gentle processes of pebble-collecting very quickly, doubling in size every thousand or so years. Arrokoth, the tiny Kuiper Belt world visited by New Horizons in 2019, bears signs of this construction process (*S&T:* Feb. 2020, p. 34).

Close to the young Sun, the planetesimals were mostly rock. Farther away, where colder temperatures prevailed, both rock and ice could condense, and planetesimals grew larger, faster. Within half a million years, uncountable tiny particles had merged into fewer, but still numerous, worlds hundreds to thousands of kilometers in diameter. They were loose piles of dust, gravel, fluffy ice, and empty space; their self-gravity could hold the particles together but couldn't pack them tightly.

Meanwhile, the radioactive Al-26 was rapidly decaying into magnesium-26, generating heat. Bigger worlds trapped that heat, warming up. In some of them, ices turned to liquids or gas. Gases escaped but liquids flowed, collapsing or filling pore spaces. The liquids chemically reacted with rocks, making new minerals and sometimes even creating short-lived underground oceans of salty liquid. Where worlds became sufficiently hot, the rock began to melt, and still-solid metal grains fell down toward their centers. This process, called *differentiation*, produced onion-layered worlds with metal cores enclosed in mantles of rock (and, if far enough from the Sun, ice), with or without a top layer of never-melted, cold material.

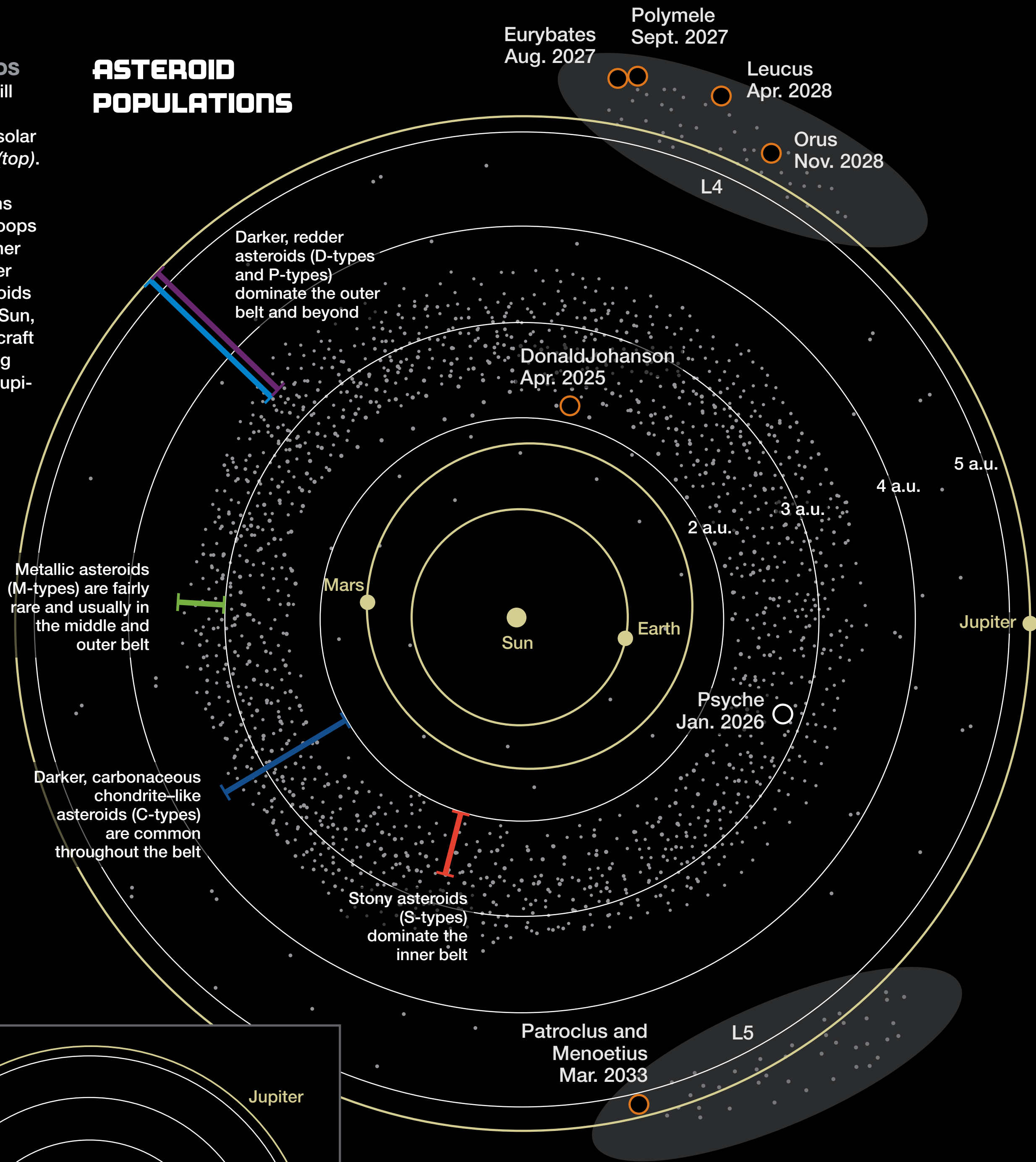
The Al-26 heat wave ended early in solar system history, except inside the largest worlds. Nowadays, nearly every small body in the solar system is too cold to retain interior liquids, but they preserve their layered structure.

Al-26 wasn't the only thing to dramatically change these small worlds. When the giant planets grew big enough, their orbits began to shift, sending the giants plowing through the planetesimals around them and scattering the small worlds across the solar system to where we find them today. The details and timing of this re-sorting should be imprinted in the worlds' characteristics — which we've only seen from afar.

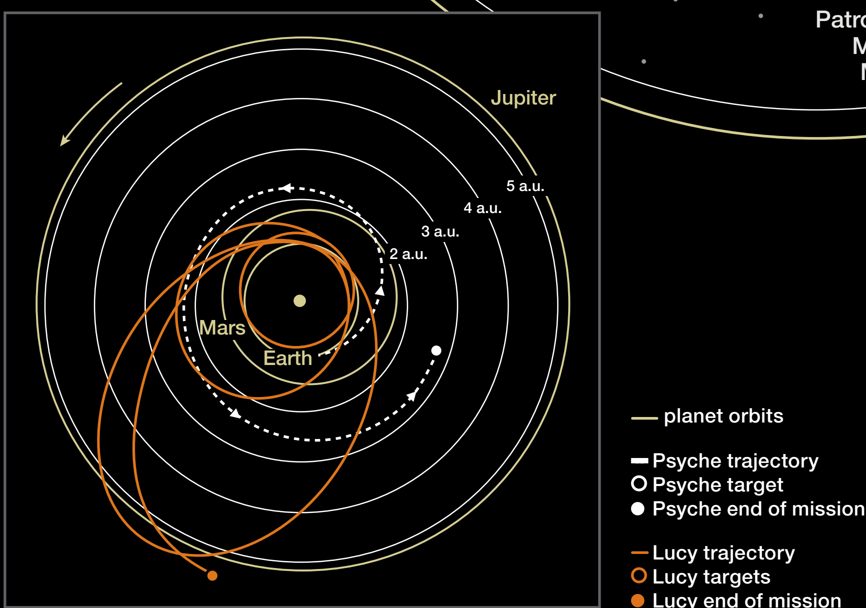
(continued on page 16)

TO THE ASTEROIDS Psyche and Lucy will investigate several targets among the solar system's asteroids *(top)*. To get there, they'll take circuitous paths *(bottom)*. As Lucy loops in and out of the inner solar system, Jupiter and its Trojan asteroids revolve around the Sun, enabling the spacecraft to visit objects along different points of Jupiter's orbit.

ASTEROID POPULATIONS

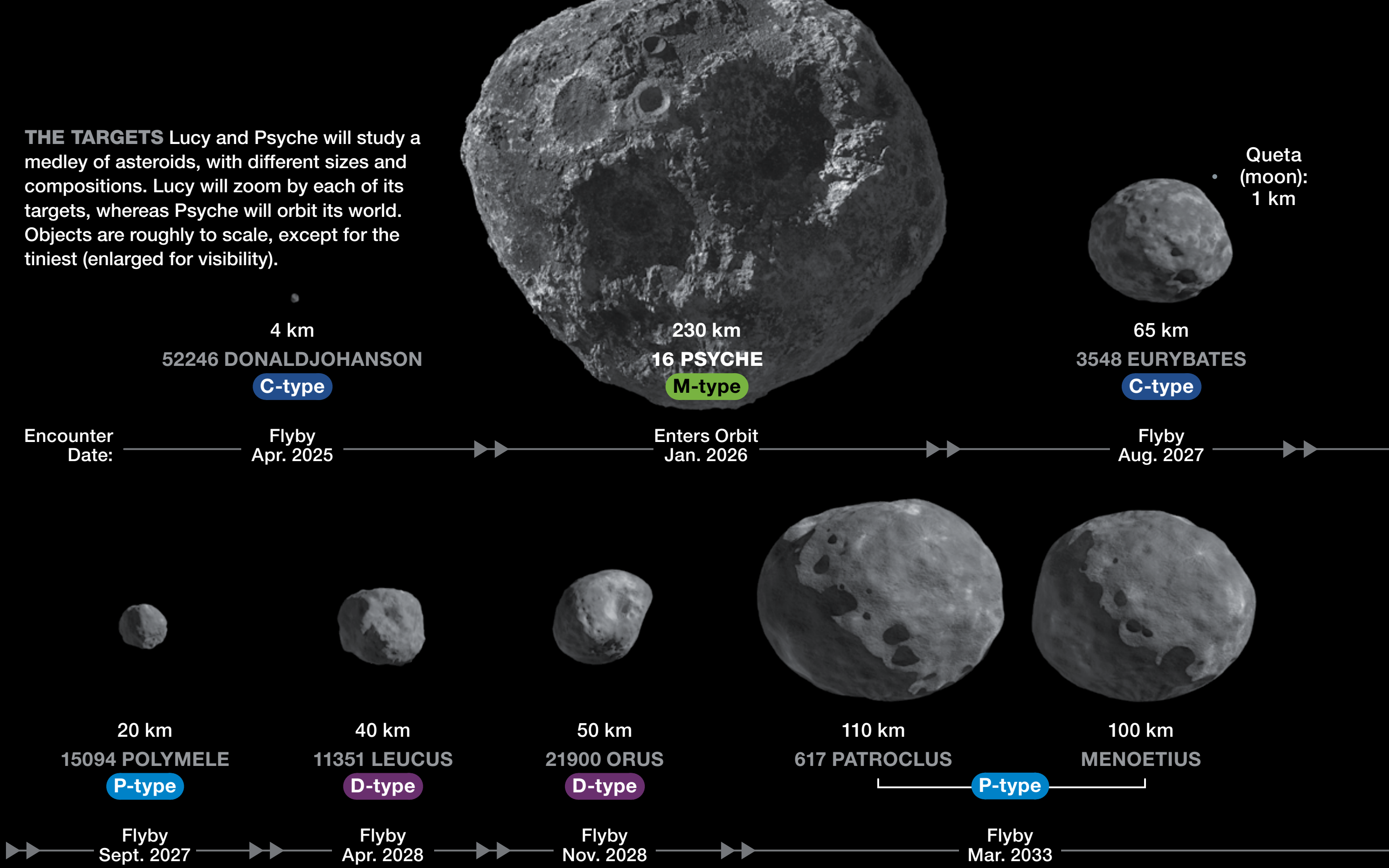


LUCY AND PSYCHE

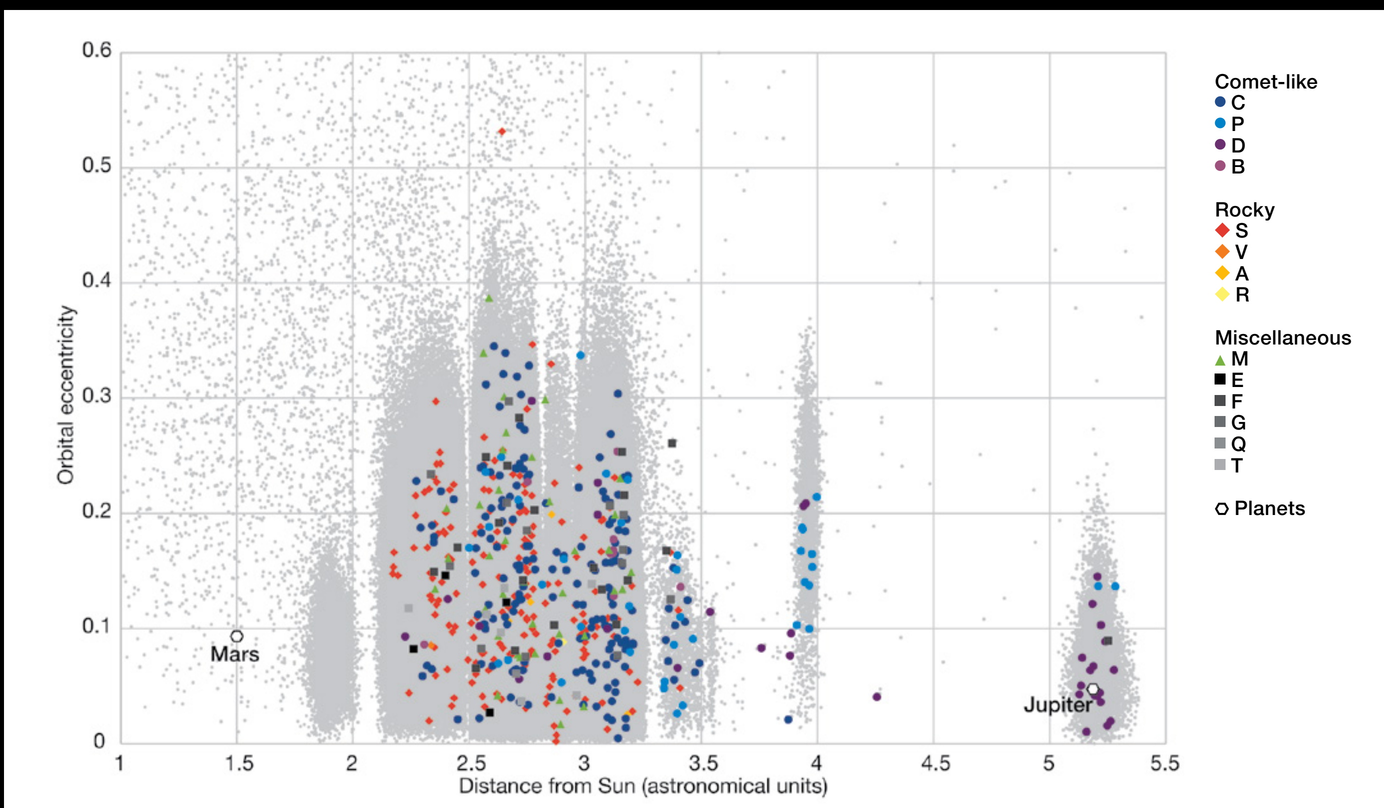


SPACECRAFT HAVE SO FAR VISITED 14 ASTEROID SYSTEMS (ONE HAS A MOON). THE PSYCHE AND LUCY MISSIONS WILL ADD ANOTHER SEVEN SYSTEMS, INCLUDING ONE ASTEROID WITH A MOON AND ONE BINARY ASTEROID.

TERRI DUBÉ / S&T



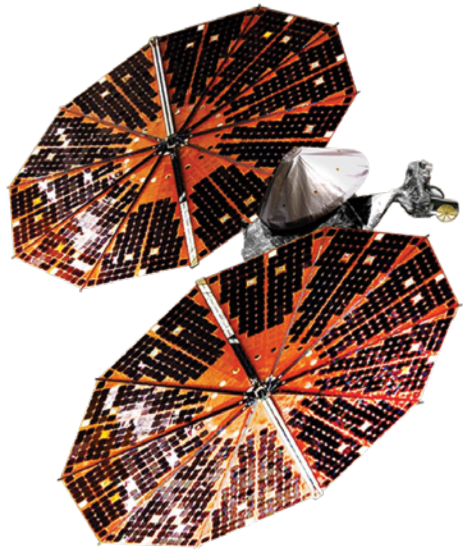
THE TARGETS Lucy and Psyche will study a medley of asteroids, with different sizes and compositions. Lucy will zoom by each of its targets, whereas Psyche will orbit its world. Objects are roughly to scale, except for the tiniest (enlarged for visibility).



ASTEROIDS GALORE Asteroids (dots) form distinct orbital clumps, controlled in large part by Jupiter. Rocky bodies are more common closer to the Sun, whereas dark red, comet-like surfaces dominate the outer regions. Carbonaceous asteroids occur throughout the belt.

LUCY TARGETS: NASA GSFC; PSYCHE: PETER RUBIN / NASA / JPL-CALTECH / ASU

(continued from page 13)



◀ **LUCY SPACECRAFT** Lucy stretches more than 14 meters (46 feet) from tip to tip, thanks to its 7-meter-wide, decagonal solar panels.

Small World Diversity

These beginnings created an assortment of small bodies, and there are patterns in their differences. Using spectroscopy, astronomers have identified numerous distinct classes and matched many with meteorites found on Earth. There are some compositional trends that make sense: Asteroids are rockier and more metal-rich closer to the Sun, while extremely dark, comet-like surfaces are more common farther out.

But atop the general trends are weird outliers. One oddball group, the 40 or so *M-type asteroids* in the main belt, appear dark in optical telescopes but bright to radar and may be rich in metals. Psyche is the largest such world.

There are also groupings among orbital properties. Just as the rings of Saturn have open lanes and denser parts, so too does the asteroid belt, for similar reasons. At Saturn, moons shepherd ring particles; in the asteroid belt, distant large worlds (primarily Jupiter) herd small bodies into denser belts and groupings through the rhythmic gravitational shoving of orbital resonances. There are also families of asteroids traveling similar orbital paths that are likely the fragments of a single primordial world that was shattered in a collision millions of years ago. The asteroids 162173 Ryugu and 101955 Bennu, recently visited by spacecraft, might be members of the same asteroid family, for example (*S&T:* May 2020, p. 14).

Between the main and Kuiper belts, a surprising number of small worlds travel around the Sun on orbits that have roughly the same period (11.9 Earth years) and average solar distance (5.2 astronomical units) that Jupiter does. They always lead or trail Jupiter on their orbital paths, clustering at two points on the giant's orbit located 60° ahead and 60° behind the planet, at the *Lagrangian points* L_4 and L_5. Here, the Jovian and solar gravitational fields balance the centripetal force of an object moving with them. These are the Trojan asteroids (*S&T:* June 2016, p. 16), named for characters in the ancient Greek epic *The Iliad*. Scientists know of a few Trojan asteroids for Neptune, Earth, and Mars, too, but no planet has as many as Jupiter does.

Jupiter's Trojan asteroids come in three spectral types (P, D, and C), all of which are also common in the asteroid belt. C-types exist throughout the belt; the very dark, red-colored P- and D-types make up larger proportions of the belt farther from the Sun. It seems straightforward to assume that P-, D-, and C-types all formed within the belt.

However, P- and D-type asteroids bear striking similarities to another population of very dark, reddish worlds: comet nuclei. Furthermore, one main-belt asteroid, Ceres, has a shocking amount of ice in it, which is difficult to explain unless it originally formed much farther out, possibly as far out as the primordial Kuiper Belt. Therefore, it's possible that the Trojan asteroids are more ice-rich and comet-like than a typical asteroid from the inner main belt.

Other evidence also points to a distant origin for one Trojan system. Equal-mass binaries are rare among asteroids but common in the Kuiper Belt. Theoretical work suggests it's not impossible for such a binary pair to remain partnered during an inward journey from the Kuiper Belt to a Trojan orbit. The Nice model of planetary migration predicts that about 10 such pairs might have been flung into Jupiter's domain, of which about one is likely to survive still paired. In fact, we've found exactly one: the L_5 binary pair 617 Patroclus-Menoetius.

So did Trojans form inside Jupiter's orbit and travel outward, or are they primordial Kuiper Belt objects like Arrokoth? That's what Lucy will find out.

Lucy to the Trojans

Lucy launched on October 16th to survey Jupiter's Trojan population, visiting at least seven Trojans in five different systems. Following two Earth flybys and one practice run at a main-belt asteroid in 2025, Lucy will make close passes by four Trojan systems in the leading (L_4) cloud in 2027 and 2028. One more Earth flyby will toss Lucy to a fifth encounter, with Patroclus-Menoetius in the L_5 cloud, in 2033.

The L_4 targets were selected for navigational reasons, by optimizing Lucy's orbital path to meet as many worlds as possible. The luck of the draw yielded a nicely representative sample that includes all spectral types, a range of sizes, the

▲ **CATCHIN' SOME RAYS** Engineers check one of Lucy's solar arrays, which will power the spacecraft as it flies out to Jupiter's orbit. After launch, one array did not fully deploy; as of press time engineers were still assessing the problem but did not expect any effect on the mission.

LUCY SPACECRAFT ILLO: SWRI; LAB PHOTO: LOCKHEED MARTIN largest member of the only known collisional family (Eurybates), and one ultra-slow rotator (Leucus).

The Lucy mission plan looks a lot like a string of New Horizons flybys. Because the flybys are so fast and the bodies so small, Lucy won't completely map each world, but it will obtain enough information to address questions of mass, shape, volume, density, surface composition, interior structure, and impact-cratering history. Its instruments draw on heritage from both New Horizons and OSIRIS-REX and comprise multiple cameras as well as a thermal infrared spectrometer.

Science observations will begin a year before each flyby, as the Lucy Long-Range Reconnaissance Imager (L'LORRI) studies how each asteroid's brightness changes with time from angles not achievable from Earth. The viewing angle also will place each body against a totally different field of stars than observers will be seeing from Earth, which will improve the precision of orbit predictions and therefore improve the precision of Lucy's navigation. As the spacecraft approaches, it will also use L'LORRI to search for satellites. We already know that one of the Lucy targets, Eurybates, has a moon, and there could be others.

All of the optical instruments will map as much of the surface of each world as they can see throughout the flyby. The instruments are clustered together on a movable pointing platform so that Lucy can keep its huge, decagonal solar panel arrays pointed at the Sun throughout most of each encounter. For targets that spin relatively quickly, Lucy will be able to map the full globe (or full potato, considering that they are not round). But some — especially Leucus, with its 445-hour day — will only show one sunlit hemisphere to Lucy when the spacecraft is close enough to map its landforms.

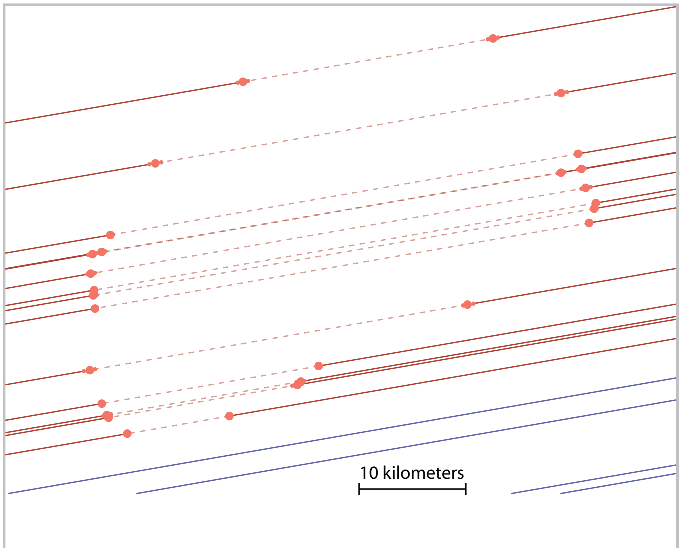
After Lucy, we will have visited enough of these (icy?) worlds for astronomers to responsibly infer what virtually all the Trojans are like, as well as the many asteroids of the outer part of the main belt that share the Trojans' qualities. That, in turn, will hopefully tell researchers where the objects came from and suggest how they arrived at their current locations.

Psyche: A Metal Asteroid?

Psyche is the largest of the M-type asteroids, measuring 290 by 245 by 170 kilometers across (about 180 by 150 by 105 miles). When the Psyche mission was first proposed to NASA, astronomers thought the asteroid could be more than 80% metal. Since then, observers have measured Psyche's mass and dimensions better, which has resulted, paradoxically, in less certainty about what it's made of.

Mass and volume estimates yield an approximate density, and Psyche's density is probably (but not certainly) just a little higher than that of the very densest rocky components of meteorites. Depending on what kinds of rock and metal make up Psyche and on how porous it is, the asteroid may be much less metallic than expected, about 30% to 60%.

No matter the answer to the composition puzzle, it's hard to explain how worlds as dense as Psyche formed. We know for sure that there is metal-rich material among the asteroids, because approximately 5% of all meteorite falls are made of a mix of iron and nickel. Scientists are relatively confident in their understanding of how these meteorites formed: If you begin with a differentiated world and shatter it in a collision with another asteroid, then some fragments will come from the core and be mostly or all metal. The problem with explaining Psyche's formation by the same mechanism is how to reassemble a big enough pile of core fragments to build an asteroid 200 km across without also incorporating lots of rock fragments. Perhaps lots of hit-and-run impacts spalled off chunks of mantle, leaving an intact core behind? It's a



MARC W. BUIE ET AL.

▲ **11351 LEUCUS** Based on more than a dozen teams' observations (chords), this plot is a projection of the shadow the Trojan Leucus created when passing in front of an 11th-magnitude star in late 2019. The dots mark sites that saw the star wink out; blue lines are observers who saw no occultation, clarifying the asteroid's extent. Combined with other occultations, these results indicate that Leucus has an oblong, irregular shape.

GET INVOLVED

Teams of amateur astronomers are already contributing to the Lucy mission. Volunteers are assisting mission astronomers by providing careful observations of how long stars wink out (or don't) as Trojans pass in front of them as seen from various locations. The stellar occultations have already yielded improved orbit ephemerides and size and shape estimates for Lucy's targets — for instance, thanks to amateurs, we now know that slow rotator Leucus is surprisingly elongated and likely heavily cratered, while Patroclus' binary partner Menoetius seems to have a huge impact crater that has gouged a void out of its south pole. Such information makes flyby planning simpler and more efficient.

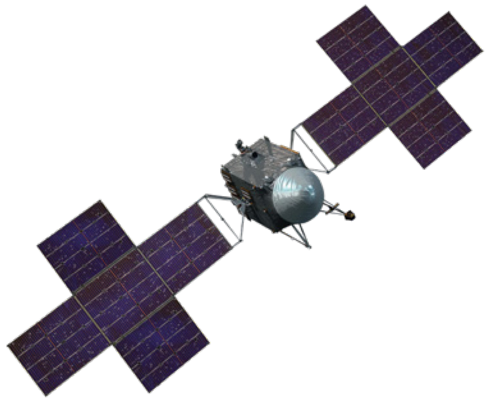
The Lucy team welcomes observers from around the world. Read more at **https://is.gd/lucyoccultation**.

possible but unlikely scenario.

Looking at meteorites for clues, there are two types that match Psyche's probable density: pallasites and CB chondrites. Both of these are mixtures of metal and rock: pallasites have blebs of green olivine and dark pyroxene embedded within metal, and CB chondrites have metal blobs surrounded by a matrix of chondritic rock. Maybe Psyche is the remnant of an ancient collision that created an intimate mixture of rock and metal? Or maybe Psyche has a layer of rubbly (and therefore porous) pallasite-like material over a more metal-rich core?

Or maybe Psyche simply accreted from unusually metal-rich material, like the innermost planet, Mercury. If Psyche formed in the same conditions, not only has it moved dramatically outward from the Sun since it first formed, but it also may represent a fossil record of material from the innermost solar system.

We just don't know what Psyche is. It's virtually guaranteed that Psyche's actual history will surprise us and challenge our freshly minted models of solar-system formation.



◀ **PSYCHE THE SPACECRAFT** Tip to solar-paneled tip, Psyche spans nearly 25 meters, a little longer than a tennis court.

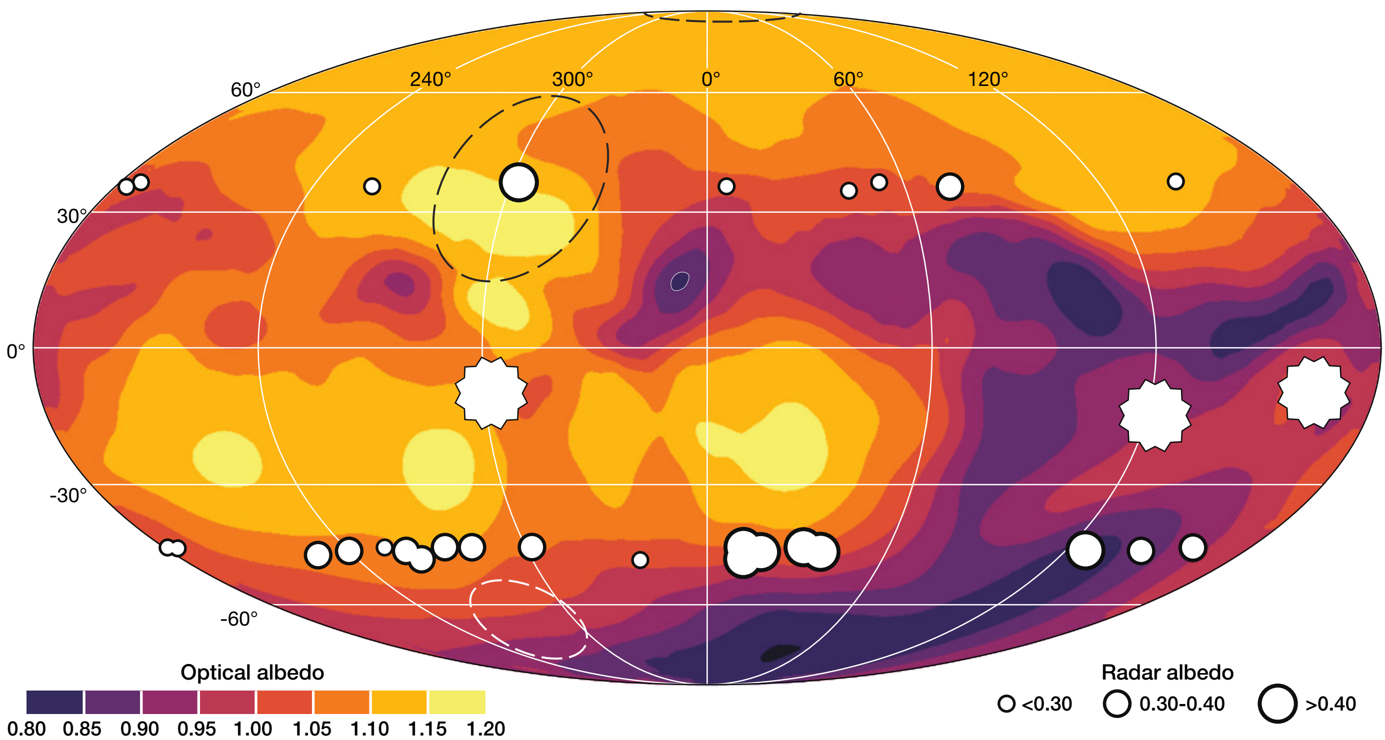
Psyche to Psyche

The Psyche mission focuses on a single world, mapping it at all scales and determining its geologic history, just as Dawn did at Vesta and Ceres (*S&T:* Dec. 2016, p. 16). The Dawn experience tells us that while the pretty pictures from Psyche will provide instant gratification, understanding the strange world will likely take years of scientific puzzling.

After its scheduled launch in August 2022, Psyche will swing by Mars on its way to a January 2026 arrival. Psyche's pathway to its target asteroid looks very similar to Dawn's, because both employ solar electric propulsion. Large solar panels supply electricity to generate magnetic fields that accelerate heavy xenon ions to high speeds, producing very efficient but gentle thrust. Long periods of engine thrust will accelerate and then decelerate the spacecraft, matching the asteroid's velocity for a slow approach and capture into orbit.

Psyche has instruments that can build up global maps of color, brightness, topography, composition, and magnetic-

▼ **MYSTERY SURFACE** Researchers extrapolated from how Psyche's brightness varies as it spins to create this contoured map of how the asteroid's reflectivity, or *albedo*, changes across its surface. Some potential craters (dashed circles) appear in 3D reconstructions. Radar observations also provide albedo information: White dots indicate the part of the asteroid that was pointing straight at Earth during a radar measurement; that location would have been responsible for most of the reflection back at Earth. The size of the dot indicates how well the asteroid reflected the ping: larger means more reflective. Some radar-bright areas also appear to coincide with optically bright areas, which might be places where ancient *ferrovolcanism* — consisting of iron-rich lava — erupted. Observers also saw three bright spots (white sunbursts) in 2019 that weren't apparent in earlier observations, for reasons unknown.



PSYCHE SPACECRAFT: ARIZONA STATE UNIVERSITY; ALBEDO MAP OF PSYCHE: M. K. SHEPARD ET AL. / *PLANETARY SCIENCE JOURNAL* 2021 and gravitational-field strength over many orbits' worth of observations. Although the asteroid likely doesn't create a global magnetic field today, an ancient one frozen into its surface would suggest it began as the core of a differentiated body. Psyche's paired magnetometers will operate long before arrival, getting contextual measurements of the solar field before they ever sense the asteroid.

On approach, the first science will come from the Psyche Multispectral Imagers, a pair of color cameras that are based on the Curiosity rover Mastcam science cameras. Curiosity has two cameras for stereo vision; Psyche carries two just in case one fails. From a distance, the imagers will help with optical navigation, search for satellites, and produce the first global views.

Different orbital altitudes permit different types of science. Psyche's first orbital phase, about 2 months long at 700 km altitude, will allow navigators to determine the gravity field, enabling lower orbits. At the end of this phase we'll know Psyche's mass, volume, and density.

The next orbit will be much lower, an average 290 km (roughly one asteroid diameter) above the surface. For almost three months, the cameras will capture frame-filling views, mapping the asteroid in full color. Gravity science and magnetometer measurements will continue. We'll begin to know whether Psyche's mass is evenly distributed, or if it has weird concentrations of higher- and lower-density material inside.

Once the photo-mapping is complete, Psyche will drop lower. The next orbit, at 170 km altitude, will allow Psyche to complete the required mapping of the global magnetic field, perhaps identifying magnetism locked into Psyche's rocks left over from its geologic past.

The lowest orbit, below 85 km, belongs to the Gamma-ray and Neutron Spectrometer (GRNS), derived from the one on the Messenger mission to Mercury. It will map Psyche's elemental composition, finally telling us what the asteroid is made of. Then, and only then, will the Psyche team have all the maps with all the kinds of data designed to answer our questions about what the world is and where it formed.

It's Gonna Rock

Lucy is an astronomer's mission, Psyche a geologist's. Lucy's science will establish facts generalizable to a class of worlds never before visited, tying its in-situ measurements to thousands of Trojan asteroids observable as only the faintest points of light from Earth. Psyche, meanwhile, will perform a deep study of one especially strange world whose origin is entirely mysterious. The data from both missions will either confirm or complicate current explanations for how the asteroid belt formed.

Because it's only going as far as the main asteroid belt, Psyche doesn't have to travel as far as Lucy. Even though it'll take almost two years to gather the full data set, Psyche will be completing its primary mission at about the time that Lucy is gearing up for its first Trojan encounter. If you're an asteroid fan, mark your calendars for 2027.

ESA

DART

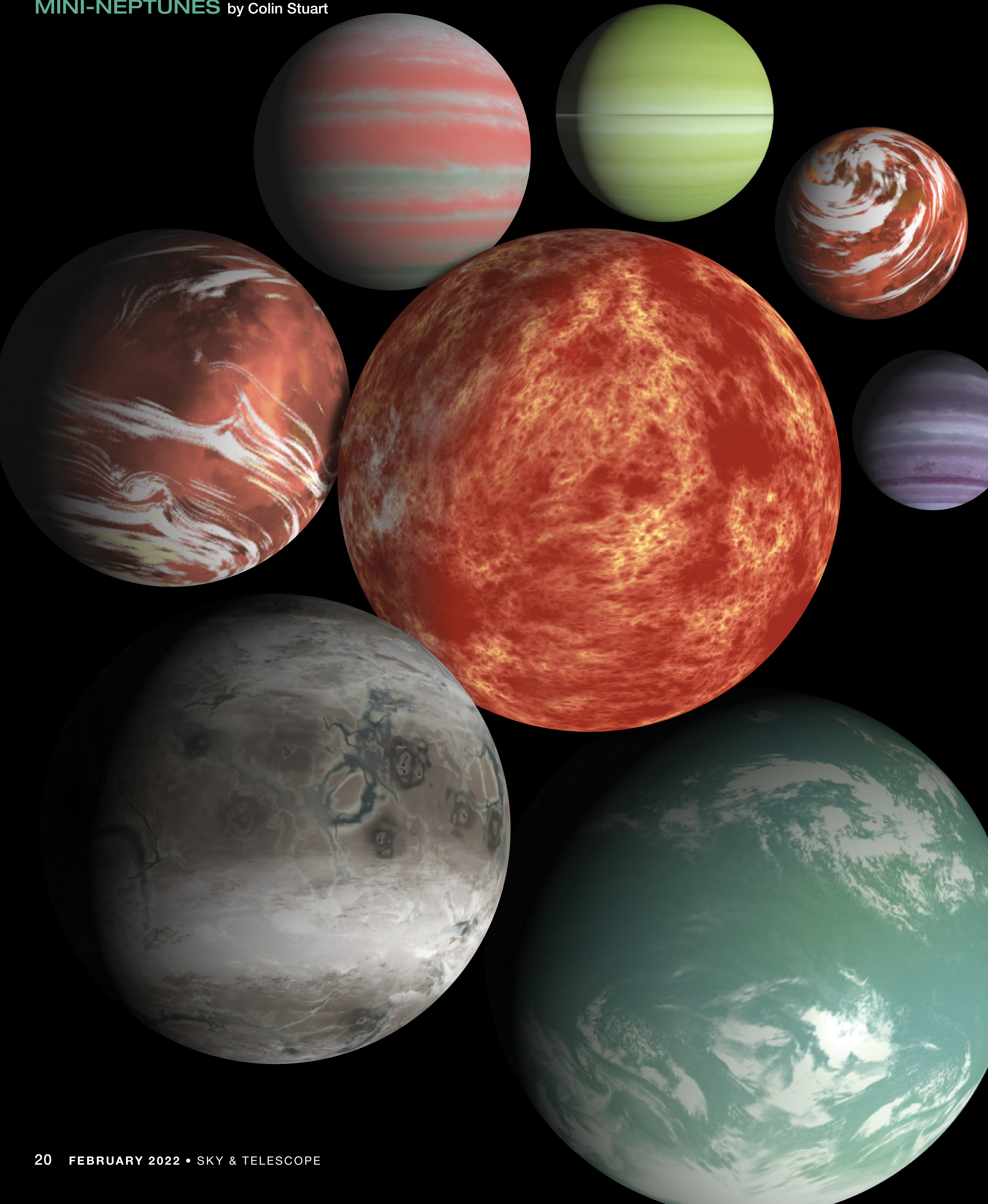
Another asteroid mission is scheduled to launch in late 2021: the Double Asteroid Redirect Test (DART). It's not a science mission but an engineering one: Its goal is to change an asteroid's orbit by slamming something heavy into it. The ultimate question the mission will help us answer is, Can humans prevent a calamitous asteroid impact on our home planet?

Before you panic, DART isn't going to change a near-Earth asteroid's orbit around the Sun. Its target is smaller. DART aims at a collision with Dimorphos, the moon of the near-Earth asteroid 65803 Didymos, in fall 2022. A small Italian-built satellite, LICIACube, will separate from DART to watch the impact unfold, sending pictures home to Earth. Meanwhile, ground-based optical and radar measurements will enable us to precisely time Dimorphos' orbit around Didymos both before and after the collision. That way, we can see the orbital effect of smashing a mass into an asteroid without actually changing the orbit of the whole Didymos-Dimorphos system, creating no additional risk to Earth.

▲ **65803 DIDYMOS** This illustration depicts the rocky, near-Earth asteroid Didymos (left), which is about 780 m across and comes with a 160-m-wide satellite called Dimorphos. Researchers plan to smash the DART spacecraft into Dimorphos, shortening the satellite's 12-hour orbit around Didymos by several minutes.

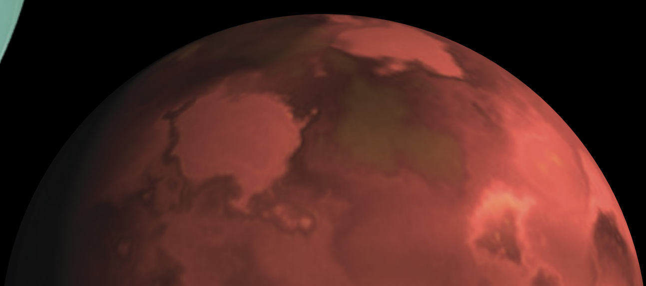
If you're not an asteroid fan, you might be wondering why these tiny worlds deserve so much attention, when there are much larger planets and moons not being explored. The answer: By studying these tiny worlds, we're actually studying the planets. Once Lucy and Psyche's data have returned to Earth, we'll find out if any theorist is right about how the solar system got its start, or if they'll have to go back to their chalkboards again. Whether they're right or wrong, the adventure is going to be fun.

■ Contributing Editor **EMILY LAKDAWALLA** is a science writer and space artist. Her first book, *The Design and Engineering of Curiosity*, was published in 2018. The author thanks researchers Marc Buie and Lindy Elkins-Tanton for fruitful discussions.



THE PLANETS THAT AREN'T WHAT THEY SEEM

Super-Earths and mini-Neptunes abound in the galaxy, but astronomers are still working out what these worlds actually look like.



When astronomers started scouring space for signs of planets around other stars, they thought they'd be looking in the mirror. Everyone expected to see ourselves reflected back at us — after all, there's supposed to be nothing special about us or our place in the cosmos. It should have been a tick-box exercise to find copy after copy of home.

Yet the more worlds we found, the more we realized that, when it comes to exoplanets, the universe is more like a deceptive hall of mirrors — it's hard to distinguish between truth and illusion.

We've found entire classes of planets that simply don't exist in our own backyard. Hot Jupiters that buzz around their stars in days, worlds where iron rain whips about on ferocious winds. Yet perhaps the most jarring revelation is that there are entire solar systems without any planets that look like ours. The Sun's planets can be neatly pigeonholed as either small, rocky worlds or large gas and ice giants. There's nothing in between to muddy the waters. Yet time and again we're finding stars that *only* have planets with sizes betwixt those of Earth and Neptune.

"According to our traditional models of planet formation, they shouldn't even exist," says Björn Benneke (University of Montreal).

Yet of the 4,438 confirmed exoplanets, 2,422 have radii between Earth's and Neptune's (1 to about 4 Earth radii). The fact that they appear to dominate the exoplanet population has left astronomers more than a little red-faced. "We should really be able to explain the most common type of planet," Benneke says. "Instead, they are the least-understood type of planet right now."

Like biologists trying to classify a newly discovered species, astronomers searched for a simple way to categorize these unfamiliar worlds. Size initially seemed a good choice. Observers found the vast majority of these mid-size planets by using the transit method, which looks for starlight dimmed by an orbiting planet periodically getting in the way. The amount of dimming, coupled with the size of the star, allows us to estimate the planet's radius.

There are plenty of planets between 1 and 1.5 Earth radii and even more between 2 and 4 Earth radii. But there's a significant drop in between, known as the "Fulton gap" after Benjamin Fulton (now at Caltech), who headed up the 2017 study presenting the observational evidence for the deficit. Astronomers used it to divide mid-size exoplanets into two groups: Worlds below the gap became rocky "super-Earths," and planets above it were gaseous "mini-Neptunes."

Yet a run of recent research suggests the division may not be that straightforward. "There's a gray zone between the two," says Angelos Tsiaras (University College London). Super-Earths could be masquerading as mini-Neptunes, or mini-Neptunes might become super-Earths over time. Mini-

◀ **IN BETWEEN** The most bountiful planets in the galaxy — the ones with sizes and masses between those of Earth and Neptune, shown here as artist's concepts — have no counterpart in our solar system. Their appearance and evolution remain a puzzle.

NASA / JPL-CALTECH / EXOPLANET EXPLORATION PROGRAM

Neptunes might also not be as gaseous as we think. Astronomers are working hard to disentangle the real properties of these planets from their distorted reflections in the cosmic hall of mirrors.

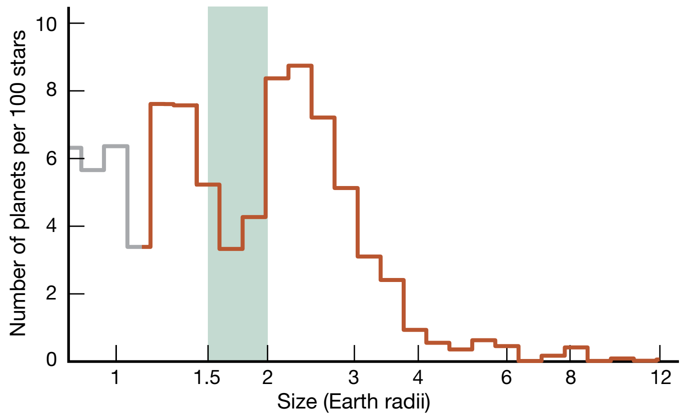
The Middle Ground

While radius may be too simplistic a tool to properly classify these enigmatic exoplanets, average density (calculated using the radius and mass) is a more useful measure. It tells us the average mass of each unit volume of the exoplanet, providing clues about what it is made of. A dense planet (that is, a true super-Earth) will contain a hefty portion of heavy metals such as iron and nickel. Extremely low-density planets — quintessential mini-Neptunes — are, on the other hand, likely made of light gases such as hydrogen and helium.

But the nature of planets in between is less clear-cut. In those cases, multiple scenarios for the interior can match the same overall density. The planet could be mostly ice, for example, or it could be a mixture of rock and gas in just the right ratio to mimic the density of ice. We would easily confuse two such planets, because we can only calculate the average density, not how the density changes with depth. "Some super-Earths and mini-Neptunes could have the same radius and mass," says Tsiaras.

Tsiaras thinks there's a more sure-fire route to classification success. "If we really want to separate super-Earths and mini-Neptunes, the question is how much hydrogen and helium they have," he says. "We can't tell that without looking at their atmospheres." The difference may be stark: Earth's atmosphere contains just 0.00005% hydrogen and 0.0005% helium, whereas together these gases make up about 99% of Neptune's upper atmosphere.

Astronomers can work out what an exoplanet's atmosphere is made of by looking at the starlight that has passed through those layers of gas on its way to Earth. Molecules in the planet's atmosphere absorb precise wavelengths, leading to gaps in the spectrum that we can observe. The locations of



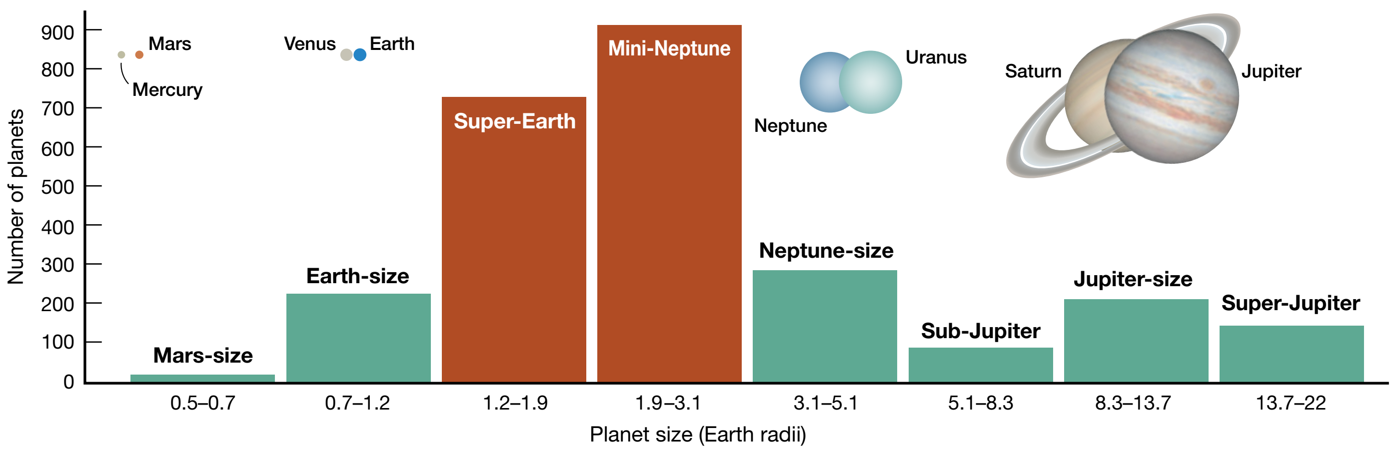
▲ **FULTON GAP** Even accounting for the fact that smaller planets are harder to spot, Benjamin Fulton and colleagues found that planets with sizes between those of super-Earths and mini-Neptunes were scarce. (The census for the smallest planets is incomplete and denoted in gray.)

the gaps are unique to each molecule, betraying the atmosphere's composition.

Not that the first attempts to do this for planets around the Fulton gap went to plan. "We kept seeing flat spectra," Benneke says, meaning no missing wavelengths at all. Flat spectra are normally put down to clouds or haze that block the transmission of starlight through the planet's atmosphere and thus prevent absorption features from appearing in the spectrum. It got to the point where the committees doling out time on big telescopes like Hubble were getting increasingly skeptical and turning down proposals. "They just thought we'd see more flat spectra," Benneke says.

So Benneke changed course, looking instead at a cooler planet orbiting farther out, where less intense sunlight might lead to fewer clouds. Eventually, he settled on K2-18b. Located some 124 light-years away in the constellation Leo, the Lion, it spins around a red dwarf star much smaller than our Sun. While it only takes 33 days to complete one orbit, the fact that the star is cooler means the world is still in the *habitable*

▼ **WORLDS ABOUND** Planets bigger than Earth but smaller than Neptune have dominated exoplanet discoveries. This diagram shows the size distribution for 2,268 confirmed planets detected via the transit method by the Kepler telescope.

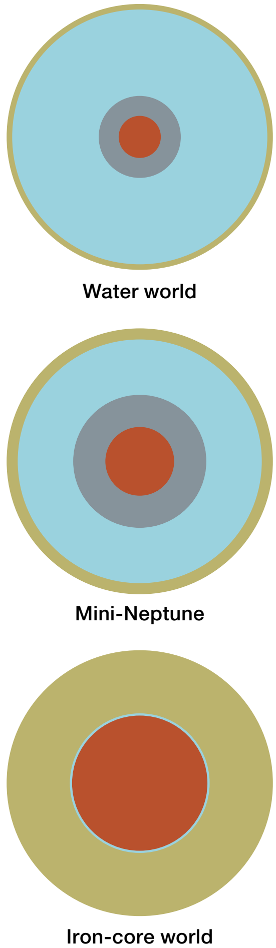


PLANET SIZES: NASA AMES / WENDY STENZEL; FULTON GAP: NASA AMES / CALTECH / UNIVERSITY OF HAWAI'I / B. J. FULTON *zone* — the region around a star where local temperatures would permit the existence of liquid water. In fact, K2-18b receives an almost identical amount of energy from its star as we do from the Sun.

Astronomers discovered K2-18b in 2015 and have since oscillated between classifying it as a mini-Neptune or a super-Earth. The planet's status was called into question again after Nikku Madhusudhan (University of Cambridge, UK) used Benneke's data to create different models of K2-18b's structure.

Madhusudhan suggests that hydrogen makes up no more than 6% of the planet's mass and, based on Benneke's estimate of the world's size (2.6 Earth radii), K2-18b's density is partway between Earth's and Neptune's. To square the amount of hydrogen with this middling density, K2-18b likely has a rocky core.

In Neptune, scientists think ices make up a mantle that lies between the planet's core and the hydrogen-rich envelope around it. But Madhusudhan argues that K2-18b's overall density might indicate something else is going on inside this exoplanet. He considered three possible models of K2-18b's interior, one of which suggests the planet could have an abundance of liquid water. Unlike the thin veneer of water



INTERIOR DESIGN This diagram shows three representative interiors that could explain observations of K2-18b. These examples are by no means exhaustive; for example, the extreme case at bottom could be made a bit less extreme by trading in some of the iron core for rock.

on Earth, K2-18b's ocean may take up most of the planet's mantle. If so, that would make it more like a super-Earth or water world — even though astronomers would classify it as a mini-Neptune based on its radius alone.

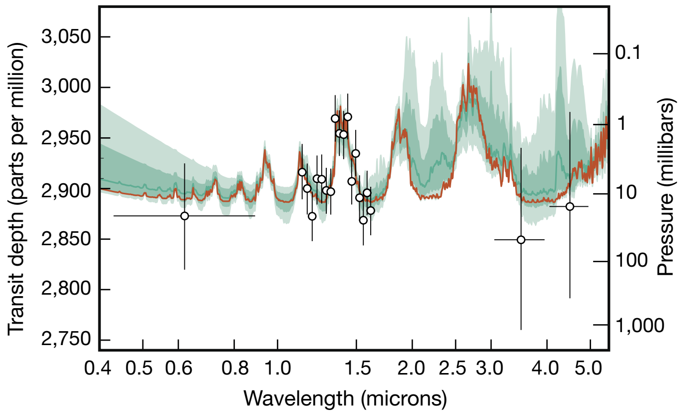
Water, Water Everywhere . . .

Water seldom gets mentioned in the exoplanet arena without piquing interest about whether life could be exploiting that liquid. "Whenever we talk about habitability and life, we immediately think about Earth-like planets," Madhusudhan says. "We've shown that even if it's a mini-Neptune [based on radius alone], the planet could still be habitable."

Benneke also claims to have found water vapor in K2-18b's atmosphere, a find that Tsiaras confirmed. (However, it's worth noting that Bruno Bézard at the Paris Observatory

SUPER-EARTH OR MINI-NEPTUNE? Astronomers have detected water vapor in the hydrogen-dominated atmosphere of K2-18b, shown here in an artist's illustration. The planet's density suggests it most likely has a rocky core.

PLANET MAKE-UPS: TERRI DUBÉ; DATA: NIKKU MADHUSUDHAN; K2-18B: ESA / HUBBLE, M. KORNMESSER



▲ **WATER IN THE AIR** The transmission spectrum of K2-18b shown here is derived by examining the planet's apparent size at different wavelengths as it transits its star. A feature at 1.4 microns indicates the presence of water vapor.

BENNEKE ET AL. / *ASTROPHYSICAL JOURNAL* 2019

argues that the absorption came from methane, not water, which would make K2-18b distinctly more Neptunian.) If Benneke and Tsiaras are right, the water vapor might lead to a familiar phenomenon. "The water vapor could condense out to form falling water droplets," says Benneke. In other words, there's a chance that it's raining water on this alien world — again, not something we'd normally associate with a Neptune-like planet (although it can rain other substances on gas and ice giants).

It's unlikely K2-18b is a one-off. "Mini-Neptunes could be water worlds," says Martin Turbet (Geneva Observatory). Astronomers have previously assumed that a thick layer of hydrogen is needed to explain both the large radius and fairly low density of planets above the Fulton gap. "We discovered that it is possible to explain [it] without the need for hydrogen," Turbet says. "We can do it only with water."

In research published in June 2020, Turbet drew inspiration from our growing understanding of climate change here on Earth. We know that water vapor is a particularly potent greenhouse gas, trapping heat from the Sun and preventing its escape back into space. A water world close to its star would receive a lot of energy, which would evaporate significant quantities of water into its atmosphere. The water vapor would then trap more stellar energy, raising the ambient temperature and creating yet more vapor in a runaway process. "This dilates the atmosphere and puffs up the planet," Turbet says. Over time, the exoplanet could even reach the same radius as those previously considered to have Neptune-like hydrogen atmospheres.

Water vapor may even be the culprit behind the flat spectra initially seen by Benneke and others. Absorption bands will be some 10 times weaker in a water-dominated atmosphere compared with a hydrogen-dominated one, Turbet explains, resulting in a flat-looking spectrum that's indistinguishable from that of a cloudy planet. "Existing telescopes don't have the precision to probe the differences between these two scenarios," Turbet says. Fortunately, the James Webb Space Telescope, due to launch in December 2021 as this article goes to press, should be able to help answer this question (*S&T:* Nov. 2021, p. 20). Webb has the capability of detecting distinct absorption features at infrared wavelengths, where water vapor absorbs photons quite efficiently.

Super-Earth Origin Stories

Taken together, these recent findings actually make it harder to understand where all the observed mid-size planets come from. One idea is that super-Earths and mini-Neptunes are two stages of the same planet. That's what Travis Berger (University of Hawaiʻi, Mānoa) thinks. In work published in August 2020, he found evidence that mini-Neptunes can shrink over time, the loss of their atmosphere revealing a super-Earth underneath. The Fulton gap would be populated by exoplanets in transition.

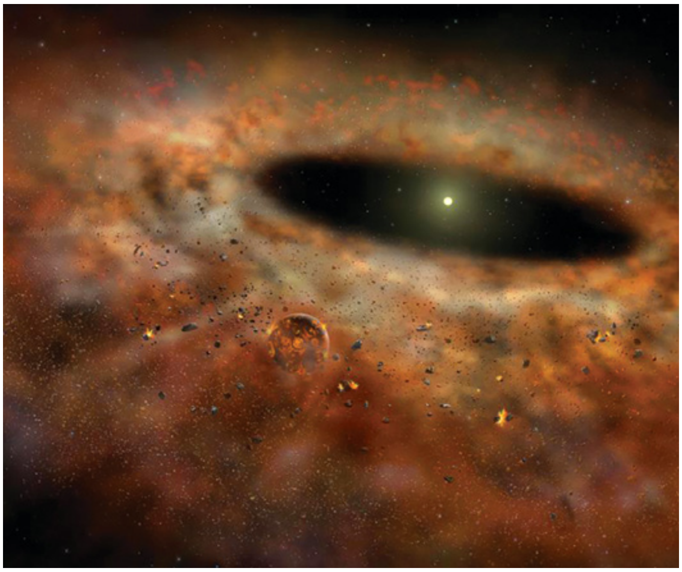
Recent work by Trevor David (Flatiron Institute) and others supports this argument. When sorted by their host star's age, the exoplanets in the Fulton gap change in size. Based

WHY WERE MINI-NEPTUNES AND SUPER-EARTHS SUCH A SURPRISE?

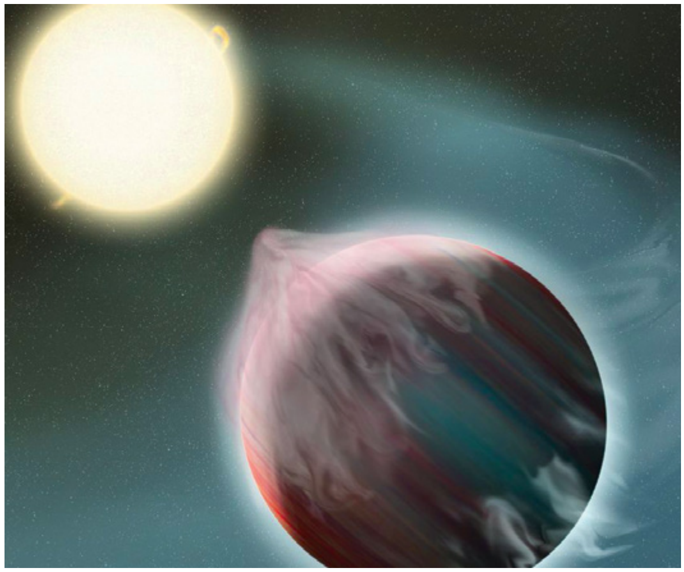
We thought we knew how giant planets were made. Once a massive-enough core has come together, it has sufficient gravity to begin gathering up gas from the disk in which it was born. The rate of this accretion increases exponentially once the mass of accumulated gas matches the mass of the core, growing quickly into a giant planet, says Hongping Deng (University of Cambridge, UK).

Conventional wisdom says that it's impossible to stop this juggernaut partway through to produce the huge numbers of planets we see between 1 and 4 Earth radii. Yet in recent work, Deng and others argue that such a feat could be possible if we account for an oft-neglected force: magnetism.

The team's simulations show that the magnetic field in a planet-forming disk triggers fragmentation, creating nascent planets much smaller than expected. The protoplanets stir up gas around them, building up a magnetic shield that inhibits further inflow of gas. Only the biggest initial cores have sufficient gravity to outdo magnetism and amass enough gas to match the giant planets we see in our solar system. If Deng is right, this could explain why less than 19% of known exoplanets have radii greater than Neptune's.



▲ **DIFFERENT FROM THE BEGINNING** Some have proposed that super-Earths never grow a gaseous envelope to begin with, while mini-Neptunes do, based on the temperature of the surrounding disk.



▲ **LATE EVAPORATION** Another scenario is that mini-Neptunes close to their host stars might lose their outer layers to intense stellar radiation, turning the planets into rocky super-Earths over time.

on an analysis of some 1,000 exoplanets, David's team found that there's an absence of smaller planets around younger stars, while older stars are missing larger planets. The result implies that, with time, the atmospheres of mini-Neptunes are eroding away.

The idea of atmospheric loss fits with the fact that the vast majority of super-Earths we've seen so far have periods under 30 days, putting them close to their stars' intense light and heat. Only 32 have periods greater than 100 days. However, this finding could be a shortcoming of the observations themselves: More far-flung super-Earths are harder to find with the transit method, because they create smaller dips in their star's brightness. If more sensitive future searches reveal a larger population of super-Earths with lengthier orbits — where atmospheric stripping is more difficult to explain — it may point the finger at an alternative formation scenario.

Eve Lee (McGill University, Canada) thinks that we'll find those far-out super-Earths. "Low-mass super-Earths began as rocky planets," she asserts.

In recent research, Lee compared how planetary cores with different masses accrete their atmospheres. Planets' gaseous envelopes cool and shrink as they form, making room for more gas to flow in. Crucially, this process stops once the temperature of the envelope matches that of the surrounding space. Through new calculations and computer simulations, Lee discovered that smaller planets reach temperature parity much faster than larger ones. The maximum amount of gas a 1.3-Earth-mass core can accrete is 100 times less than for a core of 2 Earth masses. The quick end to accretion prevents a super-Earth from ballooning into a mini-Neptune.

Yet migration may later achieve what accretion couldn't. A super-Earth migrating inwards could swell up to the size of a mini-Neptune in a complete role reversal of the atmospheric stripping idea. Perhaps the planets in the Fulton gap are super-Earths growing into mini-Neptunes. This would be more consistent with Turbet's idea that many mini-Neptunes are puffed-up water worlds devoid of hydrogen. How much water a mini-Neptune holds could help astronomers determine where it originally formed in its planetary system: Theoretical work by Bertram Bitsch (Max Planck Institute for Astronomy, Germany) and others suggests that the wettest mini-Neptunes will have formed far from their stars before migrating inwards.

Water may turn out to be the ultimate arbitrator in this debate. It's exactly why so many in the field cannot wait for the results from the Webb space telescope that will help us peer deep into the atmospheres of mini-Neptunes to see what further secrets they hold. "It's where I would put most of my hopes," says Turbet.

Meanwhile, existing and near-future planet hunters such as NASA's currently operating Transiting Exoplanet Survey Satellite (TESS) and the European Space Agency's Planetary Transits and Oscillations of Stars (PLATO) mission, due for launch in 2026, will rapidly add to our growing cache of mid-size planets. ESA's Ariel spacecraft will follow in 2029 — a largely infrared telescope that will help us to characterize the atmospheres of transiting exoplanets.

Before the decade is out, we'll be able to build a full inventory of mini-Neptunes. Such a census would hopefully solve the long-standing mystery of how these worlds came to be among the most common ones in the universe — and whether they represent a huge amount of potentially habitable real estate that would boost our search for cosmic company.

■ **COLIN STUART** is an astronomy author and speaker. Get a free ebook at **colinstuart.net/ebook**.

Derrick's Mission to Mars

Reach out to young space enthusiasts while reaching for the stars.

North Philadelphia, Pennsylvania, isn't anyone's idea of a dark-sky paradise, but on a cool October evening a few years back, it became the unlikely birthplace of a future astronomer.

It happened around Susquehannah Avenue, in an area of the city far from the well-worn tourist paths to the Liberty Bell and the Old City. The area is dotted with convenience stores and gas stations, and the night sky is bright — way too bright for a typical star party. But on this evening the Moon was rising, and a gentleman with an 8-inch Celestron set up his telescope at a neighborhood community center as the light faded from the sky.

A woman approached with her young daughter. The little girl was barely three years old. In her lacy blouse and skirt with matching shoes and hat, she looked like she was dressed for the nursery school prom. She was so tiny that she couldn't reach the eyepiece on her own, so the gentleman helped her step onto a platform set up next to the scope. The target that evening was the only thing easily visible — that rising moon. The little girl squinted through the eyepiece.

"Mommy!" she suddenly cried out. "It's so beautiful!"

This is a story about how children become scientists. It's a story about creating opportunities, encouraging representation, and celebrating the sheer joy of looking up at the night sky — and wonder who we are and how we got here. It's about how ideas turn into initiatives and how bridges are built between communities. It's about how passionate educators can help shape the future by making science fun and by bringing astronomy to inner-city communities. These dedicated individuals are exhorting young kids who may have heard "no" many more times than "yes" that they, too, can become astronomers. And best of all, *you* can be a part of making all this happen, right now.

Meet Mr. Pitts

The gentleman with the telescope that night in North Philly isn't just a member of the local observing club. He's the Chief Astronomer at the Franklin Institute, a science museum in Center City, Philadelphia, as well as director of the Fels Planetarium. And his name is Derrick Pitts. A scientist and self-described telescope jockey, Pitts holds two honorary doctorates. He felt the pull of the stars early in life. Fifty-plus years after the fact, Pitts still remembers hanging a poster of the Andromeda Galaxy on his bedroom wall. That evening with the little girl in North Philly wasn't a one-off. Pitts has dedicated his entire career to increasing opportunities in science for under-resourced communities. It's an effort that's bearing fruit today, with an assist from NASA.

Let's consider the many barriers to accessing astronomy for a moment. There's the complicated math, access to high-level coursework, and, of course, the perception that if you live in an inner city — a densely populated, often under-resourced urban region where lights blaze all night — you can't possibly see the stars anyway, right?

Yet this is the environment in which educators like Pitts thrive because they're determined to turn supposed barriers into opportunities. Why not bring astronomy right into these communities and focus on what students *can* see? The Moon, the bright planets, and even the International Space Station are all visible under light-polluted skies.

Pitts himself was the beneficiary of talented educators who entered his life at just the right moment. He grew up in the

◀ **BIG AND BRIGHT** No amount of light pollution can diminish the appeal of the Moon's breathtakingly rugged surface. Our nearest celestial neighbor is a "must-see" attraction on public observing nights and presents a wealth of detail even in small telescopes.

MOON: GARY SERONIK; ILLUSTRATION: SAM WARD

Nicetown section of North Philadelphia, two blocks and two decades removed from comedian Kevin Hart. Pitts remembers being the “weird science kid” at Gillespie Junior High School, where he performed demonstrations for the other students and earned a key to the school’s science closet — something normally reserved for staff. At Gillespie Junior High, dedicated teacher Beth Showell first impressed upon Pitts that science was a formidable subject worthy of serious study.

“She was unabashedly in love with and excited about science,” Pitts recalls. “She never masked her enthusiasm for it at all and certainly challenged students to be interested in science and to excel at science. It was the first time I had run into somebody who was dedicated and committed [to science] — no embarrassment, no apology.”

Pitts graduated from Philly’s prestigious Germantown Academy, then earned a degree from St. Lawrence University in 1978 and began working at the Franklin Institute that same year. He presides over a 10-inch Zeiss refractor on the building’s rooftop, where he once advised a high-school student from the northeastern suburbs who was studying sunspots and solar flares for a science fair project. That student was me. Reconnecting with Pitts recently, I was struck by his passion and drive for science education — he’s the same person he was when he helped me decades ago. Although he could write his own ticket to any observatory in the world, he continues to work at the Franklin Institute.

“I love what I do, I love where I work,” Pitts told me. But in a reflective moment, he confided that even today he yearns for another chance. Had the role models been there for him, he would have pursued a career as a high-performance aircraft military pilot and an astronaut. “But I grew up in an inner-city neighborhood where I knew no one who had that kind of occupation,” he says.

▼ **A GENTLE GUIDE** Astronomy educator Derrick Pitts meets students of all ages wherever they are to help them appreciate and understand the wonders of the night sky.

THE FRANKLIN INSTITUTE

Bright Lights, Brighter Stars

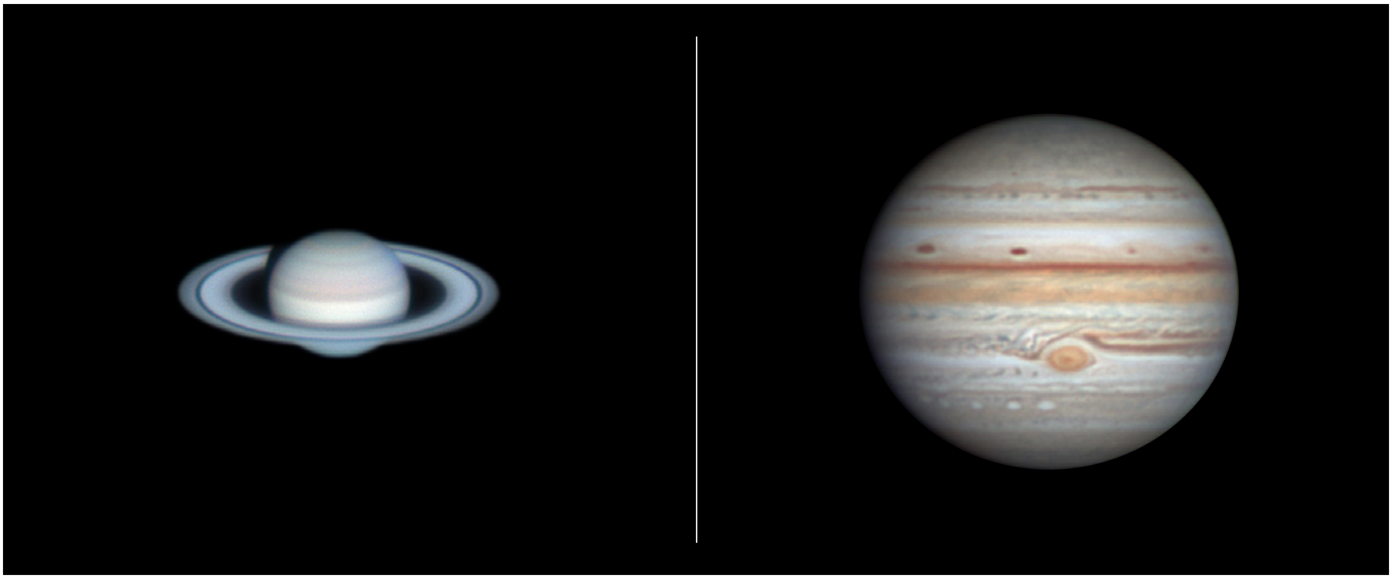
Pitts had already flexed his skills as a storyteller at star parties and planetarium shows, but it was his knack for creating connections that led to the concept behind City Skies. It’s a partnership between amateur astronomers, community centers, and informal science institutions, known as ISIs — educational institutions that support lifelong learning in STEM (science, technology, engineering, and mathematics) topics outside formal classroom settings. Supported by the educational resources of the Franklin Institute, City Skies’ goal is to bring science to the widest possible audience. The project evolved as an outgrowth of Pitts’s interest in creating innovative science-education opportunities to inspire students to see the possibilities arising from an understanding of the night sky. “City Skies is a force multiplier,” Pitts says simply.

The program attracted a $799,000 grant from NASA in 2014, which funded training, educational materials, and even small, affordable telescopes for community centers in the Philadelphia region. In all, during a period of four years, City Skies sponsored 25 workshops, reached 46 community centers, and trained 152 workshop facilitators and 17 middle-school teachers, while receiving consistently outstanding ratings from participants. Star parties were held all over the city, often in conjunction with other events such as Philadelphia’s annual Science Festival (also sponsored by the Franklin Institute).

In December 2020, the Franklin Institute qualified for a new NASA grant called TEAM II (Teams Engaging Affiliated Museums and Informal Institutions). With this funding, Pitts and the Franklin Institute are bringing the City Skies model to the national level. The expanded program is called Mission to Mars — a nod to NASA’s current efforts to plan for human space travel to the Red Planet. The initiative trains ISIs to replicate the City Skies concept of outreach and educational programs to link amateur astronomers and community centers in under-resourced communities.

In late 2021, the Franklin Institute announced the first five ISIs to receive training over the next year: the Arizona Science Center (Phoenix, Arizona); the Sci-Port Discovery Center (Shreveport, Louisiana); spectrUM Discovery Area (Missoula, Montana); Las Cruces Museum of Nature and Science (Las Cruces, New Mexico); and the Green Bank Observatory (Green Bank, West Virginia). Pitts notes that every member of this initial cohort is located in a rural or otherwise underserved location.

Mission to Mars will prepare each of these institutions to train ISIs of their own choosing in subsequent years. According to a December 2020 NASA press release, the dozens of national and community partnerships created through this program “will equip informal science institutions, community-based organizations, and amateur astronomers with the



TWO FOR THE SHOW Even first-time telescope users are sure to be impressed by Saturn and its magnificent rings or Jupiter with its cloud belts and parade of satellites. Both planets show up well even under light-polluted city skies.

TAKE IT EASY When it comes to public astronomy, the brightest sky sights are the best. The Moon and the brilliant planet Venus (shown here) are especially appealing and sure to make any observing night a success.

SATURN AND JUPITER: SEAN WALKER; MOON AND VENUS: GARY SERONIK skills and resources to develop and deploy high-quality astronomy engagement experiences for families and youth."

For Darryl Williams, a former chemical engineer who serves as the Franklin Institute's Senior Vice President of Science and Education, Mission to Mars holds exciting possibilities for amateur astronomers interested in reaching out to communities that are often rich with talent, but lack the resources of wealthier areas. "My hope is that we can create a culture where amateur astronomers and families and youth in their communities [can be] on a journey of curiosity and exploration together," Williams says, "[one] that reinforces the motivation and interest of particularly the younger participants to see that all you have to do is look up [into the night sky] to be more observant and connected to the world around you. And it can lead to a really fascinating career."

It can also turn a chemical engineer back into the kid he once was. Williams, who accompanies Pitts to star parties around Philadelphia, recalls his early experiences with astronomy as a turning point in his life. "I remember as a kid I was fascinated by the constellations," he says. He grew up in Albuquerque, New Mexico, the son of a chemist-mathematician mother. Williams attended Hampton College and earned his PhD at the University of Maryland. But he never forgot the telescope he had growing up or his early love for astronomy.

◀ **SPACEFARING** At public observing events, connecting human activities with space can be as simple as pointing out the International Space Station as it passes overhead.

Reaching New Astronomers

As it turns out, running a star party at a community center isn't all that complicated. The crucial ingredient is an amateur astronomer who knows the night sky and has access to star charts and perhaps a small telescope. Once an audience has congregated, it's a simple matter of having everyone look up and explaining what's visible. The Moon's craters, the bright planets, and the key stars in the most famous constellations — these are all basic targets for veteran observers but can enthrall and inspire newcomers. Williams has watched Pitts hold court at many a star party, bringing diverse groups together with stories that unite individual skywatchers in awe of the enormity of the universe.

Williams, who also serves as a vice chairperson of the NASA Advisory Council STEM Engagement Committee, is thoughtful when asked about the troubling statistic that fewer than 1% of doctoral degrees in physics or astronomy awarded in the United States in 2019 went to scholars who identify as Black or African-American. "We should be

▲ **PARTYING WITH THE STARS** Pitts regularly hosts star parties for students in the Philadelphia area. His favorite target is the International Space Station, a frequent and easily visible sight in Philly's night sky.

ISS: NASA / ROSCOSMOS; PITTS WITH GROUP: THE FRANKLIN INSTITUTE focusing on creating systems and spaces that are intentionally focused on inclusion, equity, access, or accessibility," he stresses. "Then diversity is the natural result — the evidence that all of these things are working."

Thinking back on my own early astronomy experiences, I reflect on how Pitts's work plays off some of the most classic concepts found in Newtonian physics. Take, for example, the famous equation $F = ma$. The force of an object in motion (F) equals its mass (m) multiplied by acceleration (a). Now imagine that the force we're talking about is the effect of astronomy on a young child and its influence on that child's future. How do you maximize that force? Increase the acceleration. Get there fast, don't worry about their age, and just put them in front of an eyepiece and let them say "Wow!" over and over again.

Here's another equation: $Ff = \mu FN$, where the friction force (Ff) working against an object's motion is the product of a friction constant (μ) that's unique to that material, multiplied by the normal force of the object (FN). When it comes to engagement, remove the friction. Forget the complex math and invite an amateur astronomer with a star map to show them the night sky.

Perhaps most important of all is the gravitational force equation: $F = GMm/r^2$, where the gravitational force (F) between two objects is equal to the product of their masses (M, m) divided by the square of the distance between their centers of mass (r^2), multiplied by the gravitational constant (G). To really engage with kids, decrease the distance between them and astronomy to increase the pull of the science. Meet them where they are — in their neighborhoods and in the community centers their families already know well.

Do these things, and just like that, astronomy becomes an egalitarian science. Suddenly, every kid can reach for the stars.

How to Get Involved

Do you want to help share the sky with a kid in need? You don't need a telescope or an observatory. You don't even need your own kid.

Mission to Mars launched in January 2022, but you don't have to wait for the program to come to your region to get involved. All you need is your knowledge and a local organization that sponsors out-of-school-time activities. Contact your library or community center to get started. Offer to come to their location and host an observing session. Should you want to leave the center with a gift they can use at future star parties, consider an inexpensive Galileoscope (available at **galileoscope.org**).

Once you're outside with the kids introduce them to the objects that they're most likely to notice right after sundown: the Moon and the bright planets. Encourage kids to keep watching these planets as they move across the sky in the months that follow. Point out bright stars and invite the kids to track how their positions change throughout the night and even the seasons. Get students excited about space-based science research by spotting the International Space Station at dusk — an activity that offers a great opportunity to connect with a human scientific endeavor in real time. Find an observing schedule for the International Space Station (including a texting app to alert you when the ISS is visible in your area) at **spotthestation.nasa.gov**.

Doesn't this kind of outreach sound like something you'd like to be a part of? Derrick Pitts and educators like him have a simple message to share: You can.

▲ **SCOPE PILOT** Pitts presides over the Franklin Institute's 10-inch Zeiss telescope at the Holt & Miller Observatory on the museum's roof. Visitors can safely observe the Sun as well as objects in the night sky.

▶ **EASY TARGETS** Even the most casual stargazer is familiar with the Big Dipper. The asterism is both bright and easily recognized, which makes it an ideal sight for public observing nights under urban skies.

■ Science journalist **NICOLE NAZZARO** spent many happy hours visiting the Franklin Institute while growing up in the Philadelphia area. Today she writes and observes the stars from her home in Edmonds, Washington.

PITTS AND SCOPE: THE FRANKLIN INSTITUTE; BIG DIPPER: ADE ASHFORD

Gems of the Win

SHIMMERING GEMS The Pleiades is a favorite night-sky object to many an observer, both novice and veteran. Known since antiquity, it has fostered many names in all cultures. Most people can easily spot five Pleiads with the naked eye; binoculars will add several more; a real treat awaits those with telescopes.

Open clusters, shimmering conglomerations of stars, adorn February's night skies.

In the July 2021 issue, I described my picks of summer's finest open clusters. Now I'd like to share my selection of favorite winter clusters. Even though the winter Milky Way is much fainter than summer's, in my opinion February's best star clusters equal or exceed July's.

The Sparkling Seven Sisters

The **Pleiades** (M45) feature prominently in many of our world's diverse cultures. I've always liked the poet Alfred, Lord Tennyson's reference:

> *Many a night I saw the Pleiads, rising thro' the mellow shade,*
> *Glitter like a swarm of fire-flies tangled in a silver braid.*

Last winter, on an evening with excellent transparency, I counted 12 Pleiads with the unaided eye from my backyard. (Longtime *Sky & Telescope* Contributing Editor Fred Schaaf also mentions 12 in his column on page 45 in the December issue.) I spotted the brightest seven plus magnitude-5.5 Celaeno, magnitude-5.6 18 Tauri, magnitude-5.8 Asterope (counted as two since Asterope was elongated, even if I couldn't split the pair that are separated by 2.5′), and the magnitude-5.4 star HD 23753 that lies 42′ south-southeast of Alcyone. In her book *The System of the Stars,* Irish astronomer Agnes Mary Clerke wrote that Kepler's tutor, Michael Mästlin, "perceived fourteen, and mapped eleven Pleiades previously to the invention of the telescope."

On that night (and on other rare occasions), 7×50 binoculars showed the Pleiades seemingly shrouded in nebulosity enveloping the "dipper" shape of the cluster. The few times that I have suspected the nebulosity have all been on nights with excellent transparency, which gives me confidence my observations are real. In the January 1981 issue of *Sky & Telescope*, Walter Scott Houston wrote: "Some amateurs claim to have seen the nebula with their naked eye, and I am inclined to agree with them."

My 80-mm apochromatic refractor at 25× shows all the main features of the Pleiades that I see with larger scopes: the Merope reflection nebula (faintly), the triple west-northwest of Alcyone, and the tentacle of nine stars running south and curving southeast from Alcyone to just past HD 23753. Extend this string of stars around 50′ and you arrive at an arc of four stars. Back in the center of the dipper figure, the 80-mm reveals a double, but its orange

ter Sky

component barely shows its color (which is always obvious in my 8-inch Dobsonian).

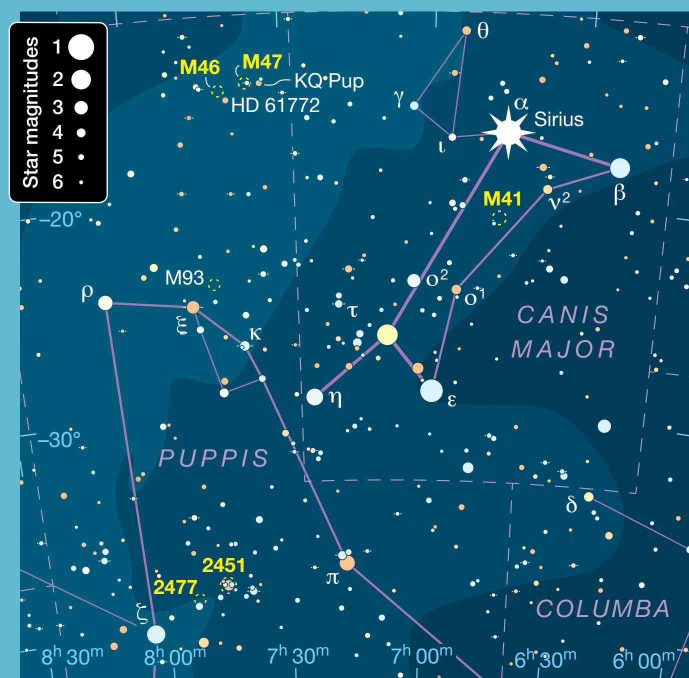
German astronomer Wilhelm Tempel discovered the Merope Nebula (NGC 1435) in 1859. Hidden within this L-shaped nebula is IC 349, a challenging, very tiny (a mere 30″ across) reflection nebula. E. E. Barnard first spotted IC 349 in 1890 with the 36-inch refractor at Lick Observatory, and former *Sky & Telescope* Contributing Editor Sue French introduced it to amateur astronomers (*S&T:* Feb. 2006, p. 69). On an excellent night I inserted my 261× occulting-bar orthoscopic eyepiece into my 16-inch Newtonian to hide Merope's glare and bagged the prize that lurks only 36″ south-southeast of Merope.

From Perseus to Puppis

In Perseus, the Double Cluster, **NGC 869** and **NGC 884**, is an obvious, elongated smudge with the unaided eye. From antiquity it has represented the handle of Perseus's sword. Both rich, young clusters include spectral type *B* and *A* supergiant stars among their gems, while NGC 884 also contains some *M*-type red supergiants.

In my 8-inch at 135× the western cluster, NGC 869, numbers about 110 stars, including many doubles. A north-south, nearly star-free band splits the cluster, with the richer part on the eastern side, which is highlighted by a bright semicircle facing a brighter yellow sun. An oval of six fainter stars is immediately to the west of this yellow star. In this view I also spot another bright, yellowish star above the first one.

Staying at 135× NGC 884 has about 100 gems arranged in short arcs, triangles, and two diamonds. An orange star lies between the two clusters, another is on NGC 884's western edge, a third is near its center, and two more orange stars ornament this cluster's northeastern side. The brightest star,



PLEIADES: MASIL IMAGING TEAM

a 6.4-magnitude yellow one, lies on the northern side. Despite a rich Milky Way field, both clusters are reasonably separated from the Milky Way. In binoculars an arc of bright sparklers leads from NGC 869 to the large open cluster Stock 2.

Heading over to Cancer, we find the Beehive Cluster, **M44**. Praesepe, as it's also known, was used in ancient times as a weather predictor — its disappearance from a starry sky due to thin, high cirrostratus clouds rolling in indicated an approaching weather system.

I spent a recent weather-free night enjoying the Beehive. My 7×50s resolved it into more than 30 stars, and the central V was prominent. In the 80-mm apo at 25× I saw about 100 stars, 40 of which are bright. At 67× three signature trios are prominent, as are nine pairs. The 80-mm provides enough aperture to show M44 well, except that the color in the trios doesn't stand out. The V that was so discernible in the 7×50s is obvious at low power, but it doesn't dominate the view of the cluster like it did earlier that same night in binoculars.

M44 is much too large for my observatory's 16-inch Newtonian, but its brilliant stars show their colors well in that scope. The brightest jewel in each of M44's three triangles is golden; two triangles also boast a blue star.

The huge **Hyades** is a cluster for the unaided eye and binoculars. The V-shaped group represents the head of Taurus, the Bull, and its brightest star — orange Aldebaran — his angry eye. But Aldebaran is actually a foreground star at a distance of about 65 light-years, while the cluster lies at around 150 light-years. Two easy, wide, naked-eye pairs lie on or near the left-hand stalk of the V. Theta^1 (θ^1) and Theta^2 (θ^2) Tauri are about 5.8′ apart, while Sigma^1 (σ^1) and Sigma^2 (σ^2) Tauri are 7.4′ apart. In the latter pair, only the brighter component, Sigma^2 (magnitude 4.7), is a cluster member. The fainter pair of 80 Tauri and 81 Tauri is just as wide as the Theta pair, but I had to use my 7×50 binoculars to make the split. The 7×50s "widen" the V by adding many more stars — I counted about 87 in total.

If you have a dark sky, look for the naked-eye cluster **NGC 1647** (a William Herschel discovery from 1784) at the open end of the Hyades. My 8-inch at 76× reveals about 80 scattered, fairly equal-magnitude stars in the cluster, and a bright wide pair marks the center.

Big and showy **NGC 2451** in Puppis is obvious with the unaided eye. It consists of two clusters superimposed along our line of sight, with NGC 2451B some 400 light-years (or more) farther away than NGC 2451A, which is at around 600 light-years. My first view of it and adjacent **NGC 2477** was in November 1996 through my 7×50s from downtown Faro, Portugal, at latitude 37°N from the roof of an apartment building across the street from the ocean. This was on the night that I first saw Canopus skimming the waves, extremely low over the

▼▶ **YEAR-ROUND DELIGHT** The shimmering Perseus pair NGC 869 and NGC 884 are known as the Double Cluster. For many northern latitudes, the duo are circumpolar, i.e., they never set, which means you can enjoy them all year round. Remember to check them out next August when you're out looking for Perseid meteors.

DOUBLE CLUSTER: RON BRECHER; ALL SKETCHES BY GUY MACKIE

Atlantic. It's remarkable how much darker the sky is once you're well above the streetlights, even downtown in a city.

Two years later at Kentucky's Twin Lakes Star Party (also at latitude 37°N) in my 4.2-inch rich-field telescope at 16× and 64× the arresting big splash of mixed bright and dim stars of NGC 2451 — anchored by the brightest cluster member, orange c Puppis — was very nice. High in Australian skies, the same scope added a diamond of four stars on the southwestern side of c Puppis, and a second fainter orange ember on the northeastern side. NGC 2477 is well within the same 16× field of view. At Organ Pipe Cactus National Monument in Arizona, my 8-inch at 203× showed it as a marvelous, rich, and compressed equal-magnitude group resembling the globular cluster M55, except that there are several voids.

Back in Australia through Tony Buckley's 14.5-inch at 81× the cluster reminded me of seats in an amphitheater since many of its stars are arranged in broad concentric arcs. I barely detected three orange sparks with this aperture. NGC 2477 at 111× in the 30-inch at OzSky Star Safari shone with hundreds of equal-magnitude gems in short lines. Beautiful!

Let's Meet Some Messiers

Gemini's **M35** is another fairly easy naked-eye object. Swiss astronomer Jean-Philippe Loys de Cheseaux discovered it around 1745.

In my 8-inch at 44× the cluster is large with bright stars. It features three star streamers, several doubles, and some multiples. Don't miss the adjacent little arrowhead-shaped cluster **NGC 2158**, another of William Herschel's finds (from 1784).

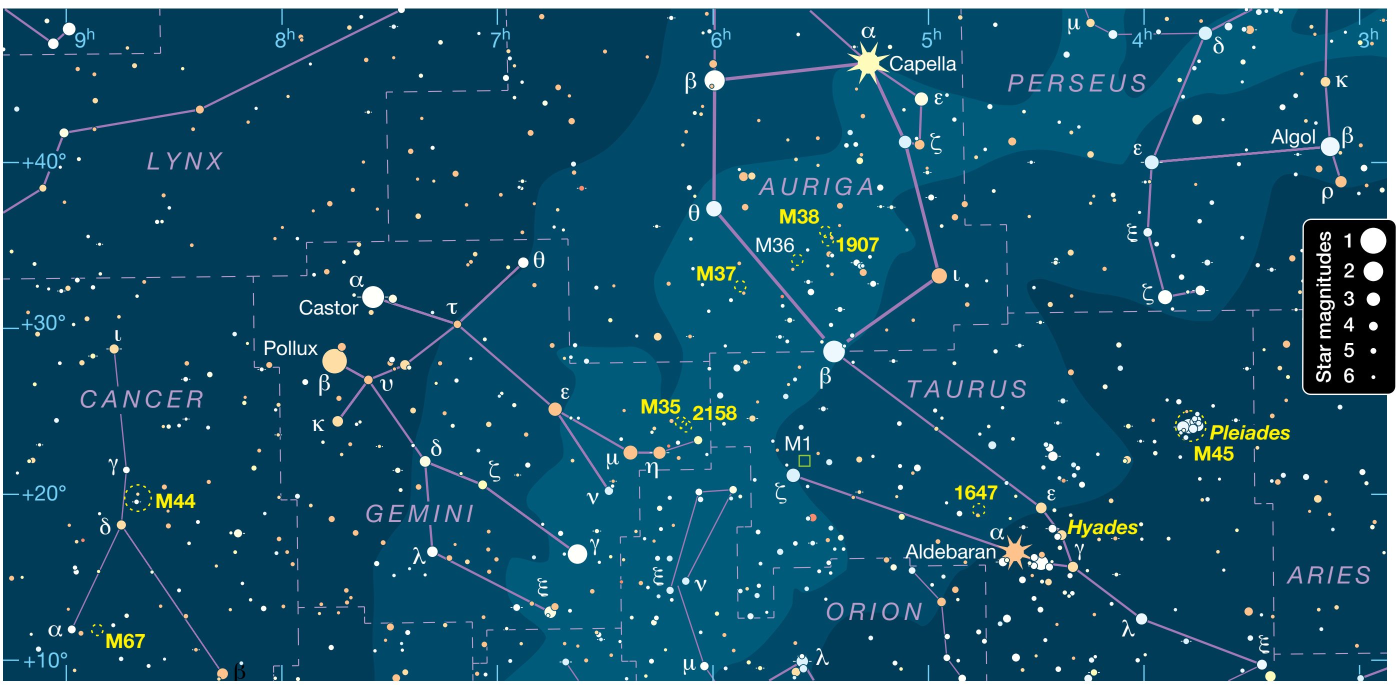
◀ **PEEKABOO IN THE GLARE** IC 349 is also known as Barnard's Merope Nebula in honor of its discoverer and is not to be confused with the Merope Nebula. This teensy patch is easy to miss in the glare of bright Merope, and you'll likely need an occulting bar to aid you (see, e.g., Sue French's article in the February 2006 issue of the magazine).

In my 16-inch at 141× M35 is a bright, rich cluster of mostly fairly equal-magnitude stars, with a few brighter ones. Compared with my 8-inch, the bigger scope adds many more doubles and three orange stars, including the fine orange and blue pair OΣ134 at the northeastern end of the prominent central arc of stars. More arcs of stars are on the eastern edge of M35 and reach out towards orange, 5.8-magnitude 5 Geminorum. Small and dense NGC 2158 is six times more distant than M35, but NGC 2158 showed about 15 resolved stellar pinpoints against the background glow.

American journalist and astronomer Charles Edward Barns noted that **M41** was "possibly the faintest object recorded in classical antiquity." Given the attention that the ancients paid to Sirius, they could hardly miss noticing such an obvious naked-eye "cloudy spot" only 4° to the star's south.

Through my 80-mm refractor at 67× M41 is well-separated from the field. It shows about 75 fairly equally spaced stars, three pairs, and a semicircle of stars in the center. I can just detect color in the central orange star. My 8-inch at 51× adds star streamers, and a backwards question mark on the northern side. Long, nested arcs of stars surround M41's red giant heart, and I can see two other fainter embers.

Sicilian Giovanni Battista Hodierna discovered the three Messier clusters in Auriga around 1654. I can glimpse all of



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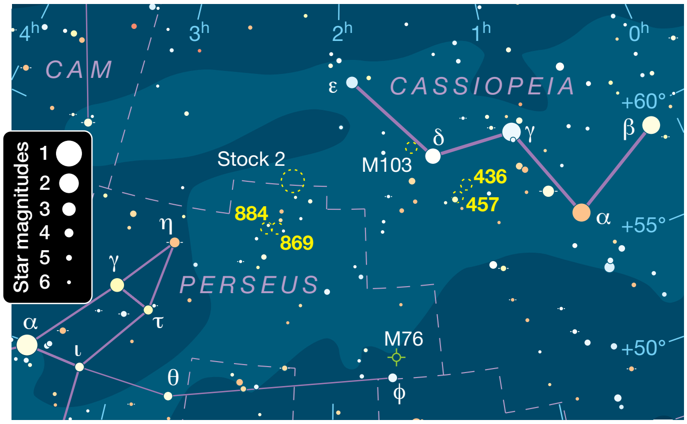
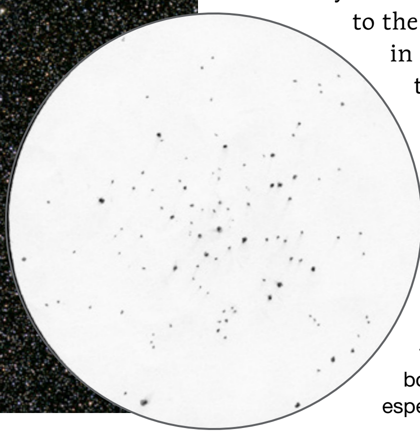




them with my unaided eyes from my backyard on superior nights. Here we'll examine two of the three.

M37 is the richest of the trio. The 80-mm refractor at 67× showcases a well-separated group of about 65 equal-magnitude sparkles. Its center is denser and contains a clump of 15 stars. I can just detect the color of the orange star in the middle, and that's only because I know that it's there from previous views with bigger scopes. With M37 centered, a bright-gold star lies at the south-southwestern edge of the 1.2° field.

The 16-inch at 73× reveals a marvelous dense throng of similar-magnitude jewels in clumps. An S-shaped star streamer in the middle has the central orange star at its northern tip. Fainter orange ones are on the cluster's western and eastern edges.

M38, viewed with my 80-mm at 67×, shows about 35 fairly faint stars of about equal magnitude, reminiscent of the Greek letter Pi. But with bigger glass I've always thought that M38 resembled the constellation Perseus. I easily found the unresolved blur of **NGC 1907** (a Herschel discovery from 1787) to the south just by sweeping around; no chart was needed. The smaller cluster is rich and compressed in my 8-inch at 61×.

The 16-inch on M38 at 141× showed five golden gems. Three are in a line — two in the lower end of the eastern leg of the Perseus constellation look-alike, and one in the center. The fourth star ornaments the western leg, and the brightest one is just north of that leg.

Bagged It!

Decades ago, Schaaf, who observes from the southern New Jersey pine barrens, told me that he could see Cancer's **M67** naked-eye. I had tried and failed many times.

I'm 75 so it has been years since I've driven up into the mountains, knowing that I would have to drive home late at night while trying to stay awake. But last April 13th the sky was so clear I could cover the Sun with my fist held at arm's length and see deep blue right up to the edge of my hand — no aerosols degraded the transparency. So, that evening I drove up a washboard gravel road to 5,110 feet altitude. Not a single artificial light was visible, not even a red light on some distant tower. The 7,500-foot-high bulk of Mount Baldy hid the light domes from Penticton and Kelowna to the north. The first larger town to the south in Washington State is Moses Lake, and it lies two-thirds of the way across the state. *The sky was utterly gorgeous*, and there was no automobile traffic to affect my dark adaption.

◀ **GUARDED BY THE DOG** Blazing Sirius is a great place to start your search for M41 — aim a bit less than 4° almost due south of the star. A lovely sight in telescopes, the cluster is a great target for binoculars, too. You should be able to fit both M41 and Sirius in the same field of view for an especially sparkly treat.

CEDIC TEAM / BERNHARD HUBL / CCDGUIDE.COM

That night I saw magnitude-6.9 M67 with the unaided eye for the first time!

In my 16-inch at 140× rich M67 is quite attractive: There are triangles, diamonds, and concentric arcs of equal-magnitude stars. I also see dense little clumps of stardust in several places amid the predominantly brighter cluster members. A yellow star — possibly a field star — sits on the northeastern edge.

Reminiscences

I found **M47** independently as a youngster. We neighborhood kids used to raid the orchard at the nearby women's prison farm. Not that we really wanted the apples; the thrill was in being chased by an angry guard. (I was never the hindmost, so I never felt the sting of rock salt.) But I'm sure that I was the only kid who also climbed the fence into the jail's grounds at night. The attraction? The prison farm was a large, streetlight-free zone, and one night from "inside" I noticed a naked-eye glow in the Puppis Milky Way, which my 1959 edition of *Norton's Star Atlas* labeled with its Herschel number, 38^8. Years later I learned that my find was eventually recognized as M47. (M47 had been one of the missing Messiers.) Dad's binoculars added nearby **M46**, one of Charles Messier's discoveries from 1771.

Through my 8-inch Dob at 94× M47 is bright and loose with a matched double, Σ1121 (magnitudes 6.9 and 7.3 with a separation of 7.4″), in the central clump. A magnitude-5 deep-orange star, KQ Pup, lies ½° west of M47. Adjacent M46 is much fainter, but it's richer with equal-magnitude diamond-dust sparkles, mostly in star chains. The planetary nebula NGC 2438's obvious disk adorns the cluster's northern margin, but it's probably a foreground object. Another magnitude-4.9 deep-orange star lies just southwest of M46.

My 16-inch view of M47 at 114× was: "Coarse with scattered bright to very bright stars, filled in with fainter ones. An adjoining equal-magnitude open cluster, NGC 2423, lies immediately north." M46 is rich and well-separated from the field with about 200 equal-magnitude white diamonds, some in arcs, and it's well concentrated. A star that appears to be the central star of the planetary nebula can't be, since the true central star's magnitude is only 18.

Alien, Owl, or Dragonfly?

Cassiopeia's **NGC 457**, a William Herschel discovery from 1782, has far more common names than any other open cluster. The currently most popular three are the E. T. Cluster (inspired by the 1982 movie of that name), the Owl Cluster, and the Dragonfly Cluster.

My 4.2-inch rich-field telescope at 44× shows 30 stars mak-

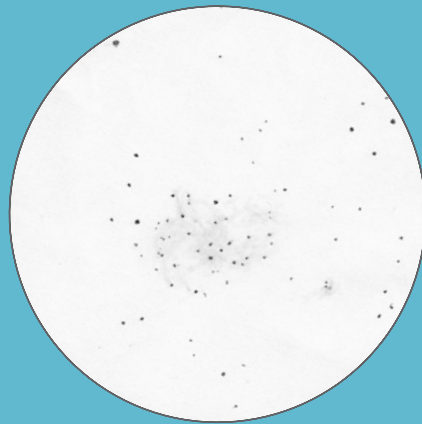
Naked-Eye Wonders

We're told that an observer's naked-eye acuity declines as they age. But I used to wear thick glasses, so my naked-eye averted vision meant looking at an angle through thick lenses. When I had cataract surgery in 2013 I had my eyes optimized for infinity and my astigmatism corrected. So now my naked-eye observing is really naked-eye: without glasses. But I had not tried for challenging objects after cataract surgery from a superb site until that memorable night when I bagged M67.

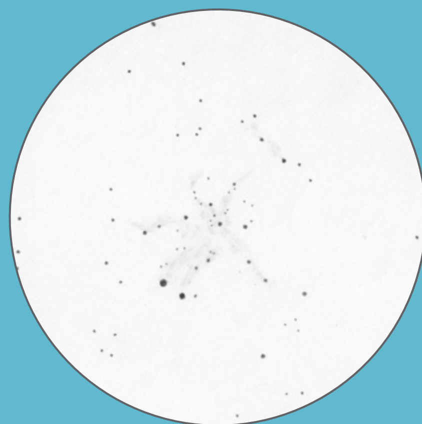
That April night, I felt inspired and continued scanning the sky. Several people have seen the magnitude-6.9 Ursa Major galaxy M81 with the unaided eye, but I never had. I also managed to spot M81 with the naked eye under that superb sky! It's always wonderful when you know that you have just formed a lifetime memory.


TWO FOR ONE Separated by 1½° in Puppis, NGC 2477 and NGC 2451 can present a delightful sight in the same field of view. Orange c Puppis lies at the center of NGC 2451 like a glowing ember. NGC 2477 was discovered by Nicolas-Louis de Lacaille in or around 1751, while John Herschel reported seeing NGC 2451 in 1835 (although it, too, may have been a prior Hodierna discovery).

TEAM CHAMELEON / WOLFGANG PAECH / FRANZ HOFMANN



◀▲ **ANCIENT CLUSTER** M67, discovered by German astronomer Johann Gottfried Köhler some time before 1779, is a very old conglomeration of stars whose formation dates back some three billion years. You'll find it in the southern reaches of Cancer, about 8° south-southeast of the Beehive.



◀▲ **MASTER OF MONIKERS** A favorite to many, NGC 457 takes on as many forms as people have imagination. It's been likened to the lovable alien from the 1982 movie, an owl, a dragonfly, and even a kachina doll, among many other things. What do you see?

ing a stick-figure alien, owl, or dragonfly. The brightest star, Phi Cassiopeiae, a multiple-star system, represents one of the eyes — of any of the three figures. Cluster membership isn't certain, but recent Gaia data suggest that Phi Cassiopeiae does indeed lie at the distance of NGC 457. The brightest component of the star system, Phi^1 Cassiopeiae, is one of our galaxy's most luminous stars, a yellow supergiant of absolute magnitude –8.76. The second-brightest star in the cluster (HD 7902), the other eye, is pale blue. The main clump forms the body, and five or six stars represent each arm or wing. If the long axis of the cluster is extended two lengths northwestwards, the faint blur of **NGC 436** appears, with four resolved stars.

My 16-inch at 114× increases NGC 457's star count to about 95, with a large range in brightness. They are denser in the body with quite a few doubles and two trios. Orange stars form the shoulder of the alien's northeastern arm and foot. The E. T. Cluster is always a big hit at public star parties. Surprisingly, even children have usually seen the movie, and they can see the figure of the endearing alien.

What your scope will show you in any cluster depends on what sort of patterns your brain discerns in a throng of stars. Also, more than with any other class of deep-sky object, open clusters can look quite different with different apertures. But no matter what optics you use, I hope you enjoy these winter clusters as much as I do.

■ Contributing Editor **ALAN WHITMAN**'s favorite open cluster is the bright, large, and very rich NGC 3532 in Carina. Many long strings of similar-magnitude stars form the Football Cluster's overall shape.

RON BRECHER (2)

Pushing Boundaries

FEAR OF A BLACK UNIVERSE: *An Outsider's Guide to the Future of Physics*

Stephon Alexander
Basic Books, 2021
245 pages, ISBN 9781541699632
US$28, hardcover

EARLY IN *Fear of a Black Universe*, Stephon Alexander describes giving his first professional talk. His topic was iconoclastic, but he felt confident, having just published a paper on it in the *Journal of High Energy Physics*. But the audience of physicists kept interrupting him with skeptical questions and comments.

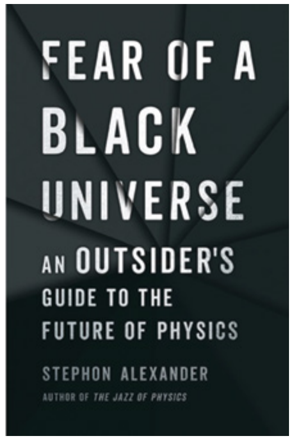
"Then came a voice from the back of the room," Alexander recalls. Everyone shushed as a distinguished Indian physicist in his 70s stood up. "Let him finish!" the old man said. "No one ever died from theorizing."

Now a professor of physics at Brown University, Alexander recalls that moment as "the biggest lesson with the fewest words" he could have learned about the art of doing theoretical physics. It's a lesson he has since taken to heart in his career tackling the most bracing questions. This book showcases that propensity in a captivating way.

> "It is even crazier that we came into being to even be able to ponder these questions."

Alexander raises one provocative question after the next. How does life emerge from a finite collection of chemical elements that are themselves lifeless? Is there some undiscovered link between quantum mechanics and consciousness? How is it that the classical universe of planets and people emerged, as physicists think it did, from quantum beginnings just after the Big Bang? Is there a link between the origin of life and the expansion of the universe?

Even as we contemplate these questions, Alexander offers refreshers on some of the field's major findings over the past century and more, from Einstein's mass-energy relation and general relativity to the concepts of emergence and entanglement. He returns multiple times to the profound mystery revealed by the famous double-slit experiment: How is it that an electron behaves like a wave until we observe it, when it reveals itself as a particle?



This weirdness is hard enough for us to grapple with today, but its implications for the early universe are truly out there. If a particular quantum state doesn't reveal itself until it's measured, then what happened to make the infant universe settle into the single state we know now? The book's title gets at such unilluminated realms, including the grand enigmas of dark matter and dark energy, about which physicists remain as in the dark as when those mysteries were first discovered.

But the title encapsulates another theme: a fear of outside-the-box thinking and those who do it. Today, Alexander says, theoretical physics suffers from a sense of dissatisfaction, a feeling that in recent decades researchers have been unable make discoveries as groundbreaking as relativity and quantum mechanics were a century ago.

"Why is this?" he asks. "Is it because these problems are too hard for us? Or is it that in the search for the truth, some scientists are afraid to look at uncharted or forbidden territories, afraid because there may be penalties, reputational and professional, for stepping outside accepted paradigms? I think it's the latter."

Alexander thrives on the uncharted and forbidden. As a Black man born in Trinidad and Tobago, he has always felt an outsider in the predominantly white man's world of theoretical physics — yet another of the book's themes. But he sees this as an advantage, along with being a self-described "positive deviant" who can shake up the order in creative ways. As he notes, scientists on the margins feel less pressure to keep within their field's constraints than those who "fit in." "Perhaps it is time," he writes, "to value and elevate minorities . . . not in spite of their outsider's perspective, but because of it."

As for those positive-deviant ideas, they keep coming in a quiet crescendo. Alexander wonders if quantum computers operated by advanced alien civilizations might explain the mystery of dark energy. He asks if consciousness, like charge and quantum spin, might exist to some degree in all matter, from humans right down to cosmic dust, and whether our consciousness is a subset of a cosmic mind.

"If you find this line of reasoning preposterous," he writes about that last thought, "it is even crazier that we came into being to even be able to ponder these questions." He ends the book abruptly, as if in mid-thought, which is essentially where he finds himself.

■ Editor in Chief **PETER TYSON** enjoys musing on the biggest questions, even if he has no hope of answering them.

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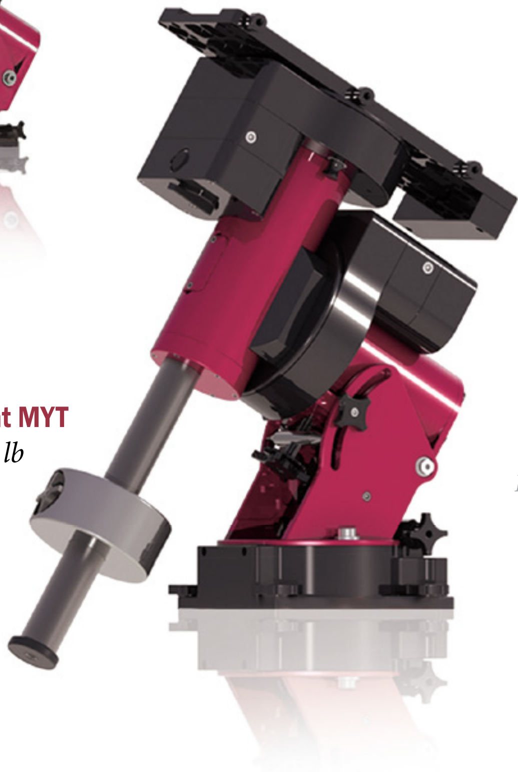

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2 **DUSK:** Look toward the west-southwest to see the thin crescent Moon, just one day past new, some 4° lower left of Jupiter. (Turn to page 46 for more on this and other events listed here.)

8 **DUSK:** High in the south-southwest, the first-quarter Moon gleams around 6° below the Pleiades.

8 **EVENING:** Algol shines at minimum brightness for roughly two hours centered at 10:42 p.m. PST (see page 50).

9 **EVENING:** The Moon poses prettily between Aldebaran and the Pleiades in Taurus.

11 **EVENING:** Algol shines at minimum brightness for roughly two hours centered at 10:31 EST (7:31 p.m. PST).

13 **EVENING:** The waxing gibbous Moon visits Gemini and lines up with the twin lights of Castor and Pollux.

14 **EVENING:** Algol shines at minimum brightness for roughly two hours centered at 7:21 p.m. EST.

16 **DUSK:** The full Moon and Regulus rise in tandem in the east; around 5° separates the pair in Leo.

18 **EVENING:** If you can find a dark viewing spot away from city lights, face west after sunset and starting tonight you might spot the soft glow of the zodiacal light (see page 48). Look for a faint, hazy pyramid of light stretching up through Taurus into Gemini and beyond. Enjoy this sight for the next two weeks or so.

20 **EVENING:** The waning gibbous Moon is in Virgo and trails Spica by about 5½° as they pop above the east-southeastern horizon.

24 **MORNING:** Early risers will see the just-past-last-quarter Moon some 3° left of the Scorpion's heart, Antares. The duo climb higher in brightening twilight.

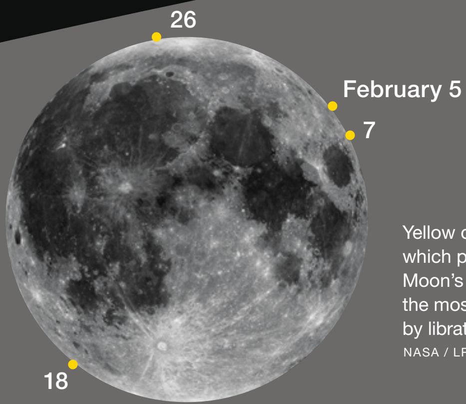
27 **DAWN:** The waning crescent Moon, ruddy Mars, and brilliant Venus grace the southeastern horizon. Catch this sight before day breaks.
— DIANA HANNIKAINEN

▲ The open star cluster M46 in Puppis, the Stern, appears to sport an extra jewel in the form of a planetary nebula. In fact, NGC 2438 is most likely a foreground object. Read more on this and other open clusters that sparkle in winter's skies on page 32.
N. A. SHARP / NOIRLAB / NSF / AURA

FEBRUARY 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					

NEW MOON
February 1
05:46 UT

FIRST QUARTER
February 8
13:50 UT

FULL MOON
February 16
16:56 UT

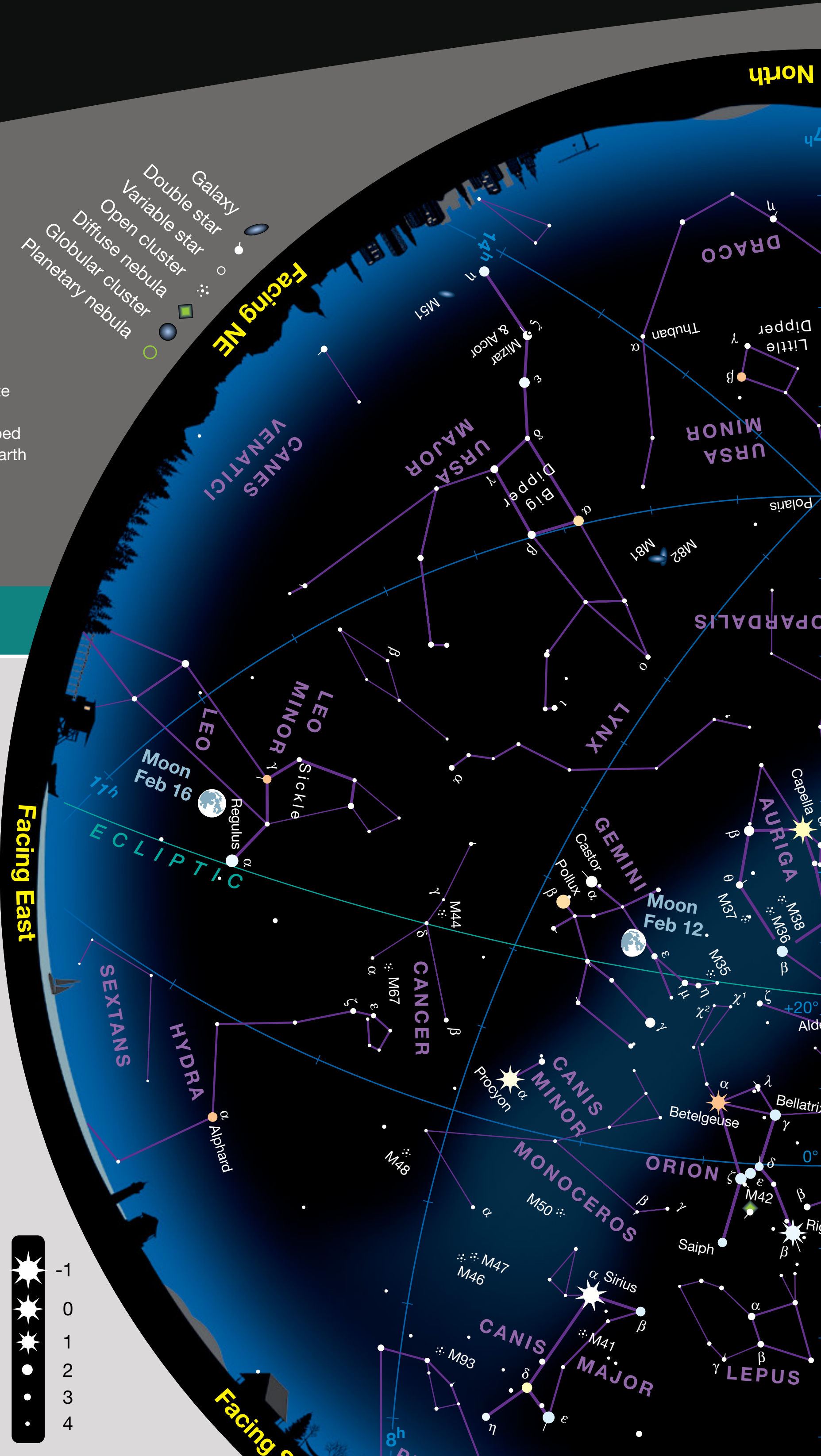
LAST QUARTER
February 23
22:32 UT

DISTANCES

Apogee	February 11, 03^h UT
404,896 km	Diameter 29′ 31″
Perigee	February 26, 22^h UT
367,789 km	Diameter 32′ 29″

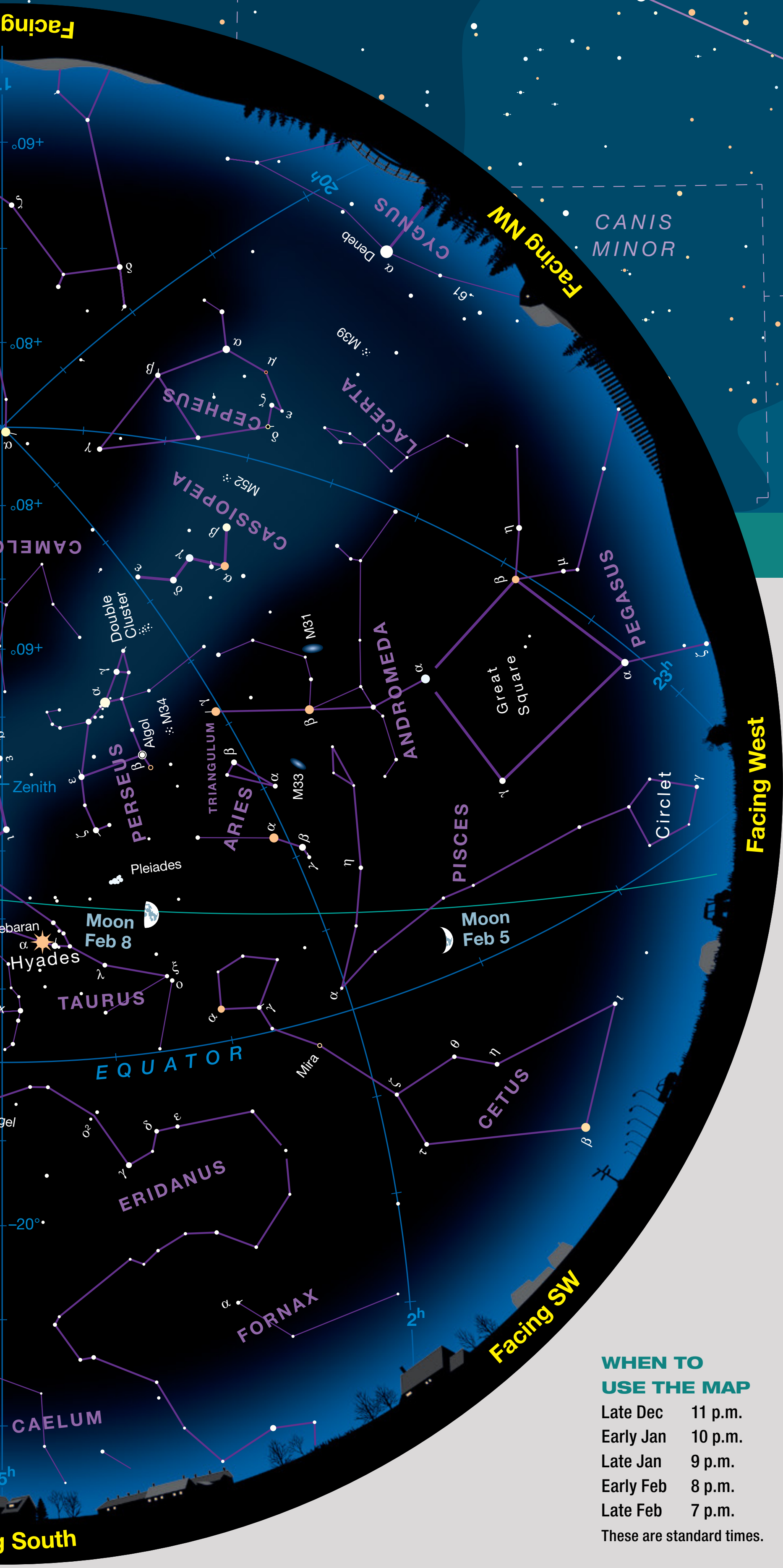
FAVORABLE LIBRATIONS

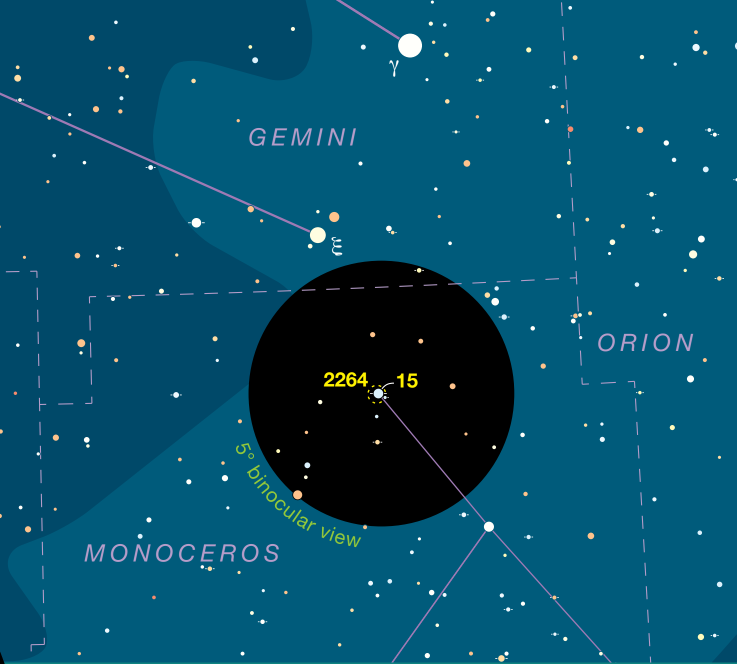
- Goddard Crater February 5
- Hubble Crater February 7
- Mare Orientale February 18
- Carpenter Crater February 26



Planet location shown for mid-month

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





WHEN TO USE THE MAP

Late Dec	11 p.m.
Early Jan	10 p.m.
Late Jan	9 p.m.
Early Feb	8 p.m.
Late Feb	7 p.m.

These are standard times.

Binocular Highlight by Mathew Wedel

Topsy-turvy Tree

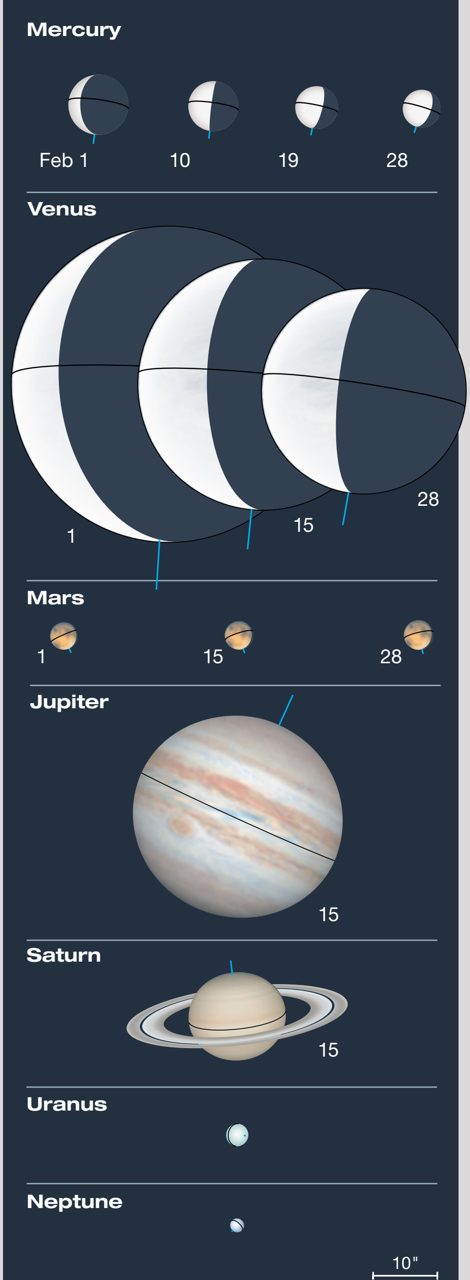
Our target this month is **NGC 2264** in the constellation Monoceros, the Unicorn. More specifically, it's the Christmas Tree Cluster within NGC 2264. I have to specify the cluster because technically the NGC 2264 designation also includes the Cone Nebula, which, even if an interesting feature, is more of a challenge object for folks with dark skies and big scopes. In contrast, at 4th magnitude and almost ½° across, the Christmas Tree Cluster is big enough and bright enough to be truly rewarding in binoculars.

To find NGC 2264, start with Xi (ξ) Geminorum, the eastern foot of the eastern Twin in Gemini. Scan slightly more than 3° south-southwest to find **15 Monocerotis**, a 5th-magnitude blue-white star that sits at the base or trunk of the Christmas Tree asterism. For Northern Hemisphere observers, the Christmas Tree is upside-down in binoculars when it culminates, pointing south like an arrow. Some asterisms require a little "averted imagination" to see, but not this one: It really does look like a Christmas tree.

The cluster is part of Monoceros OB1, a nearby association of bright young stars that sprawls along the backbone of the Milky Way from the celestial equator almost to the feet of Gemini. The entire area is spangled with open clusters, asterisms, and multiple stars almost beyond counting. Most of the stars in Monoceros OB1 formed just within the last 3 million years. That's a long time for us, going back to when our australopithecine ancestors were knocking rocks together in East Africa, but barely an eyeblink in astronomical time — less than 1⁄1000 of the age of the Sun. Grab your binos and go get acquainted with the new neighbors.

■ MATT WEDEL sometimes gets lost in the woods in Monoceros, but always enjoys finding his way back.

Planetary Almanac



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

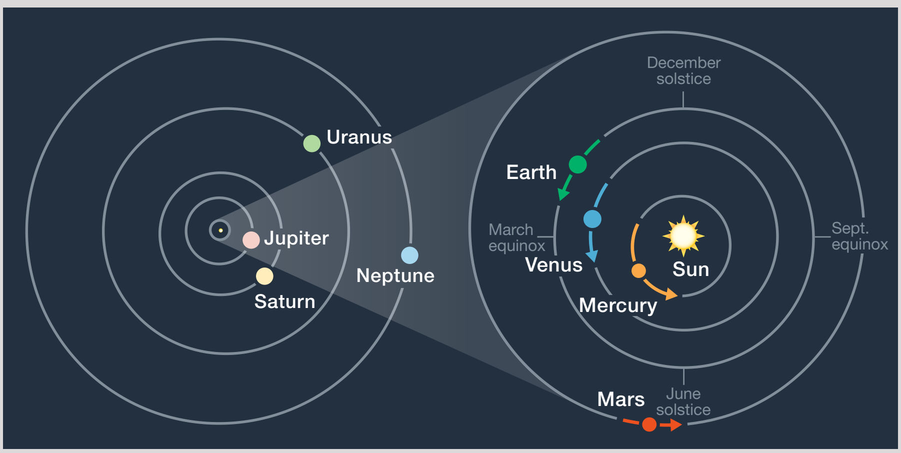
▶ **ORBITS OF THE PLANETS** The curved arrows show each planet's movement during February. The outer planets don't change position enough in a month to notice at this scale.

PLANET VISIBILITY (40°N, naked-eye, approximate) **Mercury** visible at dawn until the 26th • **Venus** and **Mars** visible at dawn all month • **Jupiter** visible low in the west-southwest at dusk until the 21st • **Saturn** lost in the Sun's glare all month.

February Sun & Planets

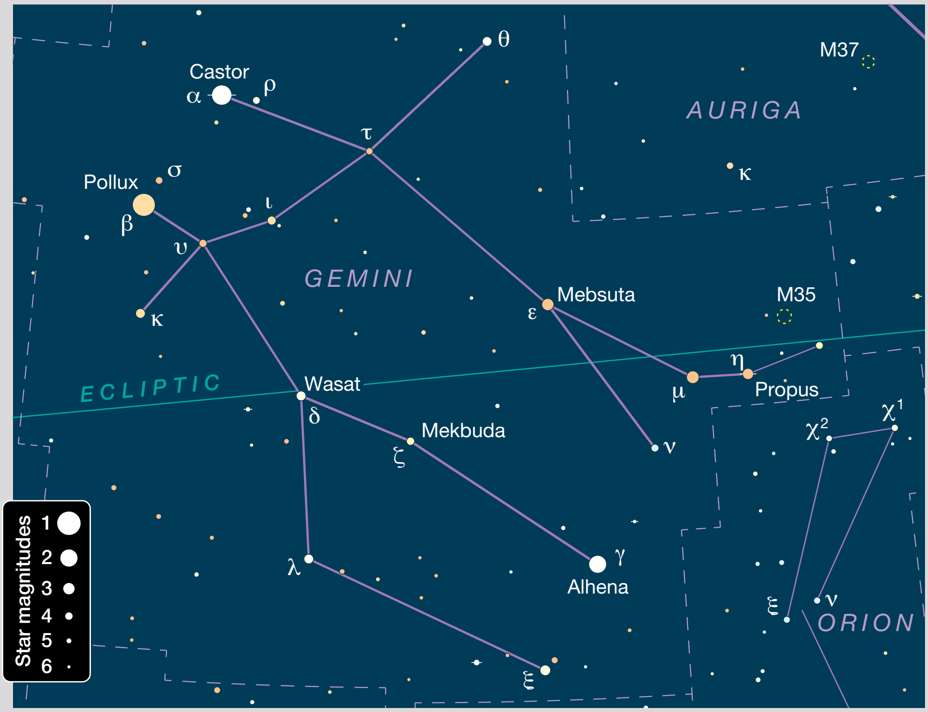
	Date	Right Ascension	Declination	Elongation	Magnitude	Diameter	Illumination	Distance
Sun	1	$20^h\ 57.0^m$	–17° 15′	—	–26.8	32′ 28″	—	0.985
	28	$22^h\ 42.6^m$	–8° 10′	—	–26.8	32′ 18″	—	0.990
Mercury	1	$19^h\ 44.3^m$	–18° 03′	17° Mo	+1.2	9.4″	20%	0.716
	10	$19^h\ 50.5^m$	–19° 26′	25° Mo	+0.1	7.8″	46%	0.862
	19	$20^h\ 24.6^m$	–19° 22′	26° Mo	–0.1	6.7″	64%	1.009
	28	$21^h\ 11.3^m$	–17° 35′	24° Mo	–0.1	5.9″	75%	1.135
Venus	1	$18^h\ 45.2^m$	–16° 16′	32° Mo	–4.8	49.2″	15%	0.339
	10	$18^h\ 55.2^m$	–16° 38′	38° Mo	–4.9	42.4″	23%	0.393
	19	$19^h\ 15.2^m$	–16° 57′	42° Mo	–4.8	36.7″	31%	0.455
	28	$19^h\ 42.4^m$	–16° 58′	45° Mo	–4.7	32.0″	37%	0.521
Mars	1	$18^h\ 22.4^m$	–23° 50′	37° Mo	+1.4	4.3″	96%	2.166
	15	$19^h\ 07.2^m$	–23° 12′	41° Mo	+1.3	4.5″	95%	2.082
	28	$19^h\ 48.5^m$	–21° 56′	44° Mo	+1.3	4.7″	94%	2.002
Jupiter	1	$22^h\ 36.0^m$	–9° 53′	25° Ev	–2.0	33.6″	100%	5.861
	28	$23^h\ 00.0^m$	–7° 27′	4° Ev	–2.0	33.0″	100%	5.968
Saturn	1	$21^h\ 11.6^m$	–17° 05′	4° Ev	+0.7	15.3″	100%	10.897
	28	$21^h\ 24.4^m$	–16° 09′	21° Mo	+0.8	15.3″	100%	10.828
Uranus	15	$2^h\ 34.2^m$	+14° 43′	75° Ev	+5.8	3.5″	100%	19.951
Neptune	15	$23^h\ 30.9^m$	–4° 22′	26° Ev	+8.0	2.2″	100%	30.807

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**.



The Other Gems of Gemini

The celestial Twins are more than a famous pair of bright stars.



To lovers of mythology, Gemini brings to mind Castor and Pollux, the mighty twin brothers of ancient Greek legends. But to lovers of the night sky, Gemini means Pollux and Castor — a pair of bright stars shining only 4½° apart. However, there's a lot more to see in Gemini than its famed pair of luminaries. Telescope users know the constellation for deep-sky treasures such as the bright open cluster M35, but the Gemini attractions I mainly want to focus on are those visible to the naked eye.

Pollux and Castor mark the imagined heads of the mythological twin brothers they're named for. Two nearly parallel lines of moderately bright stars run in a southwesterly direction from Pollux and Castor, outlining the bodies of the Twins and pointing toward Orion and Taurus, respectively.

The western foot of the twin Pollux is tipped with Gamma (γ) Geminorum, which is popularly known as both Alhena and Almeisan. Alhena seems to be from an Arabic phrase referring to "the brand mark," while Almeisan is derived from an Arabic word for either "shining" or "strutting." Alhena glows at magnitude 1.9, but consider this: Pollux shines at magnitude 1.2 and Castor at magnitude 1.6. That means Alhena is actually closer to Castor in brightness than the "twin" stars Castor and Pollux are to each other.

The western foot of Castor includes three stars and merits a full discussion of its own — something I'll tackle in a future column. For now, however, I want to note that the star in his foot called Propus, or Eta (η) Geminorum, is one of two fairly bright naked-eye stars in Gemini that is also variable. Propus is a semiregular, long-period variable star that ranges from magnitude 3.1 to 3.7 over a leisurely span of nearly 3,000 days. The star also has a shorter cycle that averages about 234 days. When it's at the bright end of its range, it's a little fainter than nearby Mu (μ) Geminorum; when it's dimmest, Propus is slightly brighter than neighboring Nu (ν) Geminorum.

A second bright and fascinating variable star in Gemini is in the eastern Twin's body and is known as Zeta (ζ) Geminorum, or Mekbuda. In contrast to Propus, Mekbuda is a star of short period and steady regularity. It is in fact one of the brightest Cepheid variables whose variations can be detected by eye. Mekbuda ranges from magnitude 3.6 to 4.2 over a period of 10.1 days. You can tell Mekbuda is near minimum brightness when it's markedly dimmer than Delta (δ) Geminorum, Wasat, the 3.5-magnitude star just a few degrees to its northeast.

Wasat is famous for being the star near which Pluto was discovered. Clyde Tombaugh first noted the little world on February 18, 1930, though his discovery wasn't announced until March 13th that year. How ironic is it that Pluto has such an inclined orbit, yet was discovered near a star extremely close to the ecliptic? Although Pluto's current designation is dwarf planet, until 2006 it ranked among the major planets — one of only three discovered since the invention of the telescope. Amazingly, Uranus — the first of the three to be discovered — was also first identified near a Gemini star. William Herschel identified the planet in March 1781 using his homemade 6-inch reflector telescope, when Uranus was roughly 6° west of Propus.

The constellation's best-known deep-sky object is near Propus: the big and bright star cluster M35. It's a fine binocular object and definitely visible to the naked eye in clear dark skies. Lying near the ecliptic, M35 is often visited by the Moon and planets. And so is nearby Epsilon (ε) Geminorum, also known as Mebsuta. This 3rd-magnitude star holds the distinction of having being occulted both by Mercury in 1940 and by Mars in 1976.

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

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

Planets Cluster at Dawn

Catch Mercury, Venus, Mars, and Saturn before sunrise.

WEDNESDAY, FEBRUARY 2

It's time to bid **Jupiter** farewell . . . for now. And stopping by for one final visit this Jovian apparition is the **Moon**. At dusk this evening, the beautifully earthlit lunar crescent sits 4° lower left of the magnitude –2.0 planet. Take a moment to soak in the sight because after this event the evening sky is going to become a pretty quiet place — at least so far as striking naked-eye solar system gatherings are concerned.

As noted below, the remaining naked-eye planets are clustered in the dawn sky, where they'll remain for months to come. Indeed, you'll have to wait until mid-April before any of them venture into the evening sky. As for our old friend Jupiter, it slips from naked-eye view around the 21st, ending an apparition that began last February. In the course of the past year, Jupiter slowly drifted eastward from Capricornus into neighboring Aquarius, where it's positioned now — the same constellation that the Sun currently occupies. Big Jove will have its conjunction with our home star on March 5th and begins a new apparition when it emerges at dawn at the end of that month.

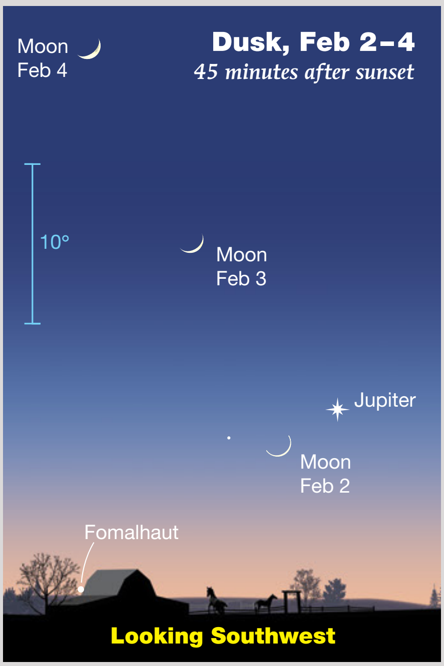
SATURDAY, FEBRUARY 5

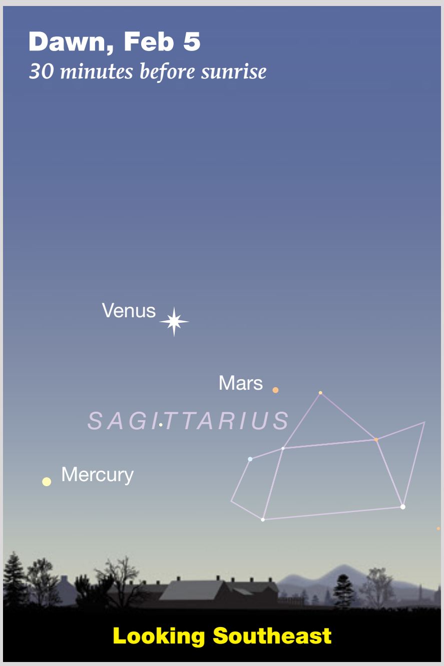
This morning and next, **Mercury** wanders as close to **Venus** as it's going to during its current appearance. This pairing of the two innermost planets probably sounds more enticing than it really is since they're separated by a generous 13°. But if we throw **Mars** into the mix, then we have something that's possibly worth setting an early alarm for. The Red Planet, found roughly 7½° lower right of Venus, forms an attractive right-triangle with its planetary neighbors. At magnitude –4.9, Venus anchors the group, followed by Mercury at magnitude +0.3, and Mars, which glows shyly at magnitude 1.4. Nice.

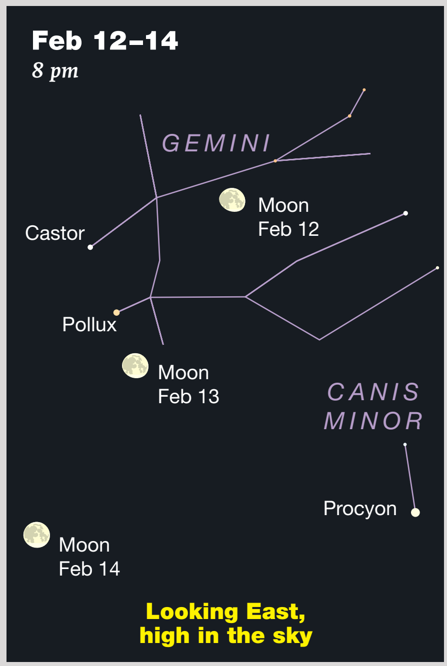
Want more enticement? How about this: Venus is about a week away from *greatest illuminated extent* (a measure of the planet's illuminated surface area as seen from Earth), which occurs on February 12th. However, the Morning Star is actually fractionally brighter before then and reaches *maximum brilliance* on the 7th (though this is *really* splitting hairs).

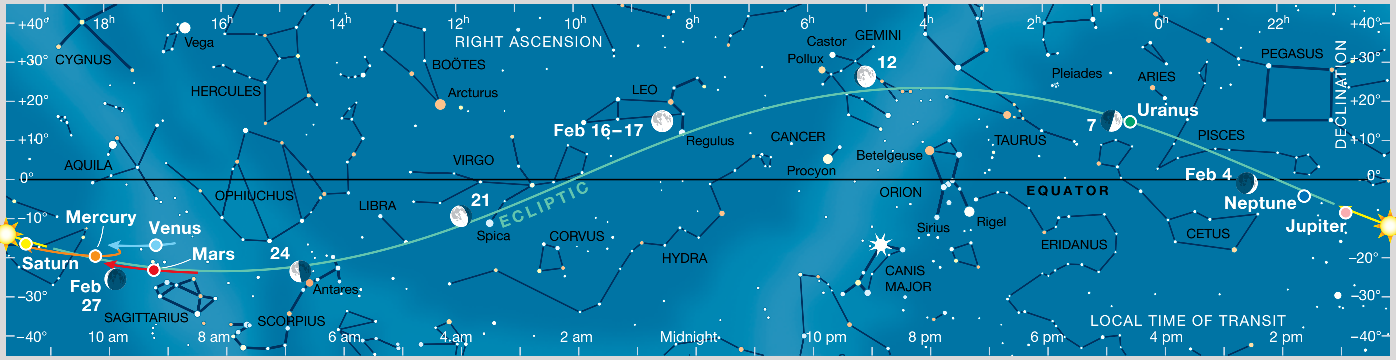
SUNDAY, FEBRUARY 13

High in the sky this evening, the waxing gibbous **Moon** forms a tidy three-in-a-row line with Gemini's leading lights:





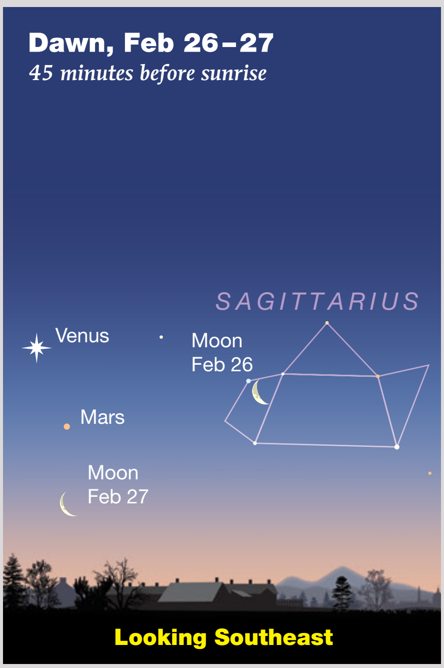




▲ The Sun and planets are positioned for mid-February; the colored arrows show the motion of each during the month. The Moon is plotted for evening dates in the Americas when it's waxing (right side illuminated) or full, and for morning dates when it's waning (left side illuminated). "Local time of transit"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

Castor and **Pollux**. If you're a stickler for perfection, time your viewing session for 9 p.m. EST (6 p.m. PST), when all three will be neatly aligned.

This conjunction also offers an interesting opportunity to note just how quickly the Moon moves across the sky. With Castor and Pollux as reference points, watch closely and after 10 minutes or so you should be able to notice that the Moon's position has shifted. Indeed, the Moon moves its own diameter in roughly an hour, on average. Of course, if you're a real stickler for symmetry, you'll also notice that the Moon is about 1° closer to Pollux than Pollux is to Castor.



WEDNESDAY, FEBRUARY 16

Mercury reaches its greatest elongation today when it's positioned 26° west of the Sun in the morning sky. However, for observers at mid-northern latitudes, the planet was highest at dawn on the 9th. You can thank the shallow angle the ecliptic makes with the eastern horizon at this time of year for that apparent discrepancy. However, even though Mercury's altitude was greatest on the 9th, it was also very slightly fainter, shining at magnitude +0.1 compared to 0.0 at greatest elongation. That's not much of a difference. The bottom line is that from a little before the 9th to after the 16th, you have a good chance to glimpse this fast-moving little world. Of the three Mercury morning apparitions in 2022, this one is second best.

THURSDAY, FEBRUARY 24

Each month the **Moon** swings by **Antares**, the brightest star in Scorpius, and one of the very brightest situated near the *ecliptic* — the path the Sun, Moon, and planets tread across the celestial sphere. Throughout 2022, the Moon approaches closer and closer to the star at each pass. However, local circumstances will have a lot to say about how close together they'll appear in the sky. In other words, if the Moon is nearest Antares when it's broad daylight where you live, the conjunction will be only so-so by the time it's dark. (Remember, the Moon moves about ½° every hour!) For their February get-together, the Moon and Antares rise in the southeast around 2 a.m. separated by less than 3°. That's a lovely naked-eye sight, but if you dig out your binoculars the view will be even better — the star's reddish hue will be enhanced and the delicate earthshine illuminating the "dark" portion of the lunar disk will be much easier to see.

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

SUNDAY, FEBRUARY 27

This morning there's a solar system traffic jam in progress at dawn. Most eye-catching is the striking 10°-long line comprising brilliant **Venus** (magnitude –4.8), ruddy **Mars** (magnitude 1.3), and the waning crescent **Moon**. And as if that weren't enough, look about 18° left of the Moon for **Mercury** (magnitude –0.1). Want even more? Haul out your binoculars and try for **Saturn**, now emerging from its February 4th solar conjunction. Sighting the low-lying, +0.7-magnitude ringed planet will be a real challenge, however. Aim your binos 4° left of Mercury to try to spot it.

■ A planetary traffic jam is the only kind of congestion Consulting Editor GARY SERONIK is happy to see.

Zodiacal Light Leavened With Martian Dust

The zodiacal light returns at dusk with a new twist.

▲ Towering past the Pleiades (center), the zodiacal light extends high in the western sky at nightfall. On late winter and spring evenings, the ecliptic's steep angle to the horizon elevates the softly glowing dust into a dark sky.

BOB KING

As winter begins to wind down, an early sign of seasonal change is the return of the zodiacal light in the evening sky. The phenomenon resembles a weak searchlight shining up from the horizon along the ecliptic. Like the Milky Way, the sight is both subtle and grand when observed under a dark sky.

As the photo above shows, the zodiacal light is a soft, tilted cone with its base near the sunset point. The glow spans about 25° across where it glows brightest and widest near the horizon. But as you trace the shape upward, it narrows and dims until it blends imperceptibly with the Milky Way some 80° away. No kidding — it really is that big. In the absence of light pollution, the plume transitions into the über-faint zodiacal band, which arcs across the sky.

When we look in the general direction of the Sun, the particles making up the zodiacal light strongly scatter sunlight forward toward our eyes to create the cone-shaped glow we see. The closer our line of sight is toward the Sun, the greater the scattering, which is why the light appears brightest near the horizon.

▶ Both the winter Milky Way and the zodiacal light gently glow in this panorama captured at Dinosaur Provincial Park in Alberta, Canada.

ALAN DYER

Dust shed by sublimating comets and colliding asteroids has long been thought to serve as the source material, with comets contributing the bulk. However, in results published in a March 2021 paper, a team of scientists working with data collected by NASA's Juno spacecraft suggest that much of the zodiacal dust may originate instead from Mars. As Juno traveled between Earth and the asteroid belt en route to Jupiter, one of the probe's star-tracker cameras serendipitously recorded minute flashes of light as dust particles chipped flecks of paint off the probe's solar arrays. Enough "hits" were recorded to map the spatial distribution of the tiny grains.

The group determined that much of the zodiacal cloud truncates at Earth because our planet vacuums up the dust in its vicinity, while Jupiter's gravity acts as a barrier that keeps the grit at bay just beyond Mars's orbit. But between Mars and Jupiter, the dust's orbital properties closely resemble those of Mars itself, implicating it as the source.

There's just one problem: No one has yet figured how the dust escapes Mars's gravitational pull. And whatever that process is, it must have been active for millions of years in order to replenish the dust lost to Earth and the Sun. Potential sources include impacts on the Martian moons Phobos and Deimos, but again, it's unknown how the material departs the Martian system. (You can read the team's paper at **https://is.gd/zodiacal**.)

In late winter and spring, the zodiacal light becomes visible in the western sky shortly before the end of evening twilight. During autumn, the phenomenon appears in the eastern sky at dawn. It's during these times of year that the ecliptic lies at a steep angle to the horizon, tilting the zodiacal light cone higher into a dark sky and greatly improving its visibility.

At mid-northern latitudes, astronomical twilight lasts about 90 minutes in mid-February. The zodiacal glow first appears about 20 minutes before twilight's end and remains in view for up to several hours. Peak brightness and maximum extent occur right at the end of evening twilight in spring, and just before the start of morning twilight in fall. You don't need perfect skies, but you'll want to avoid moonlight. Upcoming Moon-free observing windows run from January 20th to February 2nd; February 18th to March 3rd; and from March 19th to April 3rd.

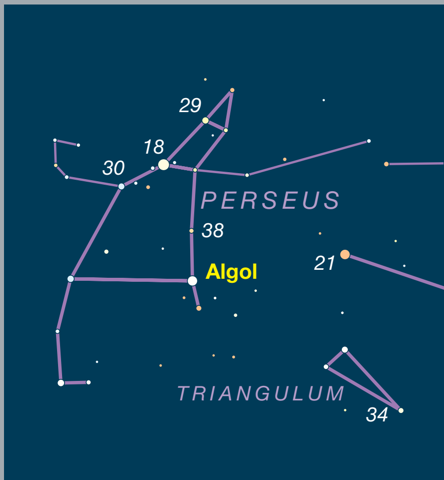
Two Lunar Occultations

Few sights ping the optic nerve like seeing a star suddenly disappear or reappear along the Moon's limb. It's a startling experience and illustrates just how devoid the Moon is of air — an atmosphere would cause the star to fade gradually instead of instantly wink out. Occultation timings are also used to measure stellar diameters and separate extremely close double and multiple stars.

On February 9th, the dark limb of the 65%-illuminated waxing gibbous Moon occults both Kappa^1 and Kappa^2 (κ^1 and κ^2) Tauri. The Kappa pair are separated by 5.7′ and shine at magnitudes 4.2 and 5.3, respectively. In the middle of North America, the event begins round 10:30 p.m. CST, though the time will vary considerably depending on your location. The occultation will be visible across most of the U.S. and Canada, but the double event excludes the far southern U.S., where the Moon only eclipses Kappa^1. For locations where the Moon passes centrally over the pair, the back-to-back disappearances occur just seconds apart.

A second noteworthy occultation occurs on the morning of February 22nd as the 66% waning gibbous Moon covers the double star Alpha (α) Librae, better known as Zubenelgenubi. The two Alpha components are a generous 3.9′ apart and twinkle at magnitude 5.2 (Alpha^1) and 2.7 (Alpha^2). The Zubenelgenubi eclipse will be visible for observers across the western three-quarters of the U.S., western Canada, Mexico, and parts of Central America. The bright limb of the Moon first covers dim Alpha^1 — a part of the show that may be tricky to see. The disappearance of Alpha^2, however, should be much easier to catch since it's considerably brighter. The potentially more dramatic moment happens when the stars pop out in rapid succession from behind the dark lunar limb.

The show starts around 5:45 a.m. CST, with the stars reappearing around 6:30 a.m. Once again, the exact time depends on where you're situated. For maps and up-to-date times for a variety of different cities for both events, consult the International Occultation Timing Association's website: **lunar-occultations.com/iota/iotandx.htm**.



▲ Perseus is positioned near the zenith during evening hours in February. Every 2.7 days, Algol (Beta Persei) dips from its usual magnitude 2.1 to 3.4 and back. Use this chart to estimate its brightness in respect to comparison stars of magnitude 2.1 (Gamma Andromedae) and 3.4 (Alpha Trianguli).

Minima of Algol

Jan.	UT	Feb.	UT
3	0:01	3	13:03
5	20:50	6	9:52
8	17:39	9	6:42
11	14:28	12	3:31
14	11:18	15	0:21
17	8:07	17	21:10
20	4:56	20	17:59
23	1:46	23	14:49
25	22:35	26	11:38
28	19:24		
31	16:14		

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

Action at Jupiter

THE CURRENT JUPITER APPARITION is drawing to a close as the planet sinks toward its March 5th conjunction with the Sun. After February 21st, Jupiter will essentially be unobservable to the naked eye and a poor telescopic target, owing to its low altitude and the resulting unsteady seeing conditions. On the 1st of the month, Jupiter has an altitude of roughly 21° at sunset and shines at magnitude –2.0 with a disk spanning just 34″. The planet will reappear at dawn in late March.

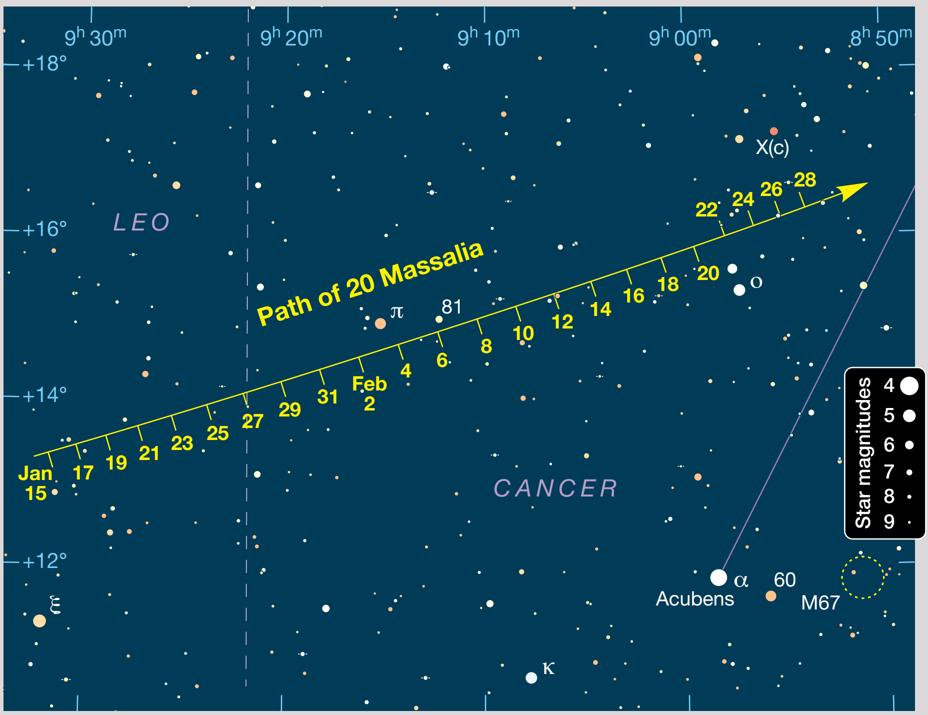
Any telescope reveals the four big Galilean moons, and binoculars usually show at least two or three. The moons orbit Jupiter at different rates, changing positions along an almost straight

Asteroid 20 Massalia at Opposition

ITALIAN ASTRONOMER Annibale de Gasparis discovered 20 Massalia on September 19, 1852. Over the next few nights, French astronomers Jean Chacornac and Benjamin Valz also independently found the object. De Gasparis had planned to name it Themis, for the goddess of justice, but Valz, unaware of the Italian discovery, dubbed it Massalia, the Greek name for the modern city of Marseilles. De Gasparis went along with the choice, making the asteroid the first one named for a place where you could buy a good baguette.

Massalia reaches opposition on February 4th, when it shines at magnitude 8.5 just 21′ southwest of 5.3-magnitude Pi (π) Cancri. The minor planet ends the month nearly a magnitude fainter and about 3° southeast of 3.9-magnitude Delta (δ) Cancri.

Massalia is a stony asteroid orbiting at an average distance of 2.4 a.u., with a period of 3.7 years. It heads up a large group of more than 6,000 space rocks called the Massalia family, all of which orbit the Sun at similar low inclinations. These fragments are thought to originate from an impact at Massalia itself 100 to 200 million years ago. Despite their number they represent only a tiny fraction of the mass of Massalia, which has a mean diameter of 146 kilometers (91 miles). Near opposition, small telescopes will show it with ease.



▶ During February, 20 Massalia makes its way across eastern Cancer. It reaches opposition on the 4th, when it shines at magnitude 8.5. (The asteroid's position is plotted for 0^h UT.)

line from our point of view on Earth. Use the diagram below right to identify them by their relative positions on any given date and time. All the observable February interactions between Jupiter and its satellites and their shadows are tabulated below. Find events timed for when Jupiter is at its highest.

Features on Jupiter appear closer to the central meridian than to the limb for 50 minutes before and after transiting. That's when details in the Jovian cloudtops (including the Great Red Spot) are most easily discerned.

Here are the times, in Universal Time, when the Great Red Spot should cross Jupiter's central meridian. The dates, also in UT, are in bold. (Eastern Standard Time is UT minus 5 hours.)

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

February 1: 3:22, 13:18, 23:13; **2**: 9:10, 19:05; **3**: 5:01, 14:57; **4**: 0:53, 10:49, 20:45; **5**: 6:41, 16:36; **6**: 2:32, 12:28, 22:24; **7**: 8:20, 18:16; **8**: 4:12, 14:07; **9**: 0:03, 09:59, 19:55; **10**: 5:51, 15:47; **11**: 1:43, 11:38, 21:34; **12**: 7:30, 17:26; **13**: 3:22, 13:18, 23:13; **14**: 9:09, 19:05; **15**: 5:01, 14:57; **16**: 0:53, 10:49, 20:44; **17**: 6:40, 16:36; **18**: 2:32, 12:28, 22:23; **19**: 8:20, 18:15; **20**: 4:11, 14:07; **21**: 0:03, 9:59, 19:54

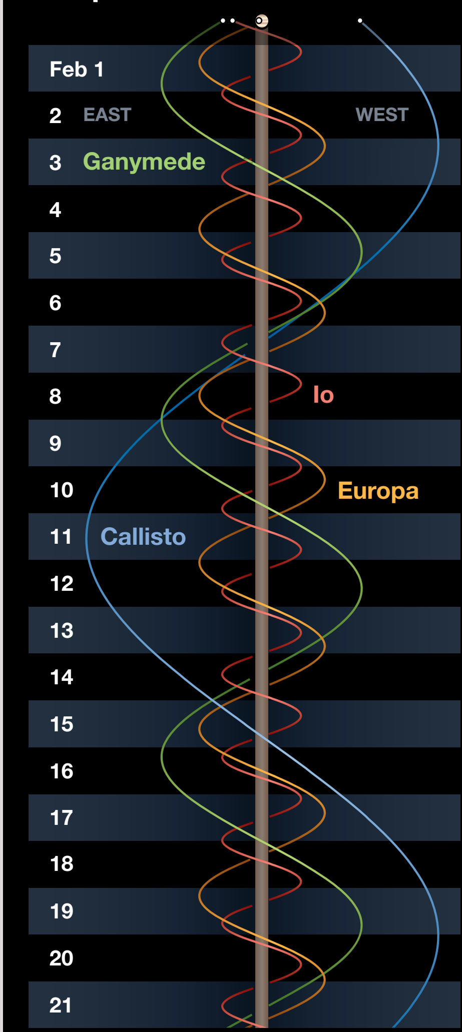
These times assume that the spot will be centered at System II longitude 11° on February 1st. If the Red Spot has moved elsewhere, it will transit $1\frac{2}{3}$ minutes earlier for each degree less than 11° and $1\frac{2}{3}$ minutes later for each degree more than 11°.

Phenomena of Jupiter's Moons, February 2022

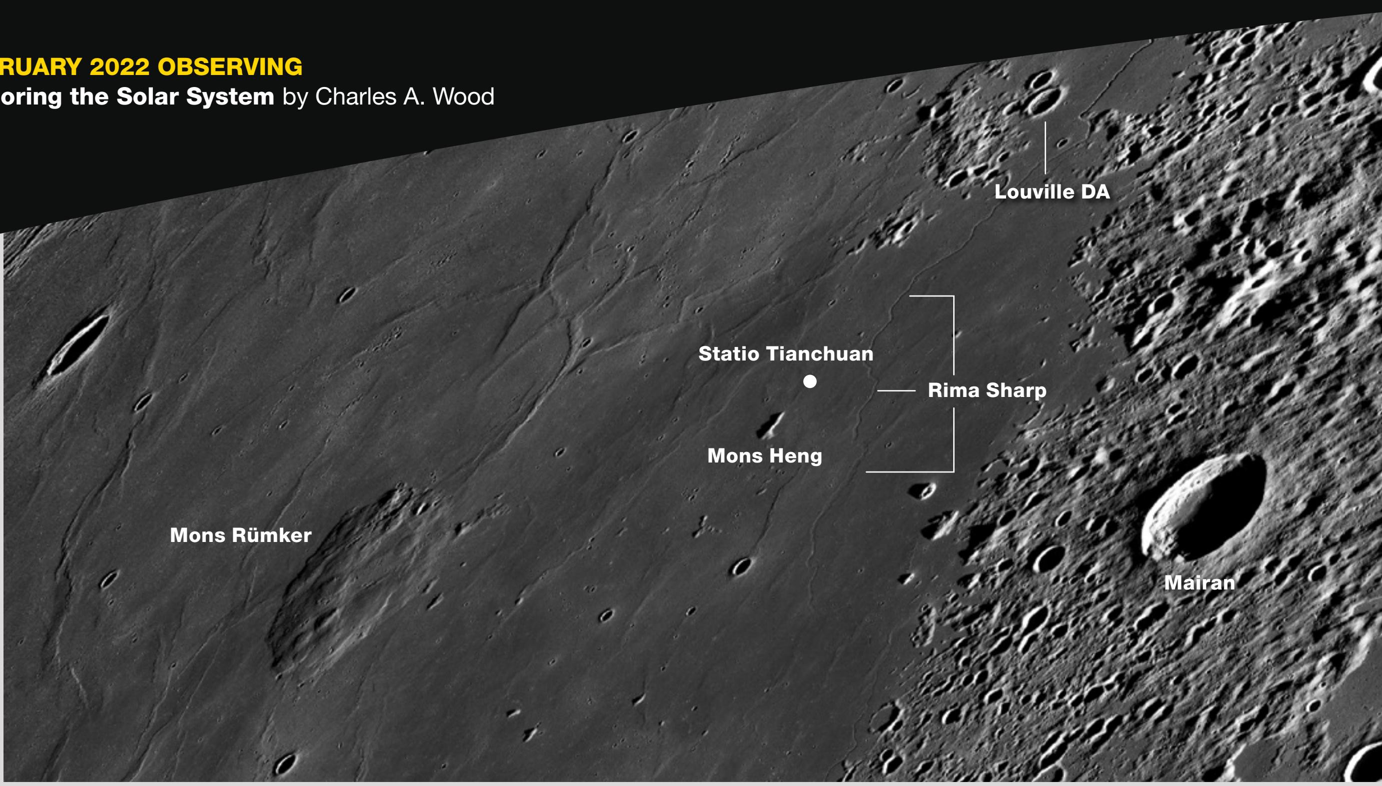
Date	Time (UT)	Event
Feb. 1	13:11	I.Oc.D
	16:02	I.Ec.R
Feb. 2	4:50	II.Tr.I
	5:58	II.Sh.I
	7:40	II.Tr.E
	8:45	II.Sh.E
	10:32	I.Tr.I
	11:05	I.Sh.I
	12:49	I.Tr.E
	13:21	I.Sh.E
Feb. 3	7:42	I.Oc.D
	10:31	I.Ec.R
	13:17	III.Tr.I
	15:28	III.Sh.I
	16:51	III.Tr.E
	18:55	III.Sh.E
	23:54	II.Oc.D
Feb. 4	3:42	II.Ec.R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

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

Jupiter's Moons



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



Chang’e 5 and the Age of Lunar Lavas

Does China’s sample return mission change our understanding of lunar chronology?

Until recently, scientists since Galileo’s time who studied the Moon were astronomers, not geologists. It wasn’t until the late 1950s and early 1960s that Eugene Shoemaker and Robert Hackman of the U.S. Geological Survey (USGS) developed a lunar stratigraphic sequence based on telescopic and photographic studies of the spatial relations among lunar landforms. They chose the southeast quadrant of **Mare Imbrium** to determine sequences of events by mapping the overlap of deposits created by each event.

The most recent Imbrium episode that Shoemaker and Hackman recognized was the formation of the crater **Copernicus**, whose radiating bright rays and secondary craters adorn nearby Mare Imbrium, **Montes Apenninus** (Apennine mountains), and more distant terrains. Copernicus’s formation must be the youngest major event in this area of the Moon, they concluded. The fact that rays and secondaries are on Mare Imbrium means that those mare lavas are older, and since the arc of the Apennine mountains borders the mare, the range must be older than the lavas. The USGS scientists considered the tall Apennines to be the rim of a giant crater or basin that the mare lavas erupted within. And the Apennines must have formed on some pre-existing terrain, which would be the oldest landform in the region.

Going to a deeper level of stratigraphy, the pair noted that the crater **Eratosthenes** lacks rays, but its small secondary craters are visible on Mare Imbrium. Eratosthenes is also overlapped by debris from Copernicus, so it must be older than Copernicus, and younger than the mare lavas. Going one step further, they saw that **Archimedes** has no rays or secondary craters and is almost completely surrounded by Imbrium lavas. Therefore, Archimedes must have formed on the giant basin floor or early lavas before Imbrium’s later lavas flooded the basin and buried Archimedes’ rays and secondary craters.

Over the next decade, USGS scientists mapped the entire Moon, producing a stratigraphy that delineated various young and old landforms.

▲ Seen above are the newly named lunar feature Mons Heng and Statio Tianchuan, where China’s Chang’e 5 mission landed and collected samples.

NASA / ARIZONA STATE UNIVERSITY / APPLIED COHERENT TECHNOLOGY CORP

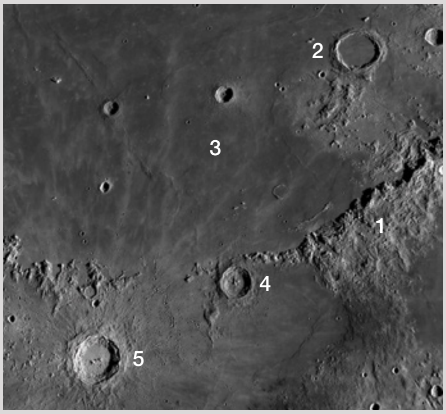
Unfortunately, they didn’t know the absolute age for any of the features.

The solution at the time was to estimate absolute age by counting the number of craters on the maria. The idea was that impact craters continually accumulate over time. Thus, the heavily cratered, bright lunar highlands must be older than the sparsely cratered mare lavas. But to convert crater counts to absolute ages requires knowing the rate at which impact craters form — and that rate apparently changed from being very high just after the Moon’s formation to the much lower rate we see today.

Before the Apollo program, Shoemaker, astronomer Ralph Baldwin, and graduate student Bill Hartmann independently estimated crater formation rates based on the number of impact craters of known ages on Earth, and from the predicted number of lunar impact craters formed by the collision of asteroids and comets. This kind of research was new in the 1960s, so it's not surprising that the age estimates for lunar maria differed widely. Shoemaker and Baldwin predicted young ages for the lavas around the Apollo 11 landing site, as little as 0.6 billion years. Four years earlier, Hartmann derived an age of 3.6 billion years, exactly what the samples returned by the Apollo 11 mission turned out to be. Hartmann's success must have been a combination of expertise and luck.

Samples brought back from the Apollo 11 landing site on **Mare Tranquillitatis** provided the first calibration point for crater counting. Four more Apollo missions landed on maria and yielded additional calibrations for crater counts. But the mare ages of Apollo samples spanned only the period before 3.2 billion years ago. As a result, there were no calibration points for lunar crater counts covering 3.2 billion years ago to today — the most recent 60% of lunar history. This gap was creatively filled by radiometric dating of certain Apollo 17 samples thought to be Tycho ejecta, which provided an age of 0.11 billion years for Tycho and its crater counts. Similarly, the age of 0.8 billion years for Copernicus stems from dating an Apollo 12 soil sample inferred to be ray material from that giant crater. All the sparse and uncertain crater count/absolute age data are memorialized on a famous graph that remains the basis of lunar chronology, nearly 50 years after the end of the Apollo program.

The situation will drastically improve now that samples returned in December 2020 from northern **Oceanus Procellarum** by China's Chang'e 5 mission have been precisely dated. China selected the landing site (recently named Statio Tianchuan, after a Chinese constellation) because crater counts indicate that the mare lavas there, originating from the nearby sinuous rille **Rima Sharp**, are among the youngest on the Moon, forming sometime between 1.5 and 2 billion years ago. The laboratory-dated Chang'e 5 samples are 1.96 billion years old, which is consistent with the age derived through crater counting.



▲This image plots the order of major events in Mare Imbrium. Montes Apenninus (1) formed first, followed by Archimedes (2). Imbrium lavas then filled the basin (3). Later, impacts formed Eratosthenes (4) and finally Copernicus (5).

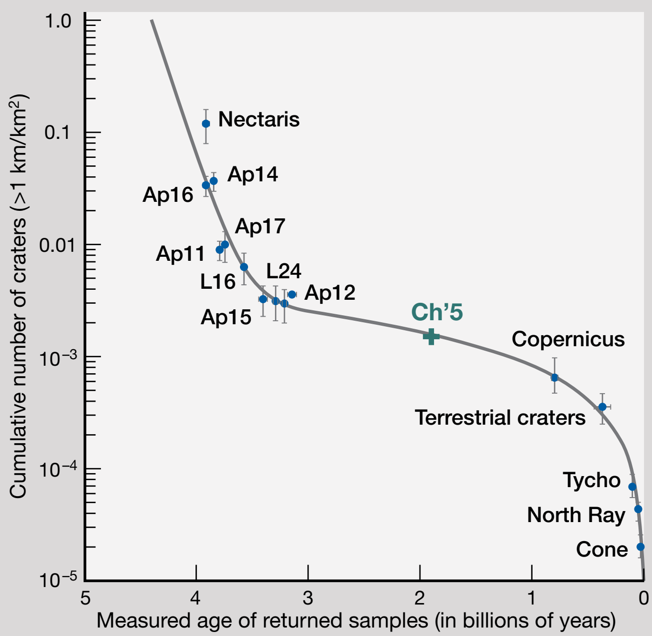
Adding a precise age and crater count number for such a young lava implies that the standard crater-counting/age models need only small corrections to the accepted lunar chronology (and all other chronologies across the solar system that are based on lunar results). The scientists who reported the new age also state that the samples are low in radioactive elements whose decay could provide heat for creating magma more than a billion years after most lunar volcanism ended. What this means is that scientists need to create new models of lunar thermal history. In science, data drive theories.

You can observe the key sites I've mentioned. The southeast quadrant of the Imbrium Basin where Shoemaker and Hackman established the first lunar stratigraphy is a familiar region, with prominent craters and mountains. Two details to notice are rays and secondary craters from Copernicus crossing Imbrium east of **Pythias**, and the lack of rays and secondaries radiating from Archimedes. The landing site of Chang'e 5 is not conspicuous but look east of **Mons Rümker** for the isolated peak **Mons Heng**, newly named after a Chinese mountain (see facing page). Northeast of Mons Heng is Statio Tianchuan and Rima Sharp. The rille is quite indistinct here but is more conspicuous 120 km (75 miles) further northeast near the 11-km-wide crater **Louville DA**.

The 1.96-billion-year age at Statio Tianchuan is considered young because the majority of the lunar surface is more than 3 billion years old, whereas the average age of Earth's surface is about 0.5 billion years. We live on a dynamic world that tends to erase ancient features. Fortunately, there's a museum of solar system antiquity orbiting just 226,000 miles away.

■ Contributing Editor **CHUCK WOOD** can't wait for more dated samples to fill in the crater curve gaps.

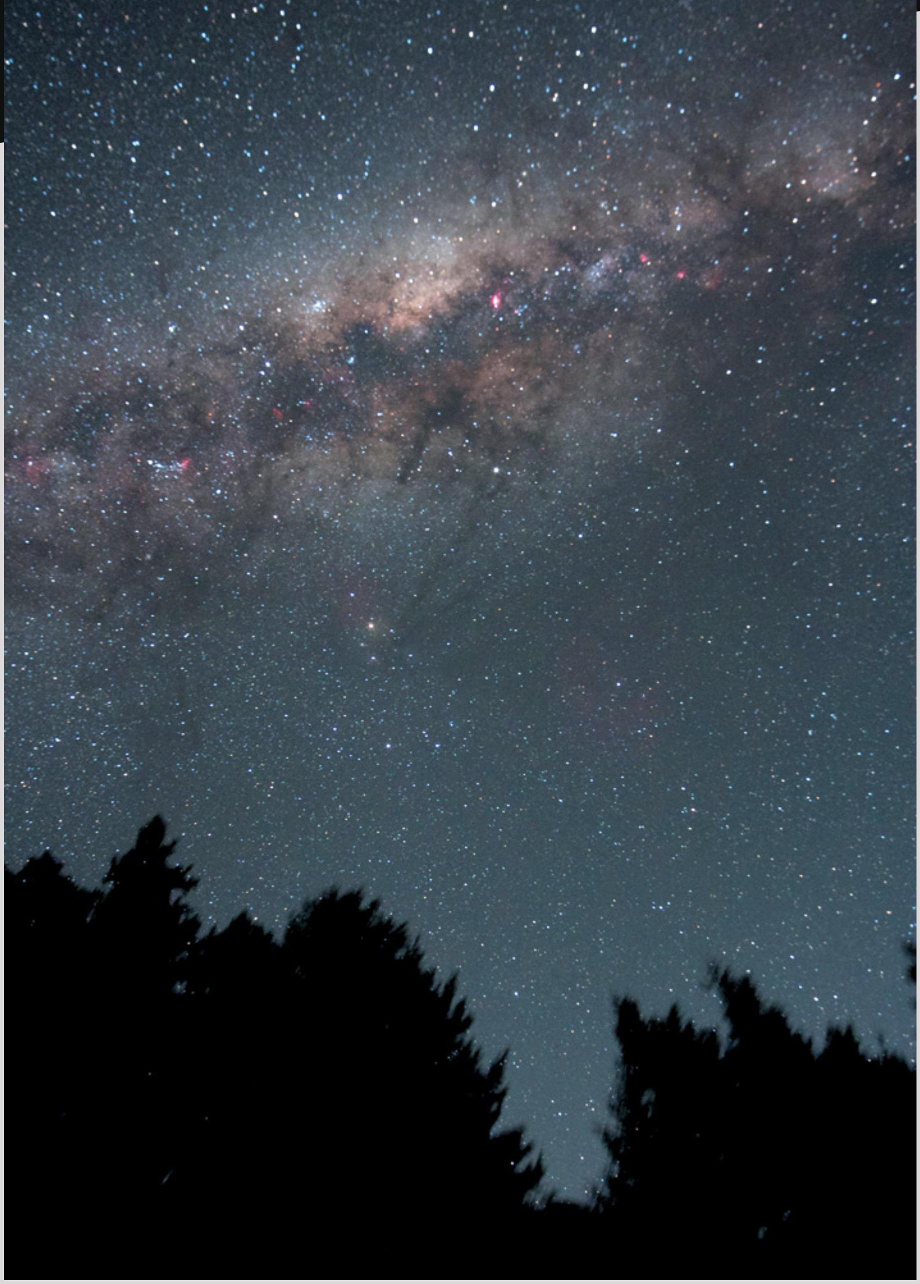
▶This graph updates the absolute lunar chronology, which plots the ages of measured lunar samples on the *x* axis against the cumulative number of craters larger than 1 km diameter per each square kilometer of lunar surface along the *y* axis. The ages of Copernicus, Tycho, and Nectaris are estimates, while samples returned by the Apollo missions (Ap), the Soviet Luna missions (L), and China's Chang'e 5 mission (Ch5) were directly measured. Gray bars represent the margin of error in the crater counts.



CRATERS: NASA / ARIZONA STATE UNIVERSITY / APPLIED COHERENT TECHNOLOGY CORP; GRAPH: H. HIESINGER

Choosing and Using a Star Tracker

A basic and (relatively) inexpensive accessory can take your astrophotography to the next level.



▲ The author captured this photo showing the heart of the Milky Way with the constellations Scorpius and Sagittarius in a 3-minute exposure at ISO 800 using a 14-mm f/2.8 Samyang lens and a Canon 1100D camera on a Sky-Watcher Star Adventurer star-tracking mount. Despite the use of a wide-angle lens, stars in an exposure of this duration would show up as little streaks without the use of a motorized star tracker.

The awe-inspiring sight of a star-filled rural night sky with the misty glow of the Milky Way arching overhead is something that you might wish to photograph and share. While a tripod-mounted camera and standard lens can record simple constellation portraits in a few tens of seconds, the stars will be rendered as unnatural little streaks and the Milky Way will look washed out and dim. But by mounting your camera on a device known as a star tracker, you can create rich, detailed pictures of the Milky Way with pinpoint stars — and so much more!

Star Tracker Basics

If you're wondering if and when a star tracker is necessary, all you have to do is consider the so-called 500 Rule. It states that for sharp stars, the longest exposure you can make with a stationary, full-frame camera is 500 divided by the focal length of the lens. In other words, if you want to avoid stars turning into little streaks, a camera fitted with a 24-mm lens is limited to exposures of around 21 seconds (500/24 = 20.8). With a 14-mm lens you're limited to around 36 seconds — good enough to record the brightest parts of the Milky Way. If you have a crop-sensor camera model, you'll have to divide your results by your camera's crop factor. For Nikon DSLRs, that's 1.5, meaning you're limited to 14-second exposures (20.8/1.5) with a 24-mm lens.

Even allowing for the incredible sensitivity of modern cameras, most 20– to 30-second exposures will look dim and noisy simply because you're not capturing enough light. A fast (f/2 or f/2.8) lens helps, but satisfactory Milky Way shots typically require a minute or two of exposure or more. And the only way to get exposures that long while retaining pinpoint stars is with a motorized tracking mount.

A star tracker not only enables long exposures, it also permits the use of longer-focal-length lenses to capture some of the larger deep-sky objects or comet close-ups. And because most camera lenses deliver improved optical performance when stopped down to f/4 or f/5.6, a tracker allows for longer exposures to compensate for the reduced light reaching your camera's sensor.

How a Star Tracker Works

Stars trail in long-exposure photographs because Earth is rotating west to east,

ALL IMAGES COURTESY OF THE AUTHOR

making one revolution per day. As a result, everything in the sky appears to move east to west. Our planet acts like a giant gyroscope, keeping its spin axis aligned with two (almost) fixed and opposing points in space: the north and south celestial poles.

In its simplest form, a star tracker possesses one motorized axis that spins at the same rate as Earth, but in the opposite direction. However, for it to accurately follow celestial objects, the tracker's axis of rotation has to be aligned precisely parallel to that of our planet. The act of making this adjustment is called *polar alignment*.

Most manufacturers supply a wedge that sits between the tracker and the top of your tripod, tilting the tracker's polar axis at an angle equal to your latitude so that it points at the celestial pole. The wedge typically has finely threaded adjustments for azimuth (left-right) and a geared sector for precise adjustment in altitude (up-down).

Basic star trackers may have a sighting tube or sights to enable you to point its motorized axis roughly north at Polaris, the naked-eye star that conveniently lies near to the north celestial pole. While sufficient for short exposures with wide-angle lenses, greater precision is needed for longer exposures, requiring you to make allowances for Polaris' small offset from the north celestial pole. (Southern Hemisphere photographers have their own fainter pole star, Sigma Octantis.)

More advanced trackers employ a small sighting telescope with an illuminated eyepiece reticule to aid precise polar alignment. Typically, these mini-telescopes are used in conjunction with a smartphone app to calculate exactly where Polaris lies in relation to the celestial pole at a specific time and date for your location. (Several methods for achieving accurate polar alignment were covered in this department in the October 2021 issue, page 54.)

Attaching Your Camera to a Star Tracker

Once your star tracker is polar aligned, you need a means of connecting your camera to it. If your camera and lens together weigh less than 2 or 3 kg (4 to 7 pounds), the most compact and convenient way to go is with a sturdy photographic ball head. Most trackers have a top mounting plate with a standard ¼-20 pitchthread that the base your ball head simply screws onto. A good ball head let's you freely aim your camera and holds your camera securely, without slipping throughout a long exposure.

If you're planning to shoot with a telephoto lens or even a small telescope, then look for a heavy-duty star tracker capable of handling gear weighing up to around 5 kg. It's likely that you're also going to need something more substantial and sophisticated than a ball head. A better option is an L-shaped declination adapter that often comes with a counterweight and shaft to balance the payload for better tracking.

◀ In the setup at left, the heavy load of a 60-mm ED f/5.5 TSAPO60 refractor and a Canon 1100D camera is carried on a Sky-Watcher Star Adventurer tracker via an L-shaped declination adapter, with shaft and counterweight.

Choosing the Best Star Tracker for You

As you may have already surmised, the choice of tracker depends a great deal on what you plan on mounting on it. Manufacturers specify payload limits for their equipment, but the total weight of your gear (camera, lens, and accessories) shouldn't exceed half to two-thirds of that figure for consistent performance and reliability.

Wide-angle lenses are very forgiving of drive errors and will likely work well even with budget trackers, but drive accuracy is paramount when lens

▼ *Left:* A full-frame Canon 5D DSLR camera appears here fitted with a wide-angle Samyang 24-mm f/1.4 lens. The equipment sits on a ball head attached to a Sky-Watcher Star Adventurer Mini tracking mount. Note the cable connecting the camera to the mount, which enables the shutter to be triggered with a smartphone app over Wi-Fi — a capability found on the more sophisticated mounts. *Right:* A Sky-Watcher Star Adventurer Mini mount with the alignment telescope about to be inserted into the hollow polar axis. Note the wedge (red) and its black adjustment knobs used to fine-tune the mount's azimuth position and elevation during polar alignment.

▲ *Left:* This image of Comet NEOWISE gracing the northern horizon is a composite of nine, 40-second exposures captured at ISO 800 with a full-frame Canon 5D camera and an Askar FMA180 f/4.5 astrographic telescope carried on a Sky-Watcher Star Adventurer Mini tracking mount. *Right:* The author captured this portrait of the Southern Cross (Crux) and the dark Coalsack Nebula in a 3-minute exposure made at ISO 1600 with a Samyang 85-mm lens at f/2.8 and a Canon 1100D camera on a Sky-Watcher Star Adventurer mount. Such a setup is both powerful and portable — a dream rig for those contemplating a trip to photograph southern treasures.

focal lengths reach 85 mm. And with telephotos of 135-mm or 200-mm focal length and small refractors, the margin for error becomes very small.

No tracker on the market possesses perfectly meshed gears, motors, or bearings, so the drive rates vary slightly. For this reason, more advanced units usually feature an autoguider port. This allows the mount to receive drive corrections from an autoguider — a setup often consisting of a small telescope, a specialized camera, and a computer. The iOptron SkyGuiderTM Pro and the Sky-Watcher Star Adventurer Pro have this capability. But if you're just looking to shoot wide-angle astrophotos, this capability might be overkill.

A common feature of star trackers is a choice of drive rates that usually include sidereal, lunar, and half speed (0.5×). Most of the time you'll opt for the sidereal rate for photographing constellations and the Milky Way. However, if your target is the Moon, the lunar rate might give better results because it compensates for the Moon's eastward drift relative to the stars. This would be the speed to select if you plan on shooting a lunar eclipse sequence, for example. If you track stars near the horizon with trees or buildings in the foreground, the terrestrial features will blur because they are stationary. This is the situation that the half-speed rate was designed for. It's a tradeoff between slightly trailed stars and a sharper foreground. Your choice of lens focal length and exposure duration will determine just how noticeable that tradeoff is.

Star Tracker Tips

Once you've shot a few frames under the night sky, you'll quickly discover that things don't always go according to plan. Don't be surprised if your first attempts yield imperfect results. Here are a few tips I've learned through experience:

- If your pictures show trailing, the most likely cause is imprecise polar alignment. Double-check that you've performed this correctly, or that you haven't accidently kicked your tripod during the night. Also, make sure that you are set up on solid ground and your tripod isn't slowly sinking into the dirt.
- When it comes to tripods, select a model that's a good match for the weight of your tracker and camera gear. An imaging chain is only as strong as its weakest link!
- All motorized star trackers require electrical power. The iOptron Sky-Tracker Pro has a built-in rechargeable battery, while the other models available require AA batteries or can be powered from an external battery pack via a USB cable. The latter is preferred if you're planning a long imaging session, so that the tracker doesn't stop working due to batteries. If you use AA cells, choose heavy-duty alkalines and carry spares in a warm pocket — batteries quickly die in cold conditions.
- The gear train of any mount has a certain amount of slack (termed backlash). You need to ensure that this is driven out before you start taking pictures. One way to do this is to set your payload so that it's slightly "east heavy" — the camera wants to drift eastward when the drive axis is unlocked. This makes the drive constantly push the load.

The limits of what you can achieve with a camera and star tracker are bounded only by your imagination, the capabilities of your camera, and the quality of your skies. If you're already familiar with the basics of astrophotography, you can quickly acquire the additional skills required to operate a tracker and capture celestial scenes of outstanding beauty that will wow your family and friends.

■ **ADE ASHFORD** has photographed the night sky from New Zealand, the United States, and his native England, where he currently resides.

Punching a Hole in the Sky

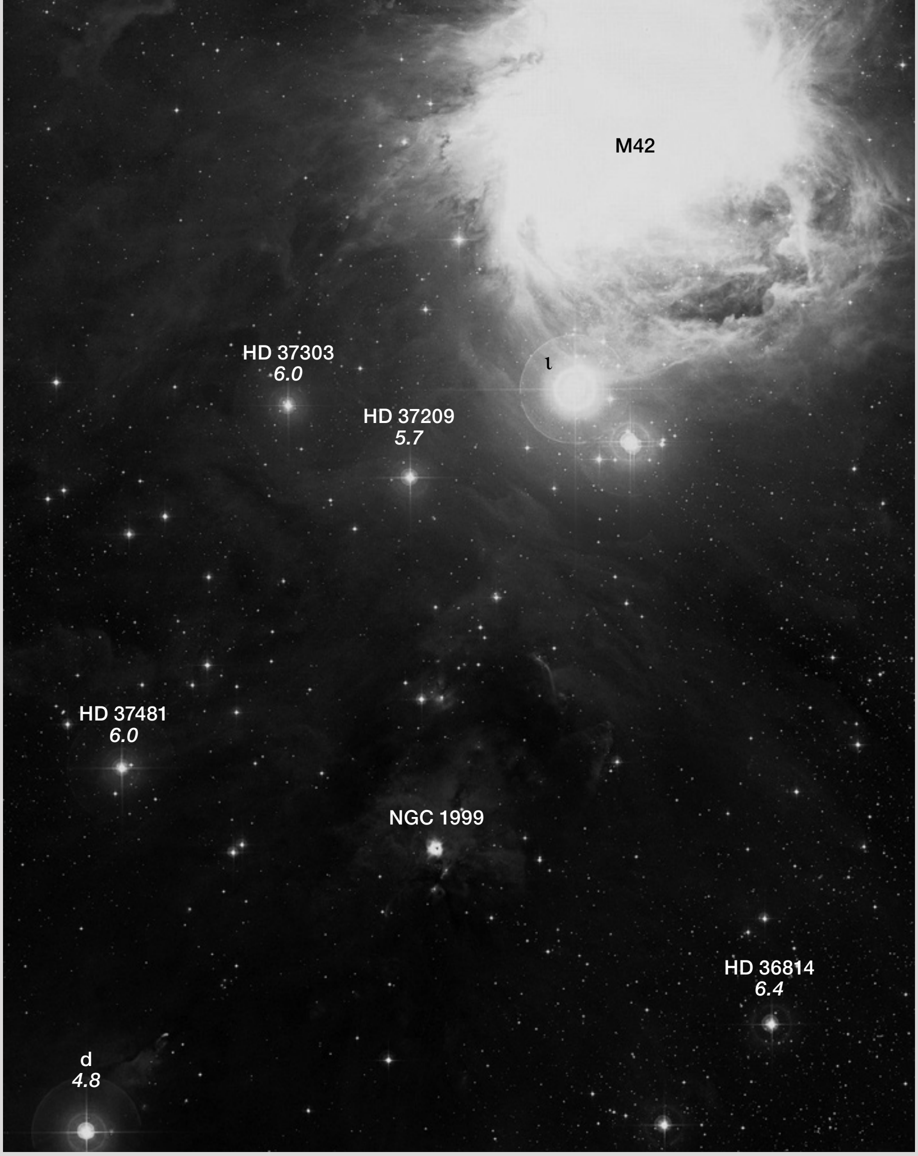
The reflection nebula NGC 1999 harbors a dark secret.

Inconspicuously tucked away a degree south of the Orion Nebula (M42) is the small reflection nebula **NGC 1999**. It sports a remarkable peculiarity: a dark, keyhole-shaped feature. Astronomers assumed that the globule was a likely star-forming region in front of NGC 1999, blocking light from the reflection nebula. That was a pretty good assumption, given that this part of Orion is bursting with new star formation. But then a 2010 study led by Thomas Stanke (European Southern Observatory) produced a startling result: The dark nebula turned out to be a void, or a cavity, running *through* the reflection nebula.

NGC 1999 is illuminated by V380 Orionis, a quadruple, pre-main-sequence star system located in the Orion A giant molecular cloud. The dark void to the star's immediate west is approximately 20″ × 30″ in size, which at a distance of 1,400 light-years translates to about 10,000 a.u. along its longest dimension. Typical nebular turbulent velocities should have closed this void fairly quickly (within a few tens of thousands of years or so).

So how did the cavity form, and why is it staying open?

The 2010 study identified two previously unknown stellar outflows running through the void. The first likely originates with the V380 Orionis system and is responsible for carving out the southern section of the void, while an unrelated outflow may have excavated the northwestern part. The convergence of these two flows likely created and currently maintains the keyhole-shaped void. By virtue of its close proximity, V380 Orionis illuminates and heats the walls of the cavity, producing the high contrast of the dark void with the surrounding bright nebula.



▲ **IN ORION'S SWORD** You'll find the reflection nebula NGC 1999 about 1° south-southeast of M42. The image is approximately 1½° × 2°. North is up in all images.

POSS-II / STSCI / CALTECH / PALOMAR OBSERVATORY

Probing the Nebula

An easy-to-remember star-hop is to start at Iota (ι) Orionis and look for a pair of 6th-magnitude stars a few arcminutes due east. NGC 1999 is less than a degree due south of the westernmost 6th-magnitude star. If you include a third 6th-magnitude star east of NGC 1999, we have a Corvus-like trapezoid.

Once NGC 1999 is in the eyepiece, it won't respond to a narrowband nebula filter because it's a reflection nebula. Even if a wideband light-pollution filter might boost contrast a little, I've always found the unfiltered view more satisfying.

Near the center of NGC 1999 the magnitude-10.9 star V380 Orionis stands out quite well against the bright nebulosity and the eastern edge of the void. The dark cavity makes the western side of the reflection nebula look dimmer than the rest of NGC 1999, which was quite evident when observing with my 8-inch f/4 Dobsonian in a moderately light-polluted sky:

> *I can see the glow of 1999 when I look at the right spot at low power (39×) and it's pretty evident. Pretty easy to pass by just by sweeping, though. With 206× and 274× the glow of 1999 is more evident and slightly oval, which is*

caused by the dark void. But the void is only suspected, probably because the sky background is too bright to show the glow of 1999 more distinctly all the way around it. 19.45 SQM [Sky Quality Meter].

I envision a 12-inch scope would provide a more satisfying peek at the void under these conditions, although the 8-inch might do the trick under more ideal sky conditions.

My 28-inch f/4 alt-az scope produces a great view, though. The void's sharply defined keyhole silhouette looks almost artificial during periods of steady seeing. The clearest views have been with magnifications of 408× and 545×, with the contours of the cavity starkly contrasted against the bright portion of NGC 1999:

The dark nebula [i.e., the dark void] *is sharply defined and has a distinct trefoil shape. The perimeter of the bright nebula has a somewhat ragged edge with hints of little (and short) streamers. Very nice! 408×, 21.30 SQM.*

▲ **LOOKING THROUGH A VOID** This Hubble Space Telescope image shows NGC 1999, its dark void, and V380 Orionis — the only star in this image. Located in the Orion A giant molecular cloud, the NGC 1999 area is also crackling with new star formation.

Still with the 28-inch, an observation from my backyard highlighted the overall shape of the nebula:

[NGC] *1999 really is asymmetrically bright — the side with the dark void is the faintest, which at first glance gives it an oval appearance, like in the 8-inch. Even so, the trefoil shape of the dark void is distinct, especially at 408× and 545×. 19.94 SQM.*

The outer perimeter of NGC 1999 appears fairly round, but my perception of a ragged edge is as real as it is subtle, as is a little notch on the nebula's northwestern boundary.

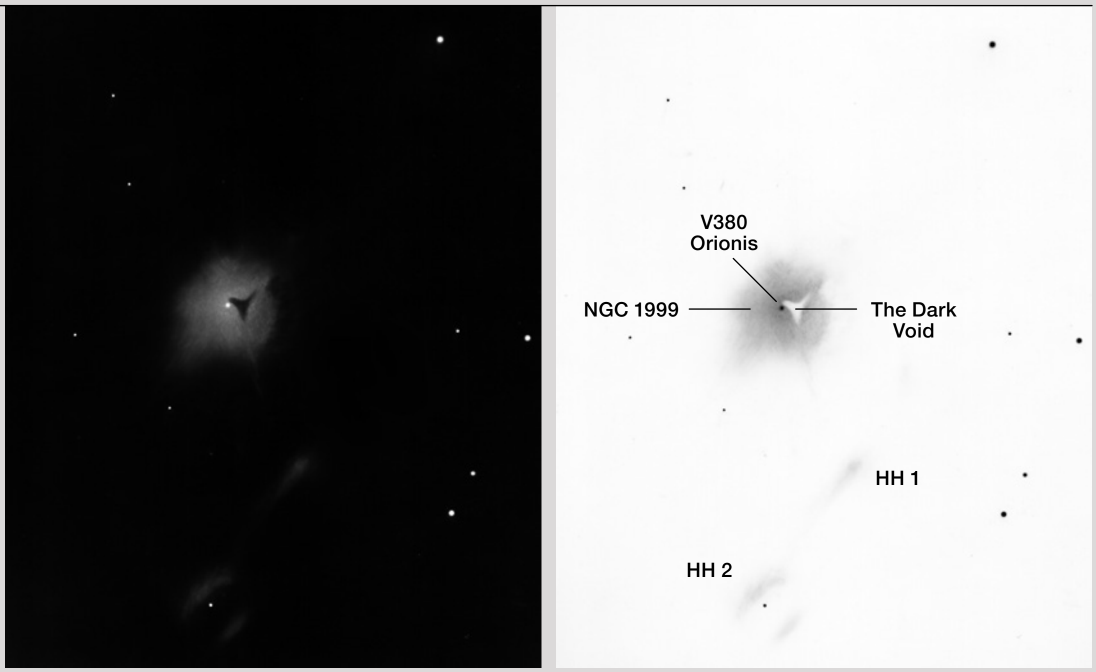
Moving up further in aperture, *S&T* Contributing Editor Steve Gottlieb had an exceptional view of NGC 1999 with Jimi Lowrey's 48-inch telescope about 10 years ago. He mentions a "stunning view" at 375× and 488× and notes that the "contrast of this dark nebulosity was extremely high and appeared virtually identical to images."

Herbig-Haro Objects

The image on page 59 shows a hive of activity — a stellar nursery in full swing. Look closely and you'll notice that many features come in pairs: These are *Herbig-Haro objects*, signatures of nascent stellar systems.

Herbig-Haro (HH) objects are "bright" nebulae that form when stellar jets (or outflows) from newly forming, pre-main-sequence stars — such as V380 Orionis — slam into nearby nebulosity, causing it to glow. These jets vary in strength and are typically about one light-year long but can sometimes exceed three light-years. Because stellar jets blast out in opposite directions from the poles of newly forming stars, the resulting HH objects are often found in pairs. The image underscores how active this star-forming region is — connect the lines between matching sets of HH nebulae and you'll find the location of a newly forming star,

▶ **CAPTURING THE VIEW** NGC 1999 shows off its dark void, with HH 1/2 immediately south. At near left is what the field of view looks like through my 28-inch scope at 545×. Note the irregular perimeter of NGC 1999, especially the faint streamers on its southern edge and the notch on its northwestern border. HH 1/2 are shown with slightly more contrast than how I see them in the eyepiece. HH 2 appears as two faint patches of nebulosity on either side of a starlike point, which is actually its brightest part. This area of sky is also a prime spot to watch geosynchronous satellites slowly glide through the field of view.



HST IMAGE: NASA / ESA / THE HUBBLE HERITAGE TEAM (STSCI); SKETCHES: HOWARD BANICH (2) which is often completely obscured by a *circumstellar disk*, or a torus of dust and gas around its equator.

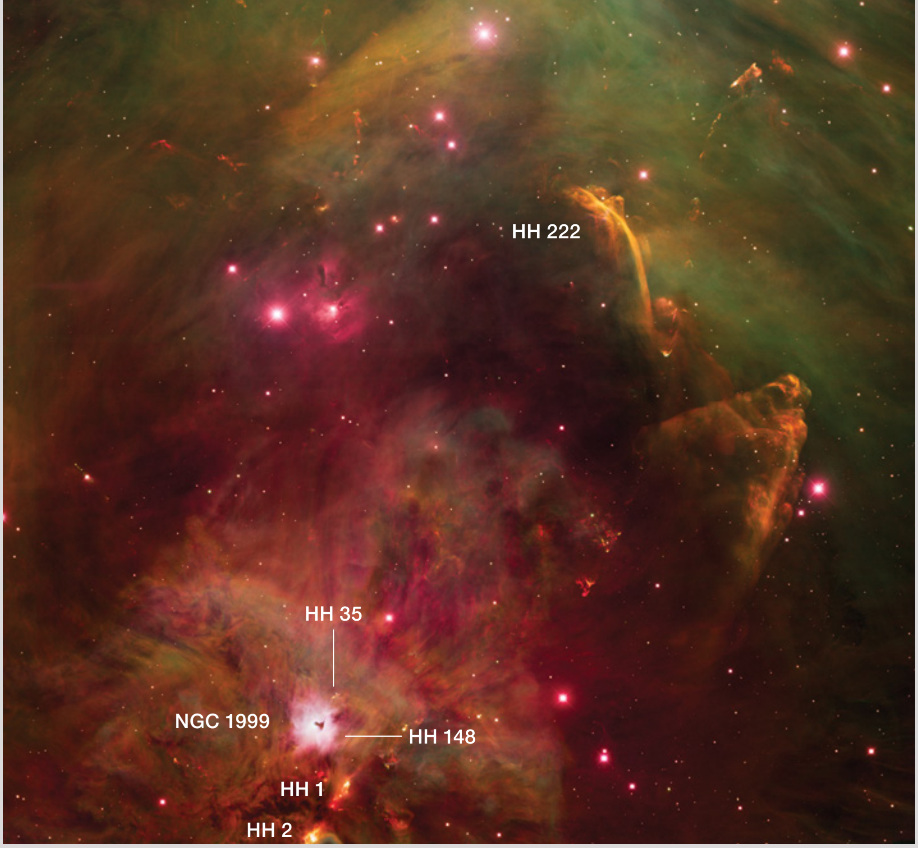
But why all the action from V380 Orionis? It's a young, multiple-star system (about one million years old) that's in the process of evolving into mature stars, which are still settling into their most stable orbits. This stirs up the surrounding gas and dust, which in turn transfers energy into the *circumsystem disk* — a thick ring of material surrounding the nascent stars — and constantly alters the orientations of the stellar jets. V380 Orionis is a busy star system, and it's too bad we can't see any of this visually.

Stellar Flows

Two main outflows from V380 Orionis are associated with prominent HH objects that I very much want to see: HH 130 and HH 222. Both are shaped like partial bow shocks, with HH 222 bearing the evocative nickname "The Waterfall." Unfortunately, they're extremely dim and may be beyond the grasp of most amateur telescopes. Spectacular as they may be, they aren't responsible for creating the dark keyhole-shaped void. Instead, two much smaller outflows, HH 35 and HH 148, are the likely culprits.

The first two Herbig-Haro objects ever discovered, HH 1/2, are conveniently located in the same high-power field of view as NGC 1999. Even though they're among the brightest of their class, they're still pretty faint, and it takes a great night to see them. But don't let that scare you away — I've detected them with my 8-inch in moderately light-polluted but very transparent skies. They're both fairly easy to see with my 28-inch scope in the same conditions.

Part of the fun of visual observing is trying to see exotic objects like this, no matter how difficult they are — especially when armed with a little knowledge of how the titanic forces of star formation can, sometimes, punch a hole in the sky.



▲ **BUSY MAKING STARS** This image obtained with the National Science Foundation's Mayall 4-meter telescope on Kitt Peak in Arizona shows NGC 1999 and nearby HH objects (many more are in the image than are labeled). NGC 1999 and HH 1/2 are in the lower-left corner of the image, with HH 222 — the Waterfall — upper right of center. A stellar jet from V380 Orionis generated HH 222 as well as its opposite feature, HH 130, which is outside the frame of this image.

Z. LEVAY (STSCI / AURA / NASA) / T. A. RECTOR (UNIVERSITY OF ALASKA ANCHORAGE) / H. SCHWEIKER (NOIRLAB / NSF / AURA)

■ Contributing Editor **HOWARD BANICH** might be out right now trying to see HH 222 and HH 130. He can be reached at **hbanich@gmail.com**.

Small World

The first time I saw HH 1/2 was in January 2012 at the Visitor Center on Mauna Kea. After the nightly sky show had ended, several local observers were sharing views through their telescopes, one of which was an intriguing 20-inch ball scope. Mike Connelley was operating the scope, which he had made himself. A small group had coalesced around Mike, including myself and Steve Gottlieb, who suggested we look at HH 1/2.

It turned out that Mike is not only a talented amateur telescope maker and observer, but a professional astronomer based on the Big Island of Hawai'i. When Steve suggested looking for HH 1/2, our gracious host said something to the effect of "you mean we can actually see them in my scope?! I'm researching HH objects right now!"

Steve replied "Sure!" and asked if he could move the scope to the proper position, and soon everyone in our small group had a look. Mike was thrilled to actually see the objects he knew so well through his research. We were all thrilled, too, both for him and because these are subtle objects most of us hadn't seen before.

As it turns out, a 2013 paper about HH 222 and V380 Orionis is one of the primary sources for this article, and I only realized Mike is a co-author just before my deadline.

Even better, all three of us have similar memories of this long-ago encounter in the dark, confirming that sometimes the world really is a small place.

ULTRA-DEEP IMAGING

Dedicating multiple nights to a single target can lead to surprising results.

Ever since digital detectors supplanted film as the dominant photographic medium, some of the most colorful and appealing images of deep-sky targets have come from talented amateurs armed with sensitive electronic cameras and high-quality telescopes. Yet many of us with relatively modest equipment look at the pictures produced with giant telescopes at professional observatories and dream about taking pictures as good. You might think, "If only I had a bigger telescope or more sensitive camera . . . " Well, the good news is that with a bit of patience and persistence, you can capture deep-sky photographs that rival or even exceed the depth of those recorded by the pros and reveal rarely seen features.

In early 2013 I set out to realize a long-time dream of mine: to take an exceedingly deep astrophoto incorporating more than

▼ **KNOTS AND JETS** The northeast portion of the author's photo (below right) compares well to a 50-hour image recorded with the European Southern Observatory's 2.2-meter telescope at La Silla (below left). While Olsen's image lacks the resolution of that produced with the larger observatory scope, all the extended features of the galaxy appear in both pictures.

ALL IMAGES COURTESY THE AUTHOR UNLESS OTHERWISE NOTED; LA SILLA DETAIL: ESO

SUPER DEEP Taking long-exposure astrophotos has been a staple among amateur imagers since at least the 1990s, but author Rolf Olsen pushes the boundaries on how deep an amateur can go. This picture of NGC 5128 in Centaurus is the result of combining more than 130 hours of image data, showing many features rarely seen in amateur or professional photos. The inset image notes several features visible in the photo.

100 hours of exposure to reveal faint and exotic structures seldom (if ever) seen before. Little did I know that this project would become so rewarding that it inspired my passion to acquire incredible amounts of data of several objects over the following years, and lead to collaborations with professional astronomers and NASA. Here's how I did it — and how you can, too.

◀ **READY FOR ACTION** The author's truss-tube 12½-inch f/4 Newtonian currently resides in a ScopeDome 3M observatory ready to image at a moment's notice. Note the QSI 683wsg camera with Starlight Xpress Lodestar autoguider in its off-axis guider port at top right.

Work with What you Have

Recording ultra-deep astrophotos doesn't require the latest, largest, or most expensive equipment, nor even the most pristine, dark skies. My observing location is on the western outskirts of Auckland, New Zealand, which has a population of 1.7 million. Although my home-built, 10-inch f/5 truss-tube Newtonian (later upgraded to a 12½-inch f/4) is tailored to image deep-sky objects, it's by no means the most capable or sophisticated instrument available within the realm of amateur astrophotography. Likewise, my QSI 683wsg camera incorporates a KAF-8300 8.3-megapixel monochrome CCD sensor that's neither the largest nor the most sensitive model available. Along with this equipment, I used readily available Astrodon second-generation RGB filters and a 3-nanometer hydrogen-alpha (Hα) filter. Until recently, the scope resided in a commercial shed converted into a roll-off-roof observatory.

Regardless of equipment type, having a permanently ready imaging system is the single most important factor for systematically collecting large amounts of data. This let me take advantage of every clear night with minimum setup time.

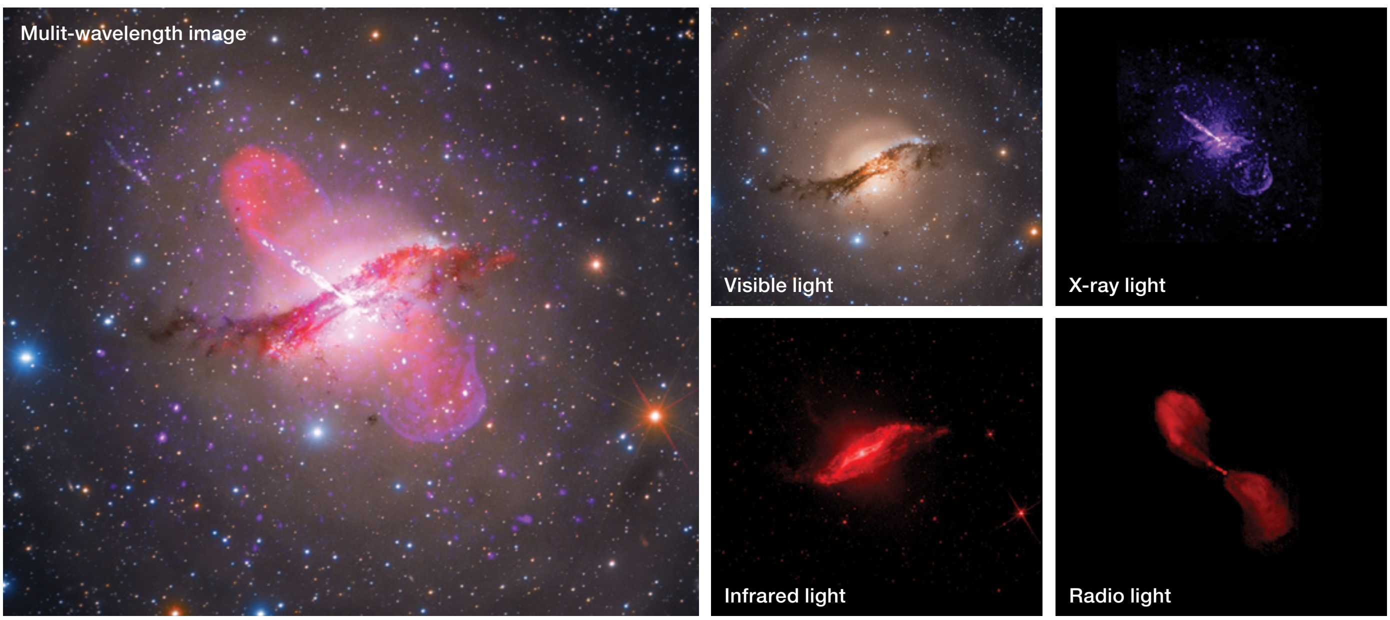
A Good Plan

An ultra-deep imaging project requires considerable planning because it's likely to span many months. Suitable targets include galaxies or galaxy clusters, which sometimes contain very faint tidal streams of stars left over from ancient mergers. Planetary nebulae may display extremely faint outer shells that become visible with long enough exposure times. Many well-known nebulae often reveal extended tendrils of nebulosity not visible in typical photographs. Almost any object can reveal something new in an exceedingly deep image. Still, composition and field of view are important considerations. For example, targeting the Orion Nebula (M42) with my system's narrow field of view (42′ by 32′) is unlikely to reveal new structures because the nebula is already very bright and extends far outside my camera's field of view.

Targets that pass high overhead are the most suitable for ultra-deep imaging. For optimal efficiency it's best to devote nights with good seeing to taking luminance data and leave color for nights with less steady conditions. This is because the sharpness of the final image is defined by the luminance alone, and the RGB data only provide the color information.

Minimizing downtime is important for long-term imaging projects, so I automated as much of the process as possible by

▼ **MULTI-WAVELEGTH COMPARISON** For a press release from the Chandra X-Ray Observatory in 2014, the author's deep image of Centaurus A was combined with data from several telescopes to showcase the unique appearance of the galaxy across the electromagnetic spectrum.



X-RAY: NASA / CXC / SAO; OPTICAL: ROLF OLSEN; INFRARED: NASA / JPL-CALTECH; RADIO: NRAO / AUI / NSF / UNIV. HERTFORDSHIRE / M.HARDCASTLE using image-capture software that let me script an entire night of imaging. I use *MaxIm DL* (**https://is.gd/MaxIm**), though full-automation solutions like *Astronomer's Control Panel* (**acp.dc3.com/index2.html**) or *Sequence Generator Pro* (**https://is.gd/sgpro**) make the process even more efficient by scripting and planning multiple nights as well as recording dark, flat, and bias calibration frames automatically.

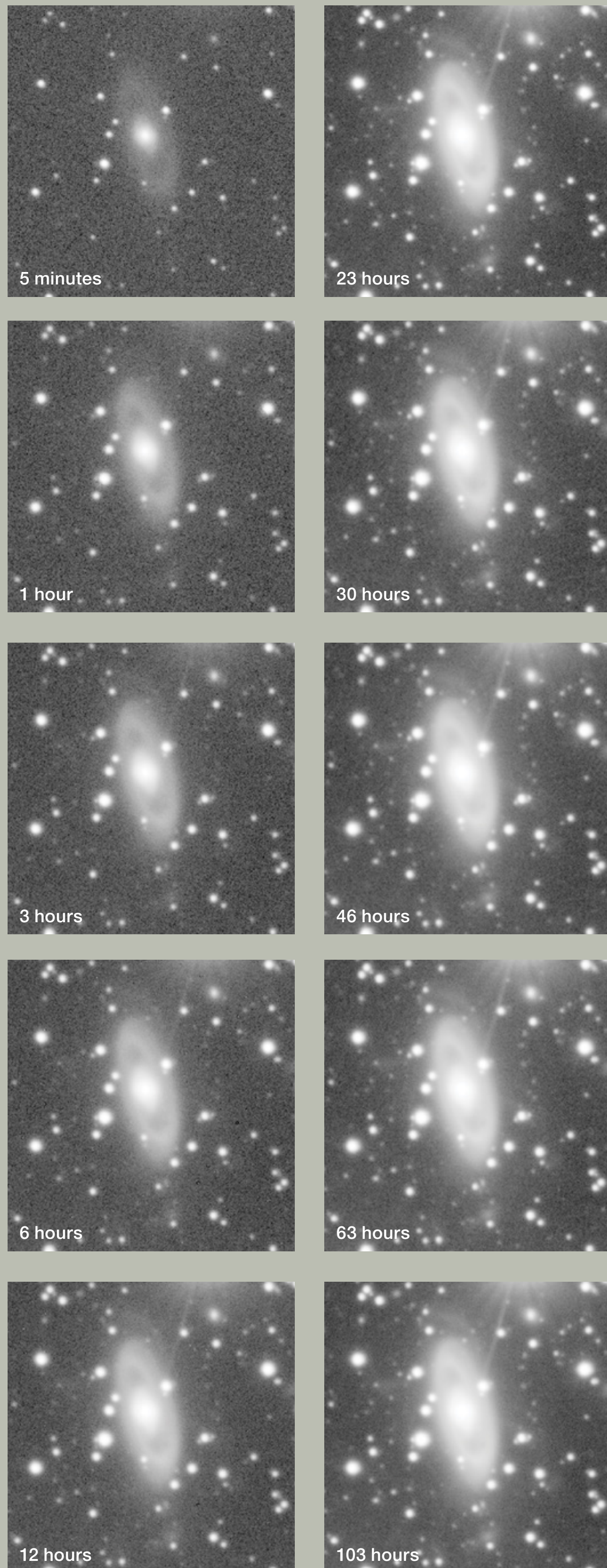
Speaking of calibration images, this kind of imaging requires maintaining a library of calibration frames. Digital detectors can change over time, developing hot pixels, dead pixels, bad columns, or "stuck" pixels that sometimes come and go. That's why a master dark frame from, say, six months ago may not correct some artifacts in newer data. Plan to update calibration frames at regular intervals. Likewise, dust slowly accumulating on any surfaces within the light path will create a mismatch between your old flat-field images and your current light exposures. By keeping organized sets of calibration frames, you can easily reprocess your pictures at any point in the future. This is especially important if your data are requested for scientific research, or you learn a new calibration or integration technique. Good data never go bad.

Proof of Concept: Centaurus A

I attempted my first ultra-deep imaging project in early 2013. My target was Centaurus A, or NGC 5128, a peculiar galaxy located roughly 12 million light-years away in the Southern constellation of Centaurus. It's the closest active galaxy to Earth and one of the most studied. Throughout the first half of 2013, I recorded 120 hours of exposure on Centaurus A on 43 nights between February and May, when the target was best placed in my sky, passing nearly directly overhead. I then spent around 40 hours reducing and processing the data, with the goal of presenting this majestic galaxy as it has never been seen before, to truly grasp what this intriguing object is all about.

The result is among the deepest views of Centaurus A to date. It may also be among the deepest images recorded to date with amateur equipment, showing stars fainter than 25th magnitude.

My image reveals several rarely seen features. The first and most prominent at the top left are the pair of enormous, reddish filaments associated with relativistic jets expelled from the galaxy's central supermassive black hole. A smaller, inner filament lies about 30,000 light-years from the core, and another, larger filament is seen some 65,000 light-years out. Interestingly, possible shock fronts from the outer filament seem to have triggered a burst of



▶ **SIGNAL TO NOISE** This series of luminance frames taken from the Antlia Cluster image on page 64 graphically displays the benefit of long integration times. Noise dominates a single 5-minute exposure (top left), but adding more time to the image lowers the noise level while increasing the signal. Note the faint outer spiral arm that becomes visible at the top of the galaxy after combining 23 hours of exposures.

star formation in the surrounding gas, visible as a sprinkling of blue star clusters to the right of the filament.

A faint trace of nebulosity related to the otherwise invisible southern jet is also noticeable as a small, red knot seen at the 4 o'clock position about halfway between the galaxy's core and the bottom right corner of the image. This is the first visible-wavelength detection of the southern jet.

Also visible in the image are the complete inner and outer shell structures of the galaxy's extended halo. These features are stars left over from past mergers with other galaxies. In addition, more than 700 cataloged globular clusters orbiting Centaurus A also riddle the field.

In 2019 I acquired an additional 10 hours of exposures, this time through a Hα filter. The updated image incorporates the new data to highlight the emission structures triggered by the relativistic jet from the central black hole. It also emphasizes the many pinkish star-forming regions within the dark dust lane crossing the center of the galaxy.

Besides the main subject, the image is littered with other faint, remote galaxies, some at the limit of detectability.

Deep in the Antlia Galaxy Cluster

Following the success of my Centaurus A project, I turned my attention to another fascinating subject well-placed in the night sky from my location in New Zealand.

The Antlia Cluster (Abell S0636) is a galaxy group located in the constellation Antlia. It forms part of the larger Hydra-Centaurus Supercluster, some 133 million light-years distant. This makes it the third-closest galaxy cluster to our Local Group, after the Virgo and Fornax Clusters. Only a few images exist of this cluster, and those taken with professional observatories merely cover selected narrow portions of the field.

Over a span of 55 nights in 2015, I accumulated 152 hours of data on this magnificent galaxy cluster. Imaging began on January 1, 2015, when the cluster had reached an acceptable altitude in the east, and then continued every clear night through June until the cluster was too low in the west.

The finished result displays an ultra-faint veil of gas and

▼ **SO MANY GALAXIES** Using the same meticulous approach as in his Centaurus A project, the author recorded this exceedingly deep photo of the Antlia Galaxy Cluster. Total exposure time was 152 hours through LRGB and Hα filters.

dust in our own galaxy not directly illuminated by stars but merely reflecting the faint combined glow of our own galaxy, often called *integrated flux nebulae*.

The vertical stretch of reddish nebulosity at lower right of the image is part of the recently discovered Antlia Supernova Remnant (**https://is.gd/AntliaSNR**). Capturing these Hα filaments was a nice surprise, as I wasn't aware of their existence until very late in the process — the filaments are essentially invisible in the individual frames and only show up after image stacking. Bringing out the supernova remnant required an extra eight hours of Hα data, and even then I had to increase the sensitivity of the CCD detector with *binning* — making a group of four adjacent pixels act as a single, more sensitive pixel, though at the cost of resolution.

With a limiting magnitude surpassing 25, a vast number of smaller background galaxies are visible everywhere in the image. Some lie several billion light-years away and are visibly reddened by the relativistic redshift due to the expansion of the universe. Many of these appear grouped into distant clusters of their own, far beyond the influence of the Antlia Cluster. Additionally, the image contains many uncataloged galaxies I couldn't identify in any of the previous studies.

Image Processing

Key to making ultra-deep images is careful stacking and processing techniques. I calibrated each of the raw subframes in *PixInsight* (**pixinsight.com**) using master darks and bias frames obtained at or near the typical operating temperature of the CCD camera (-25°C), as well as flat-field images. Because the light frames were acquired over periods of many months across changing seasons, my camera's operating temperature ranged from -25°C down to -32°C — as low as the camera could reliably operate, which helps to minimize noise. All the light frames were calibrated using automatic dark/bias scaling to adjust for these temperature variations.

I assembled the master calibration frames from large sets of images recorded during each project in order to minimize noise levels in the final result. For each filter I made a single master bias, dark, and flat-field image from 400 dark frames, 500 bias frames, and 300 flat-field frames.

I then used *PixInsight*'s Linear Fit Clipping algorithm with image weights based on noise evaluation to reject noise and other artifacts in the individual exposures, producing an exceedingly smooth stack of each set of LRGB and Hα images. Once satisfied with the results, I then combined the color, luminance, and Hα before perfoming any non-linear stretches to create the final result seen on the facing page.

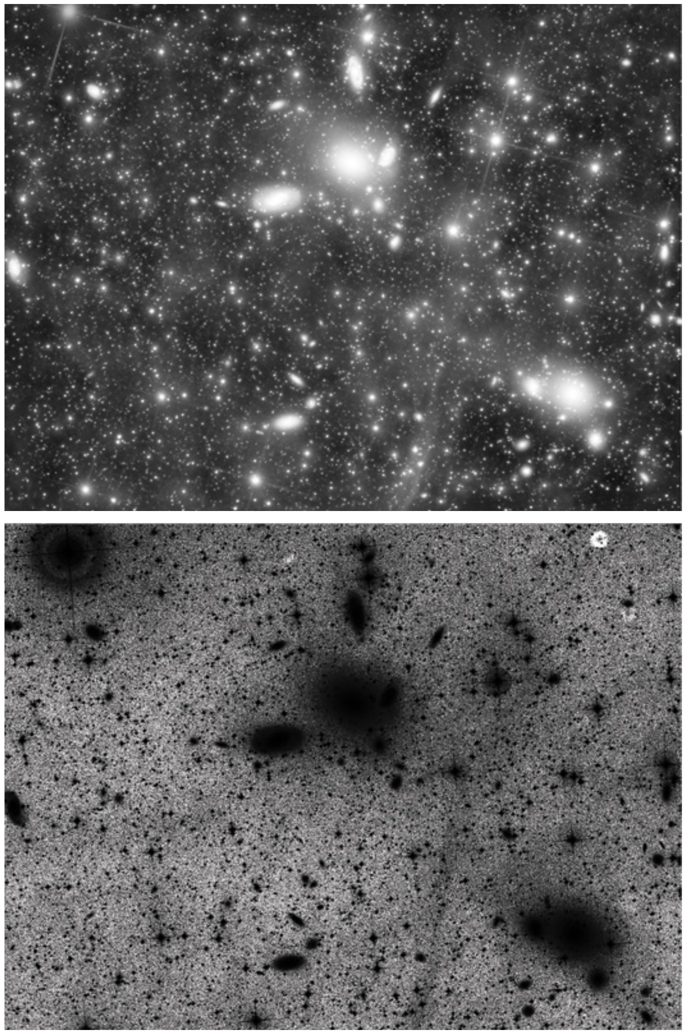
The advantage of having so much data is evident in the background noise levels. The large integration times allow for easier processing that requires little or no additional noise reduction in the final result.

Bearing Fruit

In my view, a deep-sky astrophoto can never have enough exposure. When going this deep, there often seems to be something more lurking in the background noise, waiting to be excavated and revealed.

After Steven Tingay of Curtin University saw my deep image of Centaurus A in 2017, he contacted me to discuss comparing his team's radio images with my data. As a result, I was invited (along with fellow amateur Mike Sidonio) to co-author the publication *The jet/wind outflow in Centaurus A: a local laboratory for AGN feedback* (**https://is.gd/CentA**). I can hardly think of a higher honor for an amateur astrophotographer!

These large image datasets were both a challenge and a pleasure to create. Consider undertaking your own ultra-deep astrophotography project to see what surprises lie hidden in the background sky just waiting to be noticed.



▲ **REACHING DEEPER** Olsen's luminance image (top) of the Antlia Galaxy Cluster from the facing page reveals faint nebulosity throughout the field that's only hinted at in the Second Palomar Observatory Sky Survey image recorded with the 48-inch Oschin-Schmidt Telescope (bottom).

DSS IMAGE: CALTECH

■ **ROLF WAHL OLSEN** photographs the night sky from his observatory in the foothills of the Waitakere Ranges west of Auckland, New Zealand.

Player One Planetary Cameras

We test two new high-speed video cameras.

▲ Each Player One Astronomy camera comes with a USB 3.0 cable, a UV/IR blocking filter, a blower bulb, and a 6-pin autoguider cable. The Neptune-C II also includes a UV/IR blocking filter (not shown).

Mars-M USB3.0 Mono Camera (IMX290)

Neptune-C II USB3.0 Color Camera (IMX464)

U.S. Price: $329 each
player-one-astronomy.com

What We Like

Adjustable sensor tilt

Internal memory prevents dropped frames

What We Don't Like

No models large enough to frame entire Sun or Moon at high resolution . . . yet

IN RECENT YEARS, the popularity of solar system photography has grown by leaps and bounds. Maybe it's due to people being stuck at home during the long COVID-19 pandemic, but fantastically detailed closeups of Jupiter, Mars, and Saturn (not to mention the Sun and Moon) appear in our inboxes with much greater frequency than in past years. This surge in popularity is being met by new companies getting into the business.

One of those is Player One Astronomy, a Chinese manufacturer that recently announced a line of high-speed video cameras geared specifically toward those with an interest in taking pictures of the large bodies in our solar system. We borrowed both a monochrome and a color camera late in the summer of 2021 to see how they perform.

▲ The sensor in the Mars-M (right) measures 6.46 millimeters from corner to corner, while the Neptune-C II detector (left) is 9 mm. The tilt-adjustment screws are seen along the edges of each camera.

Elegant Package

Player One Astronomy's planetary and solar cameras are housed in distinctive hexagonal bodies, which makes it easy to quickly determine the orientation of the detector when you're inserting it into your telescope's focuser. The two sides perpendicular to the text on the rear of the camera housing denote the long dimension of the sensor, while the points where the top and bottom sides meet correspond to the top and bottom of the chip. This is particularly helpful when one of us (Sean) was swapping out the camera for an eyepiece when attempting to place a target in the field of the camera's small chip.

In addition, each camera body has an adjustable front plate with three sets of push-pull screws to allow users to adjust the tilt of the camera to perfectly square it with the focal plane. This tilt plate is also useful for tuning out interference patterns in images when using the camera with a solar filter — a nice touch that suggests that the camera's designers actually use the equipment themselves. The plate has female T-threads to connect to accessories or the included T-to-1¼-inch nosepiece. The rear of both cameras has a ¼-20 threaded socket to attach it to a standard tripod.

▲ Both cameras include a ST4-compatible auto-guider port, which allows each to directly connect to most telescope mounts and function as a guide camera.

Both Player One cameras include a 6-pin

ENTIRE KIT: SEAN WALKER / S&T; SENSORS: SEAN WALKER / JOHNNY HORNE; PORTS: JOHNNY HORNE autoguiding port and a 2-meter (6½-foot) cable allowing their use as autoguiders, though we concentrated on each camera's planetary imaging performances and did not test its autoguiding capabilities.

Besides the 1¼ nosepiece, each camera comes with a 2-meter USB-3.0 cable, two hex wrenches for adjusting the tilt plate, and a well-made blower bulb, which does a nice job of cleaning dust from the detector window.

Monochrome with Filters

Sean spent a few months using the Mars-M camera while Jupiter and Saturn were well placed in the evening sky. The Mars-M is built around a Sony IMX290 CMOS monochrome detector, popular among planetary imagers who prefer to shoot with filters to isolate specific regions of the visible spectrum. The sensor is a 1/2.8-inch-format chip with a 1,920 × 1,080 array of 2.9-micron-square pixels measuring 5.6 × 3.2 millimeters. That makes it tiny by modern deep-sky imaging standards, but large enough to include Jupiter at a pixel scale of 0.1 arcsecond per pixel, with plenty of room to frame two or three Galilean moons.

Player One provides a link to download the camera drivers and *SharpCap* control software from its website. Both the drivers and software installed on Sean's Windows 10 laptop PC without a hitch. *SharpCap* provides adequate camera control, though we preferred to operate the cameras with the third-party free program *FireCapture* (**firecapture.de**), a robust program written for dedicated planetary astrophotographers. (At the time of writing, only the latest beta version of *FireCapture* can operate Player One cameras, so be sure you download the correct version.) The camera outputs several file formats, including AVI and SER video (in 8- or 16-bit format), as well as individual FIT, TIF, PNG, or JPG frames. All of these are compatible with most popular image-stacking programs, including *RegiStax 6* and *Autostakkert!3*.

A quick test showed the Mars-M camera had no problem achieving its advertised 136 frames per second in 8-bit mode, and 62 frames per second while operating at 16 bits. Even faster speeds came when using a smaller region-of-interest (ROI) crop of the sensor. This translates into a lot of frames in a very short amount of time — on the order of hundreds of frames per second. This is a crucial advantage because all planets rotate, and some — Jupiter and Saturn — do so fast enough that you need to limit video recording times to roughly one minute or less to avoid smearing fine details.

Usually you need a computer with a fast hard-drive write speed to keep up with the large data streams that high-speed planetary cameras generate. However, this isn't the case with Player One's cameras, as each model includes 256 megabytes of built-in DDR2 RAM to ensure high-speed performance even when operating the camera through a USB 2.0 port. Still, you can only achieve these high frame rates if your subject is bright enough to use very short shutter speeds.

◀ The cameras fit directly into any 1¼-inch-format focuser. With its detector mounted just 12.5 mm from the front plate, it should come to focus in most any telescope even with additional accessories in the light path.

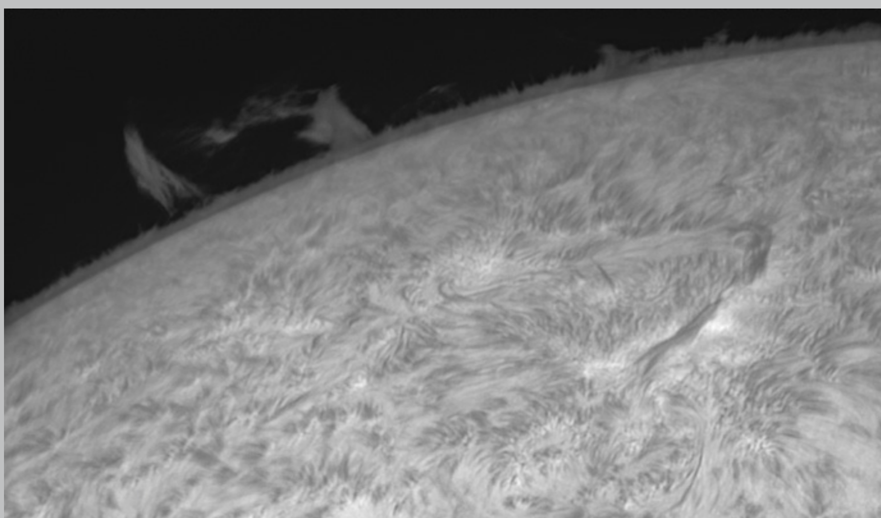
The camera performed as advertised, imaging the Moon, Jupiter, and Saturn, as well as the Sun through a refractor equipped with solar filter. But does it generate large files! For example, recording the Sun at full resolution, 136 frames per second, produced 2,039 frames in just 15 seconds, generating a 4-gigabyte movie file. Sean often filled the 150 gigs available on his computer's hard drive in less than an hour.

The Mars-M's monochrome sensor is among the more sensitive detectors available, with a peak quantum efficiency of 80% at 600 nanometers. It also has fairly good response at both the ultraviolet and near-infrared ends of the spectrum, which means the cameras should be excellent performers when imaging Venus through an ultraviolet filter or Jupiter through an 890-nanometer methane filter.

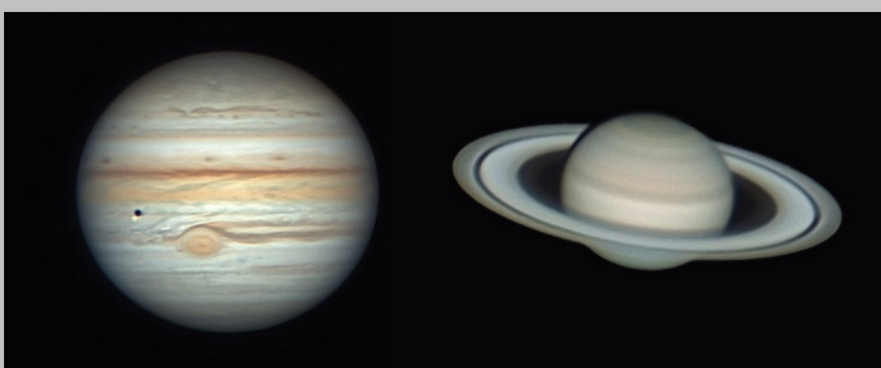
Jupiter and its moon Io display small-scale details in this image recorded on September 5, 2021, through a 12.5-inch Newtonian reflector and Astrodon RGB filters.

CAMERA IN FOCUSER: JOHNNY HORNE; JUPITER: SEAN WALKER / S&T

▲ The Mars-M camera is a great choice for imaging the Moon. The central peaks in the crater Tycho are well-resolved in this view that Sean recorded through his 12.5-inch Newtonian.



▲ The monochrome Mars-M camera works extremely well for imaging solar prominences through a telescope equipped with a solar filter. This image of the solar limb was recorded in a single video on July 23, 2021, through an Astro-Physics 92-mm Stowaway refractor and a Daystar Quark Chromosphere filter.



▲ The Neptune-C II color camera produces excellent images of the planets without the need for a filter wheel. It's hard to tell the difference between results shot with the color camera (shown here) and the image of Jupiter recorded with the monochrome Mars-M camera and RGB filters seen on page 67. Note the moon Europa seen in transit in front of Jupiter at left.

Sean employed a filter wheel loaded with red, green, and blue filters to create color images of Jupiter and Saturn by recording videos through each respective filter on his 12.5-inch, f/5.1 Newtonian reflector fitted with a Tele Vue 4× Powermate. The resulting SER videos were then processed using the popular planetary stacking programs *AutoStakkert! 3* and *RegiStax 6*.

The camera can utilize on-chip ROI, which means it only downloads the area specified by your control software. As a result, this method records many more frames than when using the entire chip. Even with the setup's working focal ratio of about f/20, Jupiter doesn't take up much space on the detector, so an ROI of 1,000 × 800 pixels was plenty enough to frame the planet as well as one or more Jovian moons in the field. A 45-second video of Jupiter through each color filter typically yielded a whopping 6,400 frames, with an average of 142 frames per second.

Since the Mars-M camera is geared towards high-resolution planetary imaging, its 1,920 × 1,080-pixel array doesn't provide enough coverage to record the entire Moon (or Sun, through a safe solar filter) with anything larger than a 300-mm lens. But the camera does take excellent high-resolution close-ups of lunar craters in any telescope and can easily produce high-resolution mosaics of the entire Moon with a little planning. Player One also offers an Apollo series of cameras billed as solar cameras, though curiously, none announced thus far provides a large enough field to record the entire Sun at high resolution.

Color with the Neptune II-C

While Sean concentrated on imaging with the monochrome Mars-M camera and color filters, Johnny put the Neptune-C II camera through its paces. He tested the camera on a Meade 14-inch ACF Schmidt-Cassegrain scope, a Celestron C11, and on a 102-mm William Optics refractor. The bodies of both cameras are identical except for the name on the rear plate. The real difference is internal — the Neptune-

MOON AND SOLAR PROMINENCE: SEAN WALKER / *S&T* (2); JUPITER AND SATURN: JOHNNY HORNE

C II uses a Sony IMX464 color CMOS sensor. This ½-inch-format chip sports a 2,712 × 1,538 array of 2.9-micron-square pixels measuring 7.9 × 4.5 millimeters. The chip is similar to Sony's IMX462 (*S&T:* May 2021, p. 30), which boasts excellent near-infrared sensitivity, but the IMX464 has twice as many pixels. Its peak sensitivity lies at about 820 nanometers and only drops to around 30% sensitivity at 1,000 nanometers, making it another good choice for imagers interested in recording details in Jupiter's atmosphere through an 890-nanometer methane filter.

In addition to the accessories included with the Mars-M camera, the Neptune-C II comes with a 1¼-inch UV/IR-blocking filter for use when imaging the planets or the Moon in natural color.

Although the camera's detector is relatively large, it was still difficult to center a target without additional aid. A flip mirror mounted ahead of the camera made finding and centering targets quick and easy.

On summer nights during testing, the camera got warm to the touch after constant use. Fortunately, this heat buildup didn't appear to add image noise even during long imaging sessions, thanks to its dead pixel suppression (DPS) technology, which replaces hot pixels with a median value of the surrounding pixels in each video frame.

The camera performed as advertised while targeting Jupiter and Saturn. Johnny notes that while atmospheric seeing conditions are always important for high-resolution planetary imaging, the Neptune C-II produced some of the highest quality lunar and planetary images he'd made to date.

He often operated the camera at its high-bit-depth setting (12-bit, which is converted to 16-bit in camera) and frequently recorded 1-minute videos of Jupiter at more than 120 frames-per-second in a ROI of 1,024 × 768 pixels. This yielded about 7,000 frames per video — plenty for sharp, detailed results when processed with planetary stacking programs.

◀▲ With the addition of Player One Astronomy's IR850nm filter, the Neptune-C II camera performs like a monochrome camera. This image of the Moon is a 4-frame mosaic recorded through a Celestron C11 Schmidt-Cassegrain telescope under poor seeing conditions.

The high sensitivity of the Neptune-C II also invites additional uses besides planetary imaging. Johnny attached a 2.1-mm CCTV lens to the camera and mounted it on a short tripod to monitor the sky for meteors.

Player One also included its optional S-series IR685nm and IR850nm near-infrared filters ($29.90 each), both of which improved videos of the Moon when imaging under unsteady skies. The detector's Bayer matrix color filter becomes virtually transparent at wavelengths longer than 800 nanometers, so videos recorded through the IR850 filter appear essentially identical to those recorded with a monochrome camera.

Both Player One Astronomy cameras proved to be excellent performers. Their high sensitivity coupled with fast download speeds make them suitable for small targets or lunar and solar vistas with a wide range of telescopes. Whether you prefer to image with a monochrome camera and a series of filters or favor the ease of use that comes with a color camera, both models should serve you well for years to come.

■ Associate Editor **SEAN WALKER** and Contributing Editor **JOHNNY HORNE** enjoy solar system imaging when the Sun, Moon, or planets are high in the ecliptic.

▶ When paired with a 2.1-mm CCTV lens, the Neptune-C II makes a very capable all-sky camera that can be employed to monitor sky conditions from indoors or capture meteors.

JOHNNY HORNE (3)

▲ DEEP-SKY CAMERA

SBIG announces a new CMOS camera in its line of deep-sky detectors. The SBIG STC-7 camera ($3,495) features a 14.4 x 9.9 mm, 7.1-megapixel Sony IMX428 CMOS detector with 4.5-micron-square pixels in a 3,208 x 2,200 array. This 12-bit camera has a full well capacity of ~22,500 e- with a peak quantum efficiency of 78%. The STC-7 operates in multiple gain modes with its innovative *Stack Pro* automatic, in-camera stacking program to produce smooth, low-noise images with high dynamic range. Additionally, the STC-7 has a built-in, 8-position filter wheel that comes complete with a full complement of LRGB and 6.5-nanometer narrowband filters. The camera is ASCOM-compatible and connects to a computer through a single USB 3.0 interface. Each purchase includes a universal power supply, a 2-inch nosepiece, a USB 3.0 cable, a copy of *MaxIm LT* control software, and a deluxe carrying case.

Diffraction Limited
59 Grenfell Crescent, Unit B, Ottawa ON, Canada K2G 0G3
+1-613-225-2732; diffractionlimited.com

▲ DOUBLET APOCHROMAT

Stellarvue adds a new model to its extensive line of SVX apochromatic refractors. The SVX 127D ($3,395) is a 127-mm (5.1-inch) f/8 doublet apochromat with one extra-low-dispersion element housed in a fully collimatable lens cell. The tube has a removable section before the focuser that allows the use of binocular viewers without the need for a Barlow or other optical amplification. The SVX 127D comes with a 3-inch-format, dual-speed focuser that has 112 mm (4.4 inches) of travel and includes both 2-inch and 1¼-inch eyepiece adapters with non-marring compression rings. Purchasers can upgrade to a Starlight Instruments 3-inch Feather Touch Focuser at additional cost. Each purchase comes with a pair of CNC-machined mounting rings and a dovetail finder mounting base.

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

▼ PLATE-SOLVING SCOPE

Celestron partners with *Popular Science* magazine for its newest observing package, the Popular Science by Celestron StarSense Explorer DX 5″ Smartphone App-Enabled Schmidt-Cassegrain Telescope ($499.95). This 5-inch (125-mm) f/10 telescope is paired with a custom alt-azimuth mount that operates in conjunction with your smartphone, using patent-pending technology to offer precise navigation. Simply install the *StarSense Explorer* and *SkyPortal* apps on any compatible device and place it in the smartphone docking port. The app will determine the exact location and direction that the scope is pointing by analyzing short exposures with the phone's camera. It then identifies star patterns in its extensive internal database, no matter where the scope is aimed in the sky, without the need of any complex alignment routines. The scope includes a StarPointer red-dot finder, 25- and 10-mm eyepieces, and an aluminum tripod with mirror. No additional power is necessary. Requires devices with Android 7.1.2 and later or iPhone 6 and newer iPhones.

Celestron
2835 Columbia St., Torrance, CA 90503
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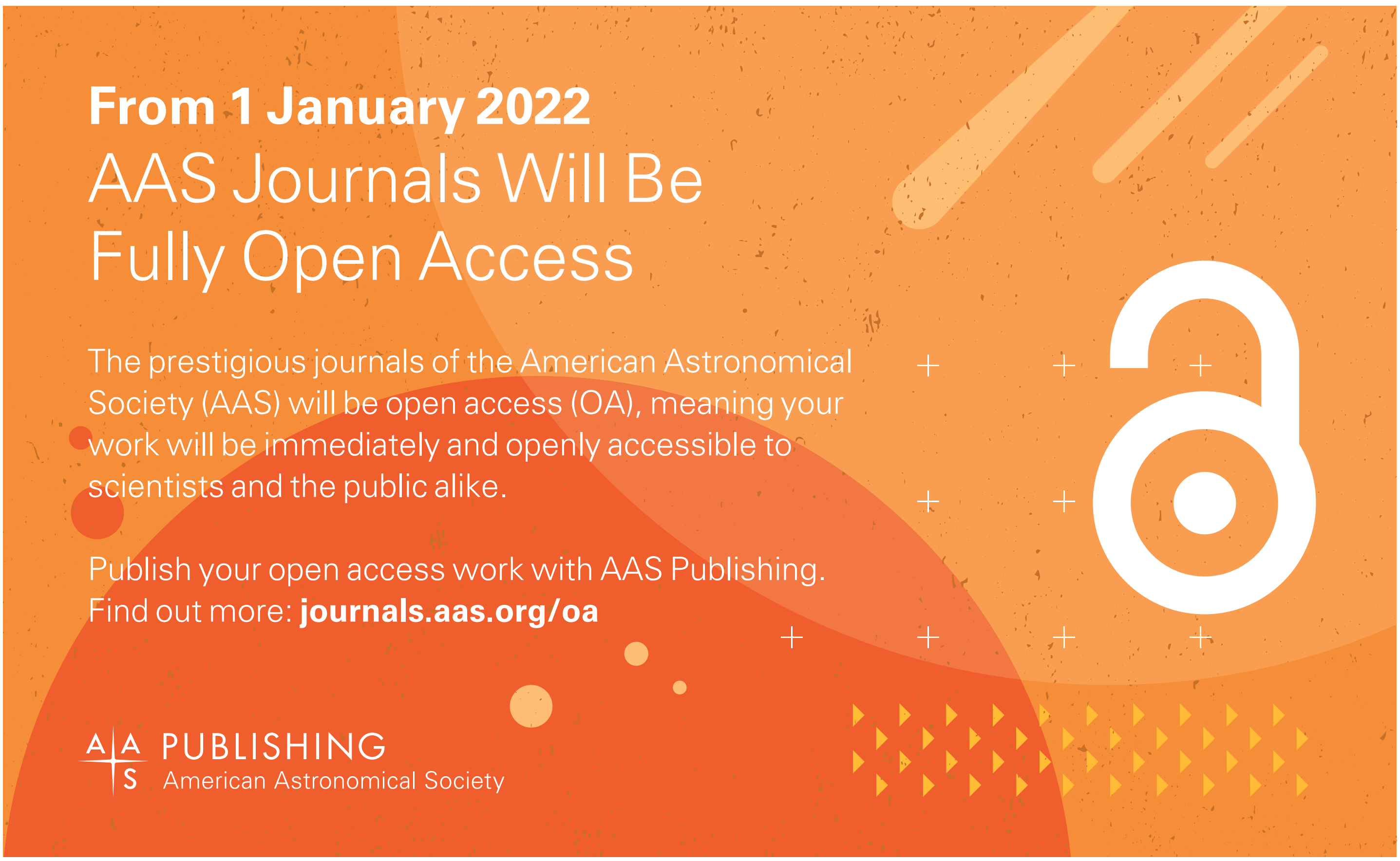
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Crafting a Wooden Refractor

Optical tubes don't have to be round.

The scope's equatorial wedge is adjustable for latitude.

LAST NOVEMBER I wrote about how you can build an inexpensive 80-mm refractor with a commercially available lens and focuser, some galvanized tin, and an oatmeal canister. This month let's look at how you can do a lot more of the fabrication yourself and do it beautifully.

Texas amateur Mike Ames purchased a 90-mm objective in its cell quite some time ago but didn't find time to do anything with it until the recent pandemic slowdown. He suddenly found himself with plenty of time, so he sat down to design a scope.

He had several design criteria he wanted to hit: Since he lives in an area with extreme light pollution, he needed it to be portable. He also wanted it to be easy to set up and use, and it had to be sturdy enough to survive the shake, rattle, and roll of travel without requiring a lot of tweaking at his destination.

He settled on a wooden tube, partly because he thought it would look great, while at the same time it would have no issues of paint chipping or the tube denting from travel abuse. He decided to make it an altazimuth mount to begin with, but always with the idea of an equatorial wedge as the project progressed.

Mike says, "My greatest choice of all was to allow myself to learn from my mistakes." Lacking a collection of power tools, he had to do much of the sawing by hand, with a lot of filing and sanding to true up the bad cuts. "I also learned that you must leave a little tolerance for fit since if you cut too small, the wood cannot be stretched to fit right."

Mike advises anyone else who tries a similar design to spend the most time working on the tube itself. That's the structure that matters most and must be made precisely. He chose a hexagon for his but says an octagon would also be a good choice. Even a rectangular box would do.

The tube is made out of spruce. The tube box (which Mike calls the "saddle") is poplar. The rocker box, wedge, and base are each made of oak. After all the wood was cut and ready to assemble, he applied a Pecan semi-gloss stain by hand-dipping with an old sock to rub it deeply into the wood grain — a trick his father taught him. The result is a beautiful surface that seems to glow with its own light.

◀ Mike Ames's 90-mm refractor is easy to transport and set up. The storage case doubles as a base to bring the scope to a convenient height for observing.

Mike made his own diagonal with a simple elliptical Newtonian first-surface mirror. Since every part of the tube assembly is glued in place, no movement of the diagonal is possible, and it never needs adjustment. The objective can be tilted, if necessary, by loosening the screws through the wooden collar, making the adjustment, and tightening them back up, but Mike reports that he hasn't needed to make adjustments in several months of use. A Campbell's Pork & Beans can provides the perfect dew shield.

▲ For proof of concept, Mike used a simple flat mirror. He replaced it with a first-surface elliptical diagonal in the final version.

ALL IMAGES COURTESY OF MIKE AMES

▲ The tube is assembled from straight boards beveled to 60° and arranged in a hexagon.

Mike used a six-inch-diameter Lazy Susan bearing on the right ascension axis and a pair of two-inch Lazy Susan bearings on the declination axis. He can easily adjust balance by moving the scope up and down inside the saddle. Friction pads allow it to hold position well once set.

Since the eyepiece is angled 90° to the tube, using the scope on a tabletop is a breeze, and tracking objects is easy and steady with only hand control. Focusing with the rack-and-pinion focuser mounted to the side of the tube is smooth and firm. The scope has a wide enough field of view at 20× that it doesn't need a finder.

The initial wedge was set only for his home latitude, but it's now a fully adjustable wedge and will be marked in major degrees of latitude for setting at any continental U.S. latitude.

Of course, transporting the scope requires a travel case, which Mike has also built out of wood. He used ⅜-inch, four-ply sheets of unknown type, and he made sure it was big enough to hold not only the telescope but two eyepieces and a Barlow.

The completed scope is a joy to use. Mike says, "I have spent hours just scanning the Milky Way, checking binary stars, looking at views of Andromeda and other wide-field views as well as making breathtaking observations and photos of the Moon, Mars, Jupiter, Saturn, and Venus."

For more information, contact Mike at **ames.mike@gmail.com**.

■ Contributing Editor JERRY OLTION is also a lignophile.

NGC 1788
Gerald Rhemann
Reddish hydrogen nebulosity glows along the edge of the molecular cloud containing the bluish reflection nebula NGC 1788 (left) in Orion.
DETAILS: *AstroSysteme Austria N12 astrograph with ZWO ASI6200MM Pro CMOS camera. Total exposure: 7 hours through LRGB and Hα filters.*

△ CELESTIAL CARNATION

Chad Leader

Sharpless 2-170 in Cassiopeia is a faint emission nebula roughly 6,500 light-years away. A single main-sequence star energizes this cloud of ionized hydrogen gas. Sequestered in the center of this nebula is the small open cluster of young stars known as Stock 18.

DETAILS: *Celestron 8-inch EdgeHD Schmidt-Cassegrain with ZWO ASI294MM Pro camera. Total exposure: 22.7 hours through Antlia narrowband filters.*

△ HEAVENLY CRUSTACEAN

Daniel Beaulieu

Messier 1, the Crab Nebula, is the expanding remnant of a naked-eye supernova witnessed by Chinese astronomers in AD 1054. Its tattered remains continue to spread away from the rapidly spinning pulsar in its center.

DETAILS: *Celestron 8-inch EdgeHD Schmidt-Cassegrain with QHY268PH M and ZWO ASI174MM cameras. Total exposure: 9½ hours through narrowband filters.*

A SPIRALING CASCADE

Mark Hanson

Pinkish star-forming regions bespeckle the arms of the nearby spiral galaxy NGC 247. A string of more distant spirals known as Burbidge's Chain trail off to the bottom right. South is up.

DETAILS: *PlaneWave Instruments CDK24 with SBIG STX-16803 CCD camera. Total exposure: 40 hours through LRGB and Hα filters.*

△ THE GREAT RIFT

Alex Roberts

The glowing edges of towering dust columns in IC 1871 appear to lie in front of the bluish nebulosity of IC 1848 to its right. Intense stellar winds from newborn stars within the nebula sculpt intricate patterns in this active star-forming region.

DETAILS: *Orion 10-inch Newtonian astrograph with ZWO ASI 1600MM Pro camera. Total exposure: 16 hours through Chroma narrowband filters.*

◁ TWO SPIRALS IN CRATER

Warren Keller and Mike Selby

Reddish star-forming regions line the arms of these galaxies in Crater. Classified as an intermediate spiral galaxy, NGC 3511 (bottom right) displays the characteristics of both spiral and elliptical galaxies, while NGC 3513 (top left) is a barred spiral galaxy since its arms don't connect directly to its central bulge.

DETAILS: *Officina Stellare RiDK 700 and RiDK 500 telescopes with FLI ProLine 16803 camera. Total exposure: 29 hours through LRGB filters.*

△ WHERE THE LAKE MEETS THE SKY

Cem Özkeser

Lake Tuz in Turkey encircles the sky in this creatively stitched mosaic. The Milky Way from Puppis at the bottom left to Cygnus at the top right bisects the scene, while the zodiacal light crosses from left to right.

DETAILS: *Sony α7 II camera with 14-mm lens set to f/4. Panorama of 16 frames, each a stack of 3 exposures recorded at ISO 5000.*

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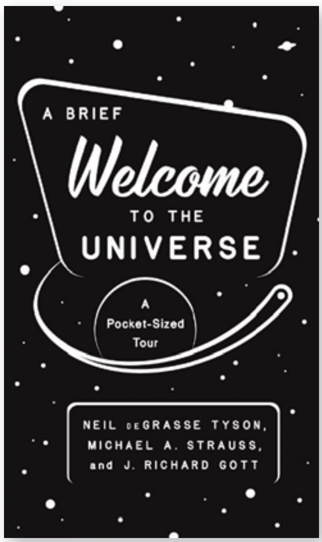

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Touching the Cosmic Scale

How an astrophysicist gets his head around enormous stretches of space and time

WE OFTEN THINK OF cosmic scales as being nearly ungraspable. Recently, on a long drive, I traveled about one millionth the distance to the Sun, which of course is only the nearest star in our galaxy, which is one of many galaxies in our local cluster of galaxies, which is one of many such clusters in the observable universe. Against such universal scales, the everyday usually doesn't compare.

But the reason for my drive was to see 190-million-year-old dinosaur footprints beside the Connecticut River in west-central Massachusetts. Here, early ancestors of *Tyrannosaurus rex* walked across muddy ground that, over time, solidified into rock and preserved these footprints as fossils.

When I put my hand inside the much larger, three-toed footprint in the sandstone, I immediately noticed how smooth the footprints were compared to the rock around them. Even more than by the size of the footprint itself, I was transported by the wonder of touching the very same spot as these amazing creatures that inhabited our planet before us. I stomped across the rock, trying to match their loping gait.

A hundred and ninety million years is a long time, especially compared to the several million years that humans are thought to have existed. Even by cosmic standards, 190 million years is an impressive stretch. It's about 5% of the age of our planet, solar system, and Sun. Over this time, our star has fused 600 Earth masses worth of hydrogen into helium, releasing the energy that powers life on our world.

On Earth, a footprint in the mud is usually one of the most ephemeral traces creatures leave as we interact with our planet. Certainly others that we humans have created, such as pollution byproducts, will be longer lived. On the Moon, however, the bootprints of Apollo astronauts may still exist 190 million years from now without geologic upheaval or atmospheric erosion processes to disrupt them.

DEEP-TIME CAPSULE Buzz Aldrin's bootprint left during the Apollo 11 Moon landing

NASA / BUZZ ALDRIN / PUBLIC DOMAIN

> Bootprints of Apollo astronauts may still exist 190 million years from now.

Ironically, these lunar bootprints are intensely fragile — held static in the dust only by the lack of anything to disturb them. Given the chance to touch one, though, a lunar footprint wouldn't be smooth. Without the polishing action of wind or water, the Moon's dust, which impacting meteorites have blasted over billions of years, is jagged and crystalline, like microscopic glass shards. It's so abrasive that Apollo 17 astronauts Harrison Schmitt and Eugene Cernan broke down laughing after struggling to pull off each other's dust-caked gloves and helmets after a seven-hour moonwalk, noting that "everything is twice as hard" to remove.

One of the great privileges of being an astronomer is having the chance to reflect on scales of cosmic magnitude every day. Even so, my mind finds a shield against such vastness in familiar numbers like "one solar radius," the radius of the Sun — which feels easier to consider than 700,000 km (435,000 mi) — or "200 parsecs," the distance to Betelgeuse, the red supergiant marking Orion's shoulder.

That mental shield begins to come down when we invoke our senses. By touching the smooth contours of a 190-million-year-old footprint or wrenching off gloves embedded with the crystalline shards of meteorite impacts, we can more deeply appreciate what it means to be one small human in a very, very large universe.

■ **MORGAN MACLEOD** is a computational astrophysicist at the Center for Astrophysics | Harvard & Smithsonian.

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