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SKY & TELESCOPE

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THE FUTURE OF ASTRONOMY

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ON THE COVER

Sometimes the future feels like it's coming at warp speed.
PHOTO: EDUARD MUZHEVSKYI / SHUTTERSTOCK.COM

ONLINE

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ASTRONOMY EVENTS
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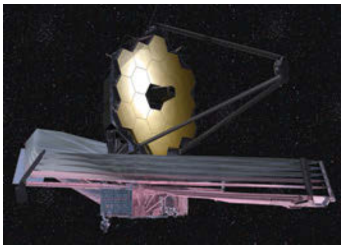
80 Years and Counting

AS WE CELEBRATE OUR 80TH YEAR of publication with this issue, I can't help but draw a comparison to a full human lifetime. In the U.S., life expectancy at birth is currently about 80 years. That number varies, of course, by gender, race, and other factors, including pandemics, but for the sake of argument let's say it's 80 years.

In terms of bare survival, *Sky & Telescope* has had its scares since its birth in November 1941. The most life-threatening, as many readers know, occurred just two years ago, when our former owner declared bankruptcy. For a few months, *S&T*'s future remained uncertain. After well over 900 monthly issues, would 2019 witness the end of *Sky & Telescope*? None of us on staff really believed that, but the question hovered around our offices like a stifling miasma.

Happily, instead of shutting our doors we threw them open to our new partners at the AAS. And here's where we diverge from an ideal human life span: We're now looking ahead to our *next* 80 years.



▲ Built on the shoulders of giants: the James Webb Space Telescope in an artist's conception

NASA

In light of this, we've structured this issue around three periods of time: where we've been, where we are now, and where we're going. And by "we" we mean not just *S&T* but amateur and professional astronomers as well.

To reminisce about where we've been, see "A Golden Age for Amateur Astronomy" (page 14) and "Arc of an Amateur" (page 58). For where astronomy is now, we offer "Building the James Webb Space Telescope" (page 20) and "To Build or Buy?" (page 66).

For where astronomy is headed, we present a special section on cutting-edge technologies and mission concepts that may soon transform the field (pages 28–39). This section wraps up with a timeline that distills top astronomers' predictions on the developments we might expect in astronomical science and exploration between now and 2050.

We're not so naïve as to forecast beyond mid-century, much less all the way to our 160th birthday in 2101. That said, find out why astrobiologist David Grinspoon feels confident that we'll have an answer to the age-old question "Are we alone?" by the end of this century (page 12).

We close this special issue with a personal look at what *Sky & Telescope* has meant to one of its longest-serving editors (page 84). Like that of many staffers we've had, Dennis di Cicco's dedication exemplifies what has been the beating heart of *S&T* throughout our eight decades: its people.

And that includes you, our readers. Thank you for your ongoing support as *S&T* enters on the next leg of its mission to share the wonders of the universe.

Peter
Editor in Chief

SKY&TELESCOPE
The Essential Guide to Astronomy

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

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Locating Messier 56

Mathew Wedel's tip for finding M56 in "Lost in Space" (*S&T:* Aug. 2021, p. 43) is outstanding! The asterisms are striking in binoculars. It illustrates once again how much the human brain loves patterns.

Bob Wieting • Simi Valley, California

▶ In his Binocular Highlight column for August, Matt Wedel discussed his solution to locating M56 in Lyra for anyone struggling to find this spectacular globular cluster.

Binoculars for the Near-sighted

I enjoyed Alan Dyer's article "Buying Binoculars for Astronomy" (*S&T:* Aug. 2021, p. 60). While I am quite near-sighted, I prefer to use my binoculars without my eyeglasses. Thus, there's one feature of binoculars that companies almost never advertise but is quite important to me, the diopter adjustment range. Even the salespeople don't always know this number, and Alan Dyer's article did not mention it. So I usually end up buying binoculars and hoping for the best. My Vixen Optics 10×50 Porro-prism binoculars are excellent in this regard and seem to compensate for nearsightedness up to −8 diopters.

Stewart Novick
Bolton, Connecticut

Alan Dyer replies: *You are correct that most manufacturers don't state the range of diopter adjustment. People with eye prescriptions where one eye differs widely from the other can find binoculars difficult to use. Most diopter adjustments vary by ± 3 or 4 diopters, which is enough to accommodate a good number of people. But for those who know their eyes are very unequal and who do not wish to use eyeglasses when observing, the best advice I can give, in the face of no published specifications, is to buy binoculars from a supplier that allows easy returns should they prove unsuitable. The same is true of interpupillary distance (IPD), which is typically adjustable over the range of around 55 to 70 mm (2 to 2.8 inches). Fortunately, the manufacturers usually provide the IPD range.*

Go To, Shoot, Enjoy, Repeat!

Hurrah for Greg Redfern's "Four Tips for Better Astropics" (*S&T:* Aug. 2021, p. 54)! I appreciate that it encourages single-exposure amateurs like me. I'm currently using somewhat older equipment with a slightly different goal.

His third tip mentions covering your setup for multi-night action. That has been my mainstay for years. I use a white drawstring kitchen bag to cover my short 5-inch (127-mm) Orion refractor, a modified Canon camera, and a piggybacked, even-older Pentax camera with a selection of Takumar lenses. I also clothespin a larger clear bag to the spreader under my Celestron mount. It controls the temperature and keeps out moisture (and bugs) indefinitely.

I take advantage of poor conditions to perfect my mount's polar alignment using the drift method, shooting 1-second guide-star tests at 10-minute intervals. This technique provides excellent tracking during the days, or weeks, that I have the telescope out.

Then I use the camera as an eyepiece! I choose objects from the Orion DeepMap 600 star chart that are relatively large but quite dim. I rarely need more than a 2-minute exposure to reveal much greater detail and color than I can see visually, even with my larger telescope. Thanks to this modest setup, my list of viewable objects has grown enormously, far beyond the Messier catalog, and now includes many dark nebulae and supernova remnants.

Steven Marshall
Milwaukee, Wisconsin

Archaeoastronomy

When I received notice of the August digital issue in my email, Douglas MacDougal's "Alas, Babylon! When Mars Draws Near . . ." (*S&T:* Aug. 2021, p. 24) caught my eye. It involved a look at ancient cuneiform texts that Babylonian stargazers used to record the movement of celestial objects. Mesoamerica also had an interesting heritage of ancient skywatchers. I recently read *Prehistoric Astronomy in the Southwest* by J. McKim Malville and Claudia Putnam. There are many books on the topics of archaeoastronomy and ancient astronomy. A good book about astronomy's past recorders is essential to better understanding the science today and tomorrow!

Most ancient peoples watched the sky. Tens of thousands of years ago, they used bones and cave walls to record lunar cycles. And, of course, the ancient Chinese provided many records of historic celestial events. Knowledge of the sky once was fundamental to many cultures.

I greatly enjoyed the article. I'm a fan of the topic!

Clarence Underwood
Pittsburg, California

▲ This replica of a cuneiform tablet depicts the ancient night sky. The original was found in the buried ruins of an Assyrian library and currently resides in the British Museum in London.

I read Douglas MacDougal's article about ancient astronomers' treatment of planetary positions with interest and appreciation. In my last semester at Brown University, I was the only student enrolled in the History of Astronomy course taught by Otto Neugebauer, whom MacDougal calls "the pioneering

M56: NASA / ESA; THE PLANISPHERE: CLARENCE UNDERWOOD

20th-century translator and scholar of ancient mathematics." MacDougal's explanations of Mars' oppositions and synodic period, and his descriptions of his calculations, shed new light on what I learned in my college course.

The one thing that puzzled me was Kepler's drawing of the path of Mars in the sky on page 28. The figure's caption doesn't explain what the small dashed circle at the center is nor the labels A and B.

Edw. S. Ginsberg
Lexington, Massachusetts

Douglas MacDougal replies: *How lucky you were to take a course from Otto Neugebauer! Your question is best answered in Kepler's own words (from William Donahue's translation of* Astronomia Nova*): "Take note, too, that since the orb of Mars requires such a vast space, the spheres of the sun, Venus, Mercury, the moon, fire, air, water, and earth, have to be included in the tiny little circle around the earth A, and in its little area B." Kepler, a devout Copernican, used the Martian spirals diagram to make a forceful argument for the implausibility of Ptolemy's geocentric solar system.*

Under Ptolemy's scheme, the order of the solar system outward from the central Earth was the Moon, Mercury, Venus, the Sun, Mars, Jupiter, and Saturn, and each sphere's maximum (apogee) radius touched the minimum (perigee) radius of the next. This meant that the Moon, Mercury, Venus, and the Sun all had to fit within the nearest perigee of Mars, the innermost loops of the diagram. All four bodies thus would be crammed tightly into the space enclosed by the circle, A. This seemed impossible to Kepler, in contrast to the much simpler system of Copernicus, which entirely rid all the planets of these extremely intricate spirals and placed the individual planets into their respective orbits.

Deep-Sky Delights

Ted Forte's article "Observing the Pegasus I Galaxy Cluster" (*S&T:* Aug. 2021, p. 57) made me concentrate on the first image. For a beginner like me, the breadth of stars and galaxies in this central image appear realistic.

The layout of the article encouraged me to continually flip back to page 57, forcing me to stop reading and focus on the visual practice of locating the deep-sky objects in my 81-mm (3-inch) and 254-mm (10-inch) telescopes.

Forte's writing is nothing short of a Bortle 1 sky. His ending lines are lovely and romantic, encouraging readers to attempt to find objects that must have taken him years of training to locate. The confident, succinct history lessons made me read this article twice.

Julian Samuel
Toronto, Ontario

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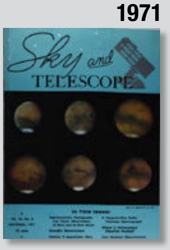
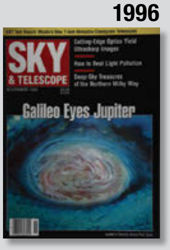
75, 50 & 25 YEARS AGO by Roger W. Sinnott

1946

1971



1996



November 1946

Galactic Bulge "[A] bright nucleus or clustering of stars about the center [of our galaxy in Sagittarius] has never been observed, presumably because of interstellar dust clouds. . . . During the summers of 1945 and 1946, Drs. Joel Stebbins and A. E. Whitford . . . made a search in infrared light [with] the 60-inch reflector . . .

"[They found a] persistent bulge . . . outlined by an elliptical figure some eight degrees long and 3½ degrees wide. [This region's] extreme redness . . . indicates that less than 1/1,000 of the ordinary blue photographic light gets through the obscuring interstellar dust."

Stebbins and Whitford were on the right track to search using infrared. The Milky Way's compact nucleus, now called Sagittarius A, was first accurately located by radio interferometry in 1974. More recently, infrared studies have been possible with large telescopes, but in visible light, interstellar dust almost completely obscures the Milky Way's central bulge.*

November 1971

Test Double "Just east of Gamma Orionis is a 4th-magnitude double star worth examining in fairly large amateur telescopes on a winter evening. It is 32 Orionis . . .

"Discovered by William Herschel in 1782, this pair consists of two stars of magnitudes 4.6 and 5.9. According to W. van den Bos, the stars probably do not form a binary system, but instead are unrelated objects that chance to lie nearly in the same line of sight. . . .

"The closest approach of the components came in 1906, when the angular separation was only 0″.20. By the end of 1971, the companion will be [northeast of the primary], separation 0″.88."

Today the stars' separation has grown to 1.5 arcseconds, making this unequal pair a good test for a 4-inch telescope.

November 1996

Protogalaxies "The building blocks of present-day galaxies like the Milky Way may have been captured in images from the Hubble Space Telescope (HST).

"[In Hercules, a] recently discovered cluster of galaxies . . . is seen as it was only two or three billion years after the Big Bang. To seek sites of star formation at that early epoch, Sebastian M. Pascarelle (Arizona State University) and his colleagues imaged the cluster with a filter centered on the Lyman-alpha emission line from hydrogen gas. . . .

"As the researchers report . . . 18 amorphous objects stood out in their filtered images. . . . The objects typically span only 5,000 to 15,000 light-years [and] a few of the curious objects show evidence of merging. These observations led Pascarelle's team to speculate that the blobs are destined to coalesce, eventually forming elliptical or spiral galaxies like those seen today."

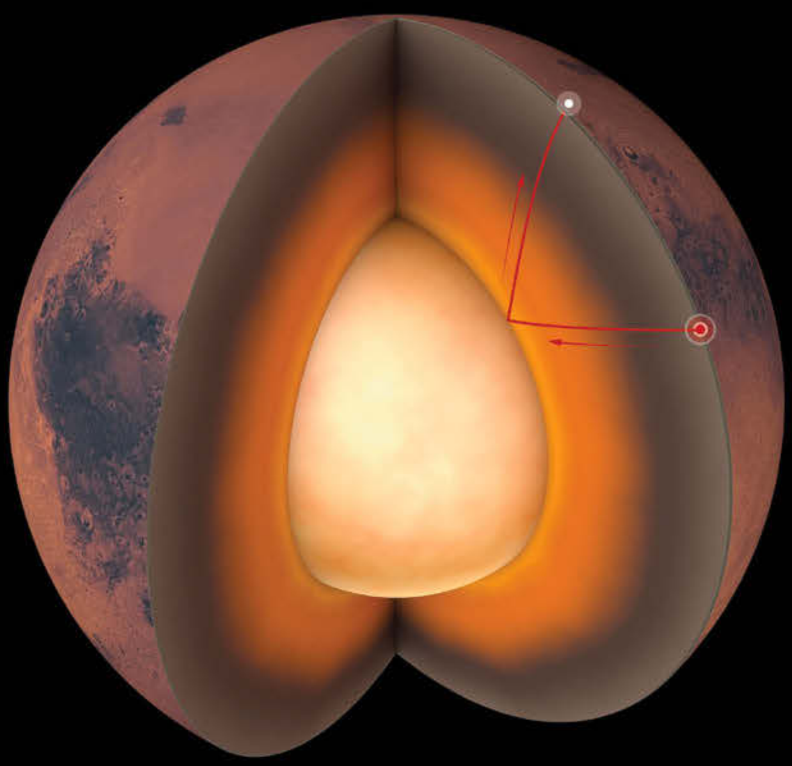
MARS

NASA's Insight Reveals First Look Inside Mars

NASA'S INSIGHT MISSION has reported the first direct observations of another rocky planet's interior structure, publishing a trio of studies in the July 23rd *Science*. The results — a surprisingly thin crust, a one-layer mantle, and a large core — will help scientists understand how Mars formed and evolved.

Measuring marsquakes wasn't just a matter of sending a seismometer to Mars; in a sense, the scientists also had to wait for the planet to come to them. While Insight recorded 733 marsquakes since early 2019, the vast majority were weak, surface tremors. "Of course, when you're in the middle of the situation, it can feel as if 'Oh my god, it's not *working*!'" says Simon Stähler (ETH Zurich, Switzerland).

▼ This illustration shows shear seismic waves reflecting off Mars's iron-nickel core, which provide an estimate of the core's size. The strength of the reflected waves revealed the core to be in a liquid state, through which shear waves cannot propagate.



CHRIS BICKEL / *SCIENCE*

The team waited several months after the seismometer's deployment before a shake occurred deep enough to probe the planet's interior, says seismometer co-investigator Brigitte Knapmeyer-Endrun (University of Cologne, Germany).

That quake already showed what additional deep ones would confirm: The Martian crust was thinner than expected. At first, analysis suggested that the crust had two layers and was only 20 kilometers (12 miles) thick beneath the Insight lander. "This was thinner than any models had predicted," Knapmeyer-Endrun says. Additional events and analysis revealed that the crust could have an additional layer, making it twice as thick (39 km) and somewhat closer to expectations.

A thinner crust would be "very surprising indeed," says Doris Breuer (German Aerospace Center), who was not involved in the study. "A thin crust would raise many questions about how it was formed and what this means overall for the thermochemical evolution of Mars."

Insight data can't distinguish between the two possibilities yet, though Knapmeyer-Endrun hopes additional data and analyses will help resolve the ambiguity.

Meanwhile, Amir Khan (ETH Zurich, Switzerland) and colleagues found that the mantle of Mars is simple and deep, extending 400 to 600 km down. Compared with Earth's two-layer mantle, Mars's single-layer version is less insulating, so the core loses heat more quickly.

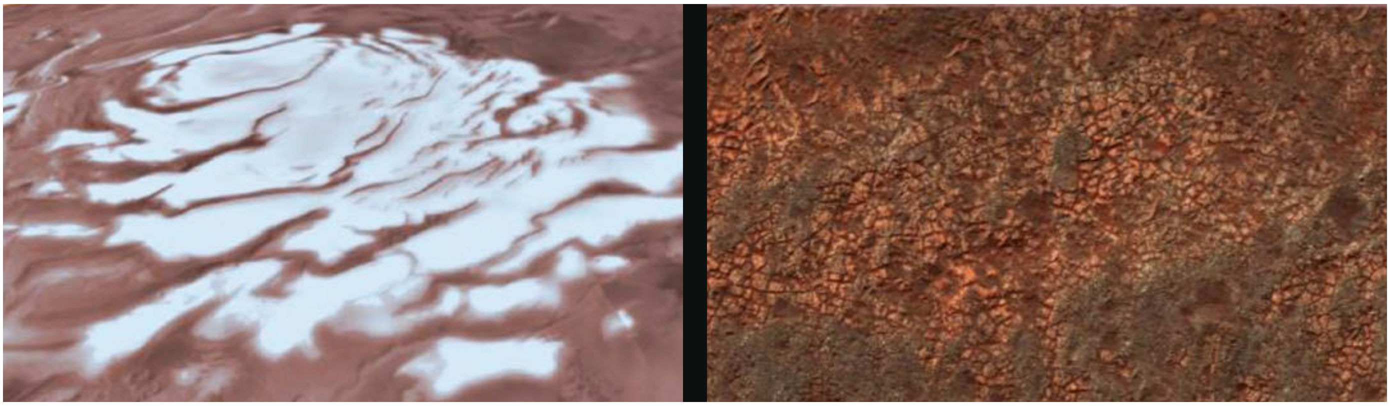
Nevertheless, Insight data confirm that the core is fully liquid. With the analysis of six marsquakes coming in at just the right angles toward Insight, Stähler and colleagues found that the core is on the larger end of what previous indirect measurements had suggested, between 3,580 and 3,740 km across. Its seismic shadow blocks quakes from the active Tharsis Rise on the other side of the planet.

Such a large core probably contains a high proportion of lighter elements. It also probably doesn't have the solid inner part that Earth's core does. On Earth, the cooling inner core is the power source of the magnetic dynamo: As it crystallizes, it releases heat that churns up the outer core. Without an inner core, the global magnetic field on Mars most likely came from the release of the intense heat of the planet's formation, which is why it only lasted a few hundred million years.

NASA recently extended the Insight mission through the end of next year (*S&T:* May 2021, p. 10), past the current Martian winter, when marsquakes are difficult to detect due to high winds. During that time, the scientists expect Insight to double the number of high-quality, low-frequency quakes that enable them to probe the planet's interior.

■ MONICA YOUNG

"Liquid Water" Spots Below Martian Surface Might Be Clay



▲ *Left:* An artist's illustration shows the ice-and-dust deposits at Mars's south pole. *Right:* This image shows radar measurements of smectite clays, conducted under Mars-like conditions in the lab. The results reproduce the radar signatures detected by MARSIS.

LEFT: ESA / DRL / FU BERLIN; RIGHT: NASA

RESEARCHERS HAVE IDENTIFIED dozens of radar-bright spots within the layers of ice and sediment deposits at Mars's south pole. These discoveries follow the 2018 announcement of a large radar-bright area beneath those deposits that researchers said might indicate a subglacial lake (*S&T:* Nov. 2018, p. 8). However, the additional finds, as well as further experiments and analysis, suggest that the spots might be ancient clay deposits instead of liquid water.

In a study published in the July *Geophysical Research Letters*, Aditya Khuller (Arizona State University) and Jeffrey Plaut (Jet Propulsion Laboratory) used the Mars Advanced Radar for Subsurface and Ionosphere Sounding (MARSIS) instrument aboard the European Space Agency's Mars Express orbiter to chart the subsurface boundary where the polar deposits end and the Martian interior begins. Their investigation revealed dozens of new smaller radar-bright regions at this interface, which appear to be widespread beneath the south pole's ice-and-dust deposits.

If these bright areas are indeed lakes, they must be very salty. Even though the subsurface temperatures on Mars drop below the freezing point of pure water, dissolved salts can keep water liquid at lower temperatures.

However, a new study from a team led by Carver Bierson (Arizona State University), also in the July *Geophysical Research Letters*, suggests that super-salty water isn't the only option. His team shows that highly conductive materials, like saline ice and hydrated clays, can strongly reflect radar.

Another study in the August issue of the same journal, led by Isaac Smith (York University, Canada), supports the case for clays. Smith's team investigated a type of clay called *smectites*, which are common on the Red Planet's surface and found near the edge of the south polar cap. The scientists studied smectites in a laboratory under frigid conditions that mimic the Martian subsurface. They found that hydrated smectites make a brittle paste when frozen, one that could reproduce the radar signatures detected by MARSIS.

Liquid water might have hydrated smectites more than 100 million years ago, before layers of ice and dust preserved the clays. But Bierson says that salty ice and other clays are still radar-reflective contenders.

■ **LAUREN SGRO**

Read additional details from these studies at https://is.gd/Marsclay.

IN BRIEF

Resolving the Mars Methane Mystery

New measurements from NASA's Curiosity rover show that methane concentrations near the Martian surface vary on a daily cycle, a finding that could help reconcile conflicting data. Curiosity first sniffed the gas on June 15, 2013, and has since found background methane levels between 0.2 and 0.7 parts per billion in volume (ppbv). But in 2019, the European Space Agency's ExoMars Trace Gas Orbiter failed to find methane after several months of operation. ExoMars examines sunlight that has traveled through the atmosphere's upper layers and should be able to detect particle concentrations as low as 0.05 ppbv. Then John Moores (York University, Canada) realized that the discrepancy could boil down to the time of day: Curiosity takes methane measurements at night, when the atmosphere is cool and calm, while ExoMars looks at the atmosphere at sunset after a day of Sun-driven mixing. The Curiosity team tested this idea by bracketing a nighttime measurement, which yielded 0.5 ppbv, with two daytime ones, which didn't pick up any methane at all. The data take a step toward reconciling the Curiosity and ExoMars results, but work remains to understand why methane doesn't build up in the atmosphere over time. Christopher Webster (Jet Propuulsion Laboratory), Moores, and colleagues reported the results in the June *Astronomy & Astrophysics*.

■ **JAVIER BARBUZANO**

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

EXOPLANETS

Kepler Finds Possible Outcast Earths

◀ An artist's impression shows a free-floating Earth-mass planet.

CHRISTINE PULLIAM / CFA

ASTRONOMERS HAVE UNCOVERED four candidate Earth-mass rogue planets by searching for microlensing events observed with NASA's Kepler satellite. Rogue planets drift aimlessly through space after ejection from their stellar system during the early stages of planet formation. Iain McDonald (now at Open University, UK) and colleagues announced the new planet candidates in the August *Monthly Notices of the Royal Astronomical Society*.

When a star or planet passes in front of a distant star, it acts like a magnifying lens to temporarily brighten the background star, an effect known as microlensing. Rogue planets are best spotted via microlensing because they're too faint to detect directly. However, the smaller the "lens," the shorter the microlensing event; Earth-mass planets magnify background stars for only a couple of hours, making them difficult to differentiate from stellar flares.

A team lead by McDonald pored through data from the rejuvenated Kepler mission, dubbed K2, to recover previously detected microlensing events and find new ones, too. Four of the new events lasted only a couple hours at most, implying rogue-planet masses comparable to Earth's. Previously, astronomers had detected only a handful of such short-lived microlensing episodes, making the new events a valuable addition.

But Przemek Mróz (Caltech), a fellow rogue-planet hunter, cautions that these planet candidates might not be true drifters. "Figuring out whether these objects are indeed free-floating or not is trickier," he says. Some of these planets might be orbiting far from their host star, he explains, so their microlensing signature would be nearly identical to that of free-floating planets.

If outcast Earths are truly typical in our galaxy, future facilities such as the Nancy Grace Roman Space Telescope should easily detect their signals.

■ LAUREN SGRO

IN BRIEF

Witnessing Gravitational Instability

Astronomers have reported a gravitationally unstable disk around the young star Elias 2-27 in the June 20th *Astrophysical Journal*. Gravitational instability is one path to planet formation: When disks become massive enough, they may collapse directly into planets or form spiral arms that trap material for future planet formation. A team led by Teresa Paneque-Carreño (now at Leiden University, The Netherlands) used the Atacama Large Millimeter/submillimeter Array to spot a hallmark wiggle, a signature of gravitational collapse, in the spiral arms of the disk around Elias 2-27. The wiggle is a disturbance in the disk's rotation on scales coinciding with instability-induced spiral arms. Paneque-Carreño's team saw the wiggle by observing the motions of carbon monoxide in the disk, which traces the harder-to-observe hydrogen gas. Furthermore, a companion study concluded that Elias 2-27's disk has 17% the mass of its star, creating conditions ripe for gravitational instabilities to occur. Together, the spiral, wiggle, and mass all indicate the disk is gravitationally unstable, providing convincing evidence of this planet-formation mechanism in action.

■ LAUREN SGRO

SOLAR SYSTEM

Amateur Tracks Down New Moon of Jupiter

AN AMATEUR ASTRONOMER has pinpointed a new moon of Jupiter, first spotted in 2003 but whose orbit was never determined. If approved by the International Astronomical Union's Minor Planet Center, the find would bring the tally of known Jovian satellites to 80.

Kai Ly, the amateur who last year recovered four lost Jovian moons (*S&T:* May 2021, p. 12), examined images that David Jewitt, Scott Sheppard (both then at University of Hawaii), and their colleagues had recorded almost two decades ago with the 3.6-meter Canada-France-Hawaii Telescope (CFHT). In 2003, that group announced the discovery of 23 tiny Jovian moons, and the images they used remained available online to the public.

Recently, Ly found another potential moon in images from the past survey, one so faint that it's probably just 1 km across. That led to its recovery in additional survey images obtained throughout the spring of 2003. "From there on, the orbit and ephemeris quality were decent enough for me to search observations beyond 2003," Ly explains.

Ultimately, Ly tracked the moon — provisionally designated S/2003 J 24 — through 76 observations taken over 15.26 years (5,575 days). That's the equivalent of nearly eight orbits, says David Tholen (University of Hawai'i), more than enough to show it's bound to Jupiter and to consider the trajectory well-secured for decades. Ly reported the orbit they determined to the Minor Planet Mailing List on June 30th.

The moon is a typical member of the Carme group, which includes 22 other small retrograde satellites with periods of around two years. They are probably all fragments of Carme, the first of the group to be discovered and by far the largest.

■ JEFF HECHT

GALAXIES

Lost & Found: Milky Way-size "Orphan Cloud"

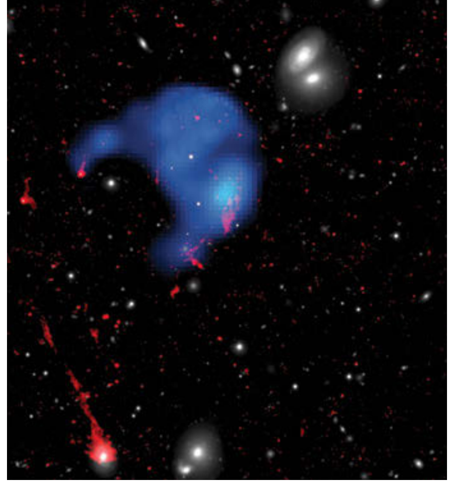
TEN BILLION SUNS' WORTH of hot gas are hanging in space in a fog almost 6 million light-years across. Bigger than the Milky Way, this "orphan cloud" was probably torn long ago from the galaxy it once called home.

Astronomers found the cloud by its hydrogen's deep-red glow, roughly 310 million light-years away in the Leo Cluster (Abell 1367). Follow-up observations revealed X-rays coming from the cloud, making it unique among lonely clouds that astronomers have previously spotted, Chong Ge (University of Alabama, Huntsville) and colleagues report in the August *Monthly Notices of the Royal Astronomical Society*.

When a galaxy falls into a cluster, it passes through hot gas that fills the in-between space. This material rams into the galaxy's cooler, denser gas, pushing it out. Even bereft of its stellar nurseries, the galaxy will sail on through the cluster with its older stars and dark matter still bound to it. Astronomers have nicknamed gas-streaming galaxies "jellyfish" for their appearance.

In this case, though, Ge and colleagues couldn't find an obvious parent galaxy. Based on this and observations of motions within the cloud, the researchers estimate that it's half a billion years old. Yet, the orphaned gas ought to mix into the hotter and sparser surrounding medium, evaporating within 30 million years. The team suggests a weak magnetic field (6 microgauss, typical of that between stars in the Milky Way) might have helped the cloud survive.

"The fun thing to me about the 'orphan' is how unusual it is," says Rhys Taylor (Astronomical Institute of the Czech Academy of Sciences), who



▲ The "orphan cloud" is the blue Klingon battle cruiser–shape part of this image. X-rays are shown in blue, hydrogen-alpha emission is red, and visible light is white.

was not involved in the study. "Clearly, whatever process formed it can't be all that common, or we'd find such features everywhere."

Team leader Ming Sun (also at University of Alabama, Huntsville) says the team is obtaining more information about the cloud's cooler gas to help unravel its mysteries.

■ MONICA YOUNG

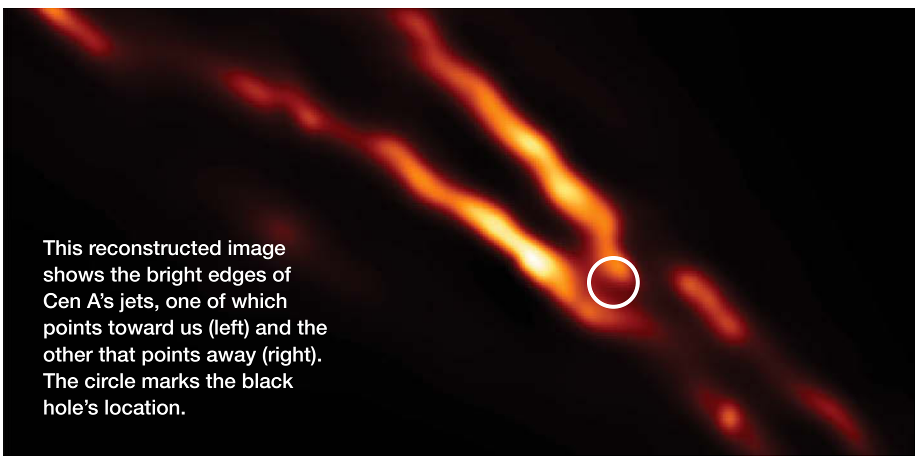
BLACK HOLES

Event Horizon Telescope Reveals Curious Black Hole Jet

THE EVENT HORIZON TELESCOPE collaboration has peered deeply into the heart of the radio galaxy Centaurus A, revealing details of its long, powerful jets. The results appear July 19th in *Nature Astronomy*.

Cen A lies only about 12 million light-years from us and hosts a supermassive black hole that's actively swallowing gas and shooting out a narrow jet from top and bottom. The team used seven facilities across half the globe to image the jet at radio wavelengths.

Based on years of detailed simulations, astronomers think that the center of a black hole's jet (its "spine") is largely empty — it's essentially a giant, corkscrew-like magnetic field with a few electrons and other particles zooming through, explains team member Michael Janssen (Max Planck Institute for Radio Astronomy, Germany). An immense number of particles, blown off the black hole's big fluffy gas disk, sheath this spine. Because the jet doesn't point directly at us, the light from its fast-moving spine largely misses our line of sight. But the electrons spiraling around in the sheath emit photons at all sorts of angles, so we can see the edges quite well.



This reconstructed image shows the bright edges of Cen A's jets, one of which points toward us (left) and the other that points away (right). The circle marks the black hole's location.

"What should be emphasized is how incredibly rare it is to have images on this scale, so close to the black hole," says Eileen Meyer (University of Maryland, Baltimore County), who wasn't involved with the study. "There are basically four or five. So any new data on this scale is important."

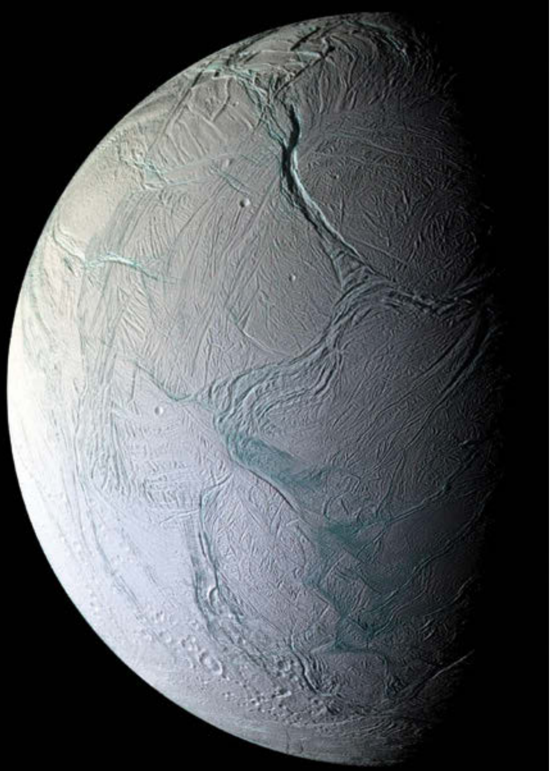
Especially interesting, both the team and Meyer point out, is that an edge-brightened jet structure also appears in the active galaxies M87, Markarian 501, and 3C 84. These galaxies' black holes all consume gas at fairly low rates, like Cen A's, so there may be something universal going on in such systems.

■ CAMILLE M. CARLISLE

ORPHAN CLOUD: ESA / XMM-NEWTON; CEN A JET: M. JANSSEN ET AL. / EVENT HORIZON TELESCOPE

Life Beyond Earth?

By century's end, the author thinks we'll have an answer to this question. But what kind of answer?



◀ Saturn's moon Enceladus, captured here after a close pass by the Cassini spacecraft in 2008, is a prime target in our search for beyond-Earth life.

NASA / JPL / SPACE SCIENCE INSTITUTE

OVER THE 80 YEARS in which *Sky & Telescope* has been informing us about the universe and those who explore it, scientific and popular beliefs about extraterrestrial life have fluctuated between grim and optimistic.

Before the Space Age, many scientists were naively confident about the prospects for life nearby. With only telescopic data to constrain our wishful thinking, it was possible, and popular, to imagine vegetation forming the seasonal "wave of darkening" on Mars or soaking up the water we thought was raining down on Venus.

In 1962, NASA's Mariner 2 began the work — which continues today — of replacing conjecture with observation. With the first successful spacecraft visit beyond the Earth/Moon system, it showed conclusively that the surface of Venus was too hot for liquid water or organic life. Three years later, Mariner 4 revealed a cratered "moonscape" on Mars that dampened hopes of finding the Red Planet awash in green.

Since then, we've been through several rounds of raised and then dashed hopes of finding nearby company. Orbiting Mars, Mariner 9 spied dried-up riverbeds. Carl Sagan and a number of colleagues convinced themselves that Martian soil organisms might be merely awaiting a splash of "chicken soup," but their 1976 Viking life experiments came up short.

NASA soured on Martian life, but only temporarily. Expectations that life on Mars lies just under the next rock have repeatedly risen and fallen. A "discovery" (later proven false) of chlorophyll, a hint of possible fossils in a meteorite, and perennial announcements of water and whiffs of methane all have revived hopes, at least for a little while.

Meanwhile, in the outer solar system we've discovered worlds that hold their oceans on the inside. Europa, Enceladus, Titan, and several other moons, even the dwarf planet Pluto — all are possible homes for aqueous life. And don't count out Venus. As I've written here (*S&T:* Jan. 2021, p. 15), there are reasons to suspect that, despite Mariner 2's reality check on our dreams of an Earth-like neighbor, a habitat may yet lurk in the clouds. So even if, as some of us suspect, Mars is completely dead, multiple places remain in the solar system where life-optimists can invest their hopes — if only because we haven't really explored them yet.

But I believe that in another 80 years we'll have the answer to "Are we alone?" The discovery could come in one of these unexplored corners of our own system. But given the sheer number of exoplanets, the odds seem good that, after we've carefully observed thousands of them, we'll have found unmistakable biosignatures (*S&T:* May 2021, p. 34) or even technosignatures. By the time the next century arrives, I bet we'll have identified several classes of inhabited worlds and be well on our way to a mature science of comparative astrobiology that can investigate the cosmic distribution of life.

> By the time the next century arrives, I bet we'll have identified several classes of inhabited worlds. But what if we haven't?

But what if we haven't? It's hard to prove a negative. Yet what if we've plumbed the ice-moon oceans, sifted through the Venusian clouds, and examined scores of high-resolution exoplanet spectra and found not a trace of anything swimming or breathing? Then we will be pretty far down the path of concluding that there really is something very peculiar and unique about our planet and its denizens after all. If that's the case, then in some strange sense the universe is our responsibility.

Either way, life is precious. Let's work toward a sustainable presence here on Earth so we can keep exploring and find out how lively our universe is.

■ **DAVID GRINSPOON** wrote his first Cosmic Relief column — about how the field of astrobiology is looking up — for the January 2009 issue.

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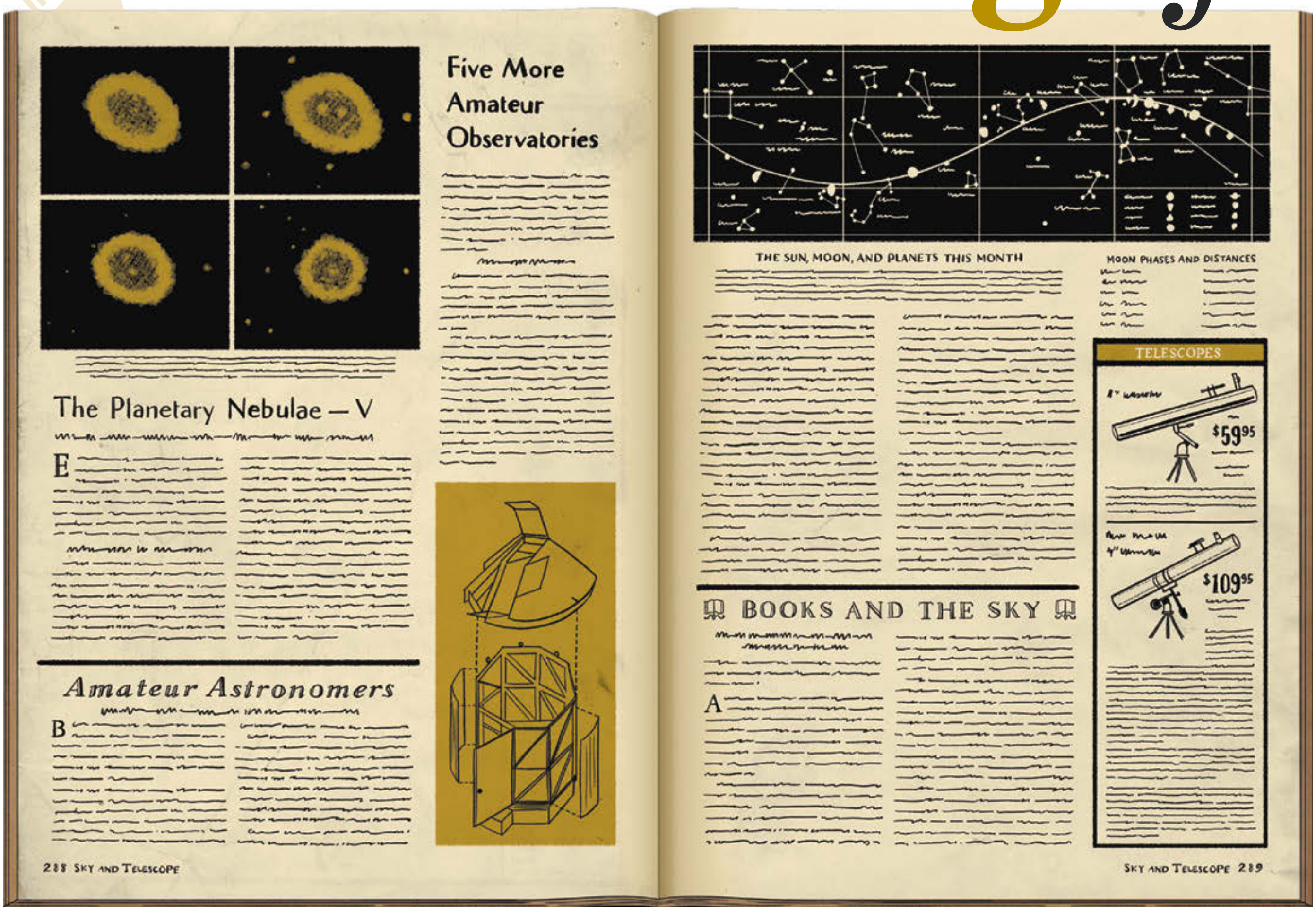
80 YEARS: WHERE WE'VE BEEN by William Sheehan and Klaus Brasch

A Golden Age *for*



LEAH TISCIONE / *S&T*

Two veteran observers reflect on the hobby's modest beginnings.

With this issue, *Sky & Telescope* marks 80 years of existence. Having commenced publication in 1941 as the merger of *The Sky* and *The Telescope*, the resulting magazine was immediately successful, though it really came into its own in the postwar decades of the 1950s and 1960s. That era happened to coincide with the first high-altitude rocket tests, artificial satellites, and probes to the planets. The era reached its dramatic climax in 1969 with astronauts walking on the surface of the Moon.

In some ways, those same decades were a golden age for amateur astronomy, too. Every era consists of an alloy of precious metal and dross, and the one the authors came of age in was no different. In our golden age, amateurs could still make cutting-edge observations with modest backyard scopes (often homebuilt) and their own eyes — something that probably seems rather quaint today. And in many ways, it was quaint. From the perspective of the 21st century, it's almost impossible to imagine just how exciting it was to live at a time when our understanding of the solar system was little more than a crude sketch, and when so much knowledge still lay in the future.

Our memories of that time are colored and rendered imperfect by the gauzy haze of nostalgia, and doubtless capture only a partial truth. But this is our story — a personal and idiosyncratic view of the times we grew up in and of the iconic magazine that did so much to stimulate what has become a lifelong passion for both of us.

A Good Beginning

One important way our golden age differs from today is how information is disseminated. Instant access to vast amounts of data provided by the internet — including the latest images from rovers on Mars or orbiters around Jupiter — would have seemed like science fiction in the 1950s and 1960s. After all, for most of us the main source of astronomical nourishment was found at the local library, where many books were years, even decades, out of date.

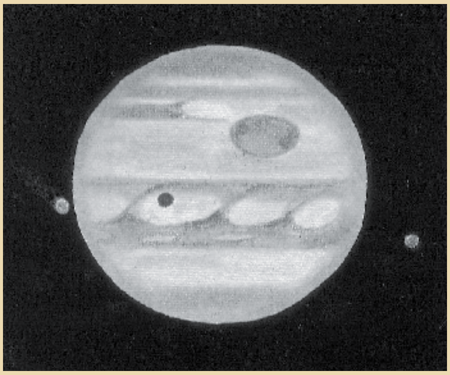
For amateurs (and many professionals) at the time, the most up-to-date and authoritative information was found in the pages of *S&T*. Readers looked forward to regular features on astronomy and astrophysics, including those by the famous director of Yerkes Observatory, Otto Struve. But the magazine also served the varied interests of its readership with an astronomical history department (led by the incomparable Joseph Ashbrook), briefs on telescope-making with stunning examples produced by self-taught amateurs, notes on important meetings, astronomical charts, detailed predictions of noteworthy celestial events, and book reviews. In many respects, the basic formulation remains in place today.

The magazine succeeded where others had failed partly because Charles Federer (cofounder, with his wife, Helen) had solid business sense. Rather unusually, though, he never ran the magazine to squeeze maximum revenue from the venture. Mainly, it succeeded because of a clear and timely vision. Its estimable goal was to create as large a community of amateur astronomers in the U.S. as possible, and to use the magazine as a means of connecting them. In that sense, *S&T* was a kind of low-tech internet.

As editor in chief, Federer was an exacting taskmaster. He insisted that his staff be well read and encouraged them to talk to astronomers directly to get all the details exactly right, which they consistently did. Thus, from its start the magazine established a very high standard from which it has never strayed.

When Amateurs Ruled

Readers who grew up in our golden age could regard themselves not just as spectators or consumers of information, but also as participants. No less an authority than Gerard P. Kuiper, one of the first professional astronomers to devote himself mainly to research on the Moon and planets, asserted as late as 1961 that among professionals "the phenomenal growth of astrophysics and the exciting explorations of the Galaxy and the observable universe led to an almost complete abandonment of planetary studies." As a result, he noted, "more and more this branch of planetary work, including the study of the Moon, became the topic par excellence of amateurs — who did remarkably well with it." It followed that many a youngster, including the authors, dreamed of making significant contributions with our telescopes. The prospect was exhilarating.



◀ **AN AMATEUR'S PLANET** Although Mars gets a lot of attention from amateur planetary enthusiasts, Jupiter is a more rewarding target for study, as this sketch by coauthor Brasch illustrates. He made the rendering in 1961 while using the instrument pictured below.

▲ **HOMEBUILT PIPE-MOUNTED "CAVE"** Coauthor Klaus Brasch with the 8-inch f/7 Newtonian he built in using Cave optics. The scope rides on an iron pipe equatorial mount — something commonly described as a "plumber's nightmare." He fashioned other components out of wood, sheet metal, and assorted hardware as suggested in the now-classic *Amateur Telescope Making* book series.

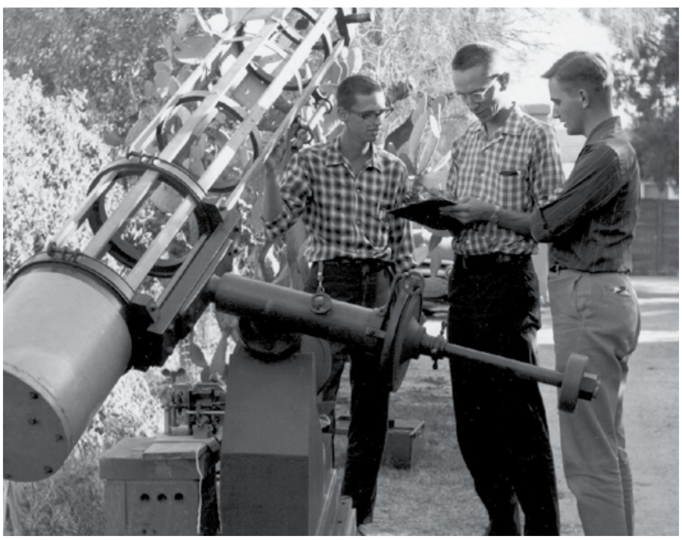
KLAUS BRASCH AND TELESCOPE: HEINZ BRASCH

▲ **A GOLDEN AGE** This trio of November *S&T* covers are from 1951, 1961, and 1971 — a span covering the height of the authors' golden age of amateur astronomy. The magazine first appeared 80 years ago when *The Sky* and *The Telescope* became one.

We had many role models to choose from. The British amateur Hugh Percival Wilkins had just completed the largest (if not best) Moon map ever made using traditional, visual methods. He and Patrick Moore regularly observed together, often crossing the English Channel to observe the Moon with the Grande Lunette of the Meudon Observatory in France.

Moore was not only a keen observer but also a prolific writer. The 1950s saw some of his most enduring output, including *Guide to the Moon*, *Guide to the Planets*, *Guide to Mars*, and *The Planet Venus*. These titles dominated the astronomical bookshelves of many libraries. Both in his books and in his monthly *The Sky at Night* television broadcasts, Moore presented science in an accessible, almost chatty style. He continually urged his audience to undertake systematic observations of the Moon and planets so that they might contribute to the great edifice of astronomical science and earn the gratitude of professional scientists. Like *S&T*, Moore came on the scene at just the right moment, and many amateurs — including the authors — regarded with envy his main telescope, a 12½-inch reflector. We made hundreds of drawings of the Moon and planets in emulation of what Moore had done.

This was also an era in which the worlds of amateur and professional astronomy frequently overlapped. Ewen Whitaker was a professional spectroscopist at the Royal Greenwich Observatory, yet he regularly "moonlighted" as an amateur pursuing his real interest — the poorly mapped limb areas of the Moon. He later emigrated to the U.S. to work on Kuiper's lunar mapping efforts, first at Yerkes and then at the Lunar and Planetary Laboratory in Tucson. Later they were joined by a younger group of enthusiastic amateurs who gravitated to Tucson to pursue professional careers at Kuiper's lab. Among them were Dale P. Cruikshank, William K. Hartmann, and Alan Binder.



▲ **PROFESSIONAL AMATEURS** Dale Cruikshank (right) shows Bill Hartmann (center) and Alan Binder — future solar system experts all — his personal telescope, in Tucson circa 1961. At the time, all three were grad students under Gerard P. Kuiper at the University of Arizona.

The Solar System Frontier

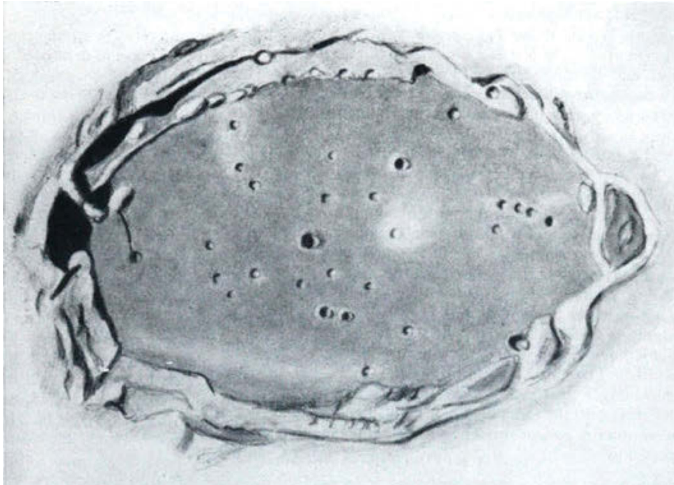
Many amateur observations graced the pages of *S&T* in those days. The magazine emphasized a very hands-on approach, which was consistent with the do-it-yourself and hobby movement of previous decades.

In the 1950s and 1960s, the Moon and planets were far more popular with amateur astronomers than star clusters, nebulae, and galaxies. Solar system targets offered the chance to actually *see* changes over time. Also, since many fundamental planetary mysteries were still unsolved, amateurs felt much of the exhilaration of the Kevin Costner character in *Dances with Wolves*, who wanted to visit the frontier before it disappeared. The deep sky was instead regarded as the province of large observatories like Mount Wilson and Palomar.

Although Mars was always the most alluring planet, its small disk meant it was a tricky target for amateur scopes. As a result, Jupiter, with its generous diameter and wealth of intricate detail, was long regarded as *the* amateur's planet. Much of what is known of this gas giant is due to the systematic efforts of amateurs, many of them members of the Jupiter sections of the venerable British Astronomical Association (BAA) and the Association of Lunar and Planetary Observers (ALPO), which was founded in 1947 — just six years after *S&T* began publishing.

Between 1949 and 1963, Elmer J. Reese of Uniontown, Pennsylvania, achieved extraordinary results with only a 6-inch reflector. Working in the family grocery store by day and observing Jupiter at night, Reese became fascinated with the periodic outbreaks known as South Equatorial Belt Disturbances. In 1949 he proposed that they might be due to volcanic eruptions deep below the visible clouds. The erupted material would tend to drift across the visible surface, but its sources might be used to reveal the rotation of the planet's solid core. Reese's rotation rate was later confirmed through observations of Jovian radio outbursts. Despite lacking professional credentials and having a very introverted personal-

THREE COVERS: *S&T* ARCHIVES; PROFESSIONAL AMATEURS: DALE CRUIKSHANK



▲ **SUPERB SEEING AND SKILL** Alika K. Herring was not only Cave Optical's most talented optician, but also a highly skilled observer, as this detailed sketch of the lunar crater Plato demonstrates. He made this drawing on November 8, 1962, using a 12½-inch reflector that he built himself. Herring's lunar observations appeared regularly in *S&T* for nearly a decade, starting in 1958.

ity, he went on in 1963 to join Clyde Tombaugh's and Brad Smith's planetary photography program at New Mexico State University. Reese became one of many amateurs who, with skill and diligence, eventually was able to build a professional career. With Smith, Reese succeeded in establishing the six-day internal rotation of the Great Red Spot in the 1970s, which, remarkably, he had already suspected with his 6-inch as far back as 1949.

The Rise of Commercial Telescopes

Even in our golden age, many of us started out with the much-maligned department-store refractors. These were mostly Japanese-made and usually boasted a 60-mm aperture lens and an altazimuth mount. Although such instruments are still often derided, in fact they offer a worthy entrée into solar-system observing, showing vast amounts of detail on the Moon, surface markings and the polar caps of Mars, Jupiter's four bright moons and main cloud bands, and (of course) the famous rings of Saturn. There is truth to something said by the great American astronomer E. E. Barnard, who as a fledgling amateur with a telescope no better than one of these, made out the phases of Venus and later recalled that it "made a more profound and pleasing impression" than his celebrated discovery of Jupiter's fifth satellite.

When longtime readers think back to their formative experiences with *S&T*, it's the advertisements that often evoke the strongest nostalgic response. At the affordable end of the spectrum were instruments from Edmund Scientific, Criterion Manufacturing Company, and A. Jaegers, among others. And then there were the high-end products enticingly featured in full-page ads. Truly beautiful telescopes offered by Cave Optical, Unitron, and Questar launched the dreams of a thousand would-be astronomers, including those of not a few future professionals.

Unitron refractors and the legendary Cave Astrola reflectors still sell today as valued antiques on popular astronomy exchanges. The legendary and jewel-like Questar Maksutov telescope has been in continuous production since the early 1950s. Fortunate indeed was the amateur who owned any of these prestigious instruments — showing up with one at a club meeting or star party was sure to provoke feelings of envy.

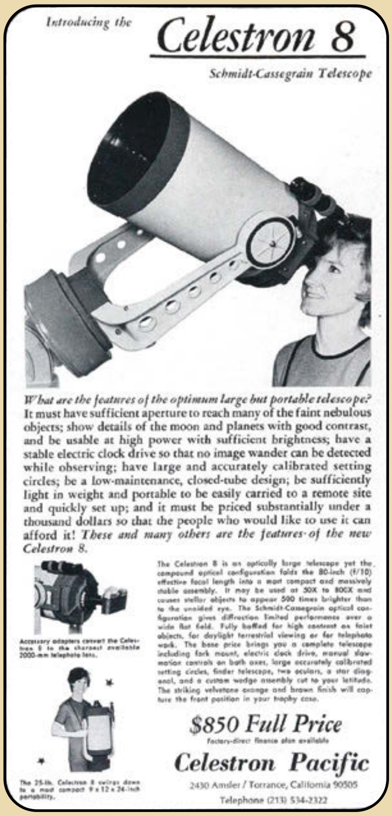
For those who could not afford commercial offerings, there was always the option of fashioning a telescope of one's own. Amateur telescope making in the U.S. began in the 1920s with contributions by Russell W. Porter in *Popular Astronomy* (who described a homebuilt Newtonian reflector as the "poor man's telescope") and by Albert G. Ingalls in *Scientific American*. Ingalls's columns, which included

◀ **SCOPES BOUGHT AND MADE** Coauthor Bill Sheehan, aged 15, in his basement "optical workshop," grinding a 10-inch mirror that would take several years to complete. In the meantime (right), he explored the solar system from his backyard with his 4¼-inch "Palomar Junior" from Edmund Scientific.

DRAWING OF LUNAR CRATER PLATO: *S&T* ARCHIVES; COAUTHOR AND TELESCOPE: BILL SHEEHAN (2) articles from such luminaries as Porter, James Gilbert Baker, and George Willis Ritchey, were eventually collected into the three volumes of *Amateur Telescope Making*, the bible for aspiring ATMs. *S&T* joined in with its own regular column, "Gleanings for ATMs," which debuted in 1941 and over the decades featured countless homebuilt telescopes.

Both authors attempted to build their own telescopes. In 1958 Brasch, with help from his father and young sister, built an 8-inch f/7 Newtonian, with Cave optics and assorted hardware. With it he dutifully observed and sketched the planets and submitted his efforts to ALPO. Sheehan began working on a 10-inch telescope as a school science-fair project in 1967. Since it wasn't finished until decades later, he continued observing during his high school years with the 4¼-inch Palomar Junior from Edmund Scientific, pictured on the preceding page.

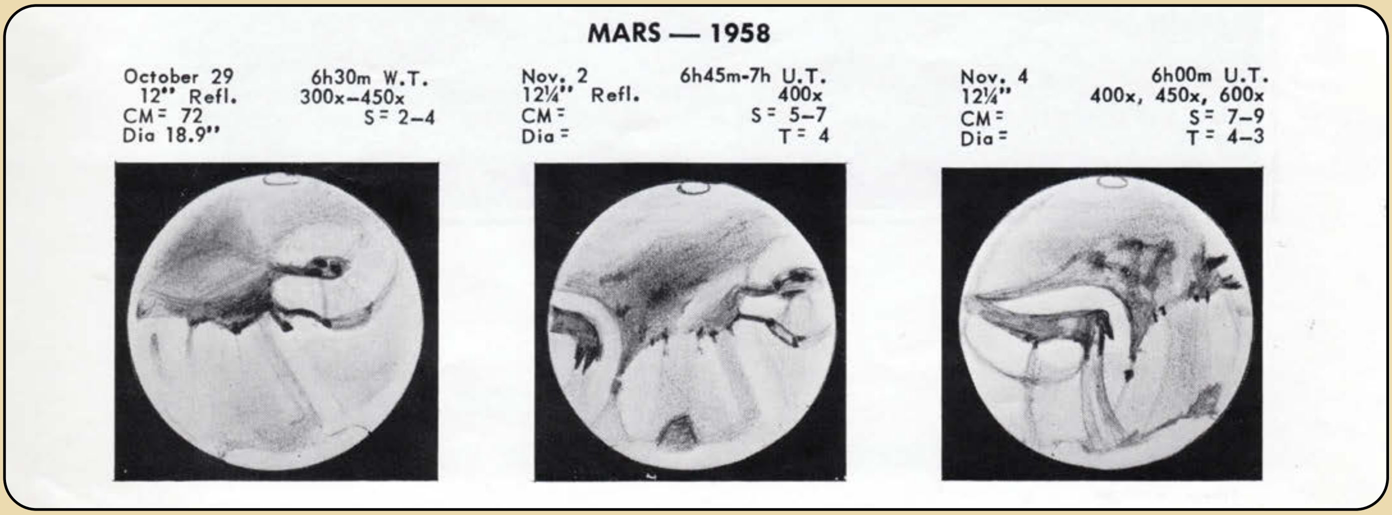
Other ATMs from that era included future solar system scientists such as Binder, Cruikshank, Hartmann, and Clark R. Chapman. All began as avid amateur observers while still in their teens, and once bitten, acquired a fever that never broke.



◄◄ REACHING FOR THE STARS This 4-inch Unitron refractor was probably more popular in the dreams of amateur astronomers than it was in reality. Those with an eye for detail will note that the model is holding a copy of *Sky & Telescope*, open to its center star chart.

◄ AUSPICIOUS INTRODUCTION Readers of *S&T* got a glimpse of the future when the Celestron 8 Schmidt-Cassegrain telescope first appeared in this June 1970 advertisement. The instrument would go on to become one of the most popular ever produced. Its introductory price of $850 translates into a jaw-dropping $5,800 in 2021 dollars.

▼ TELESCOPE BAIT Detailed views of the Moon and planets enticed many amateurs to purchase Cave Astrola telescopes. These drawings of Mars by Thomas Cave were published in the company's catalog under the banner of "Proof is in the observing!"



CELESTRON AD: *S&T* ARCHIVES; UNITRON AND CAVE ASTROLA ADS: COLLECTION OF GARY SERONIK (2)

Daring to Dream Big

Perhaps no telescopes during our golden age were more desirable than Tom Cave's legendary Astrola reflectors. Cave, a colorful personality, was born and grew up in Hollywood, where he mingled with movie stars in his youth. Not only were his instruments optically superb, but Cave was also a skilled observer who formed friendships with astronomical celebrities such as Robert S. Richardson of Mount Wilson and Griffith observatories, and Earl C. Slipher of Lowell Observatory. Slipher was a believer in life on Mars, as many astronomers of that era were. He was steadfastly loyal to Percival Lowell's theory that the blue-green areas on the planet were tracts of vegetation and that the "canals" were strips of vegetation along waterways, though not necessarily artificial.

Cave was a fervent Mars observer, and as an astute businessman, he realized that nothing sold telescopes like the Red Planet. A 1960 pre-Christmas ad for Astrola reflectors featured one of his own drawings made with an 8-inch during the previous opposition of October 1958, showing dark areas and several canals:

> *On Christmas Eve, next month, Mars will be closest to the Earth, and if you have just received your new Astrola, you will be doubly thrilled observing the planet with an instrument of truly adequate aperture and resolution. . . . When seeing is really good, the Martian canals and a multitude of fine maria details will flash into view.*

One can only imagine how many Astrolas were sold because of that one ad. Although the hype was perhaps over-the-top, these telescopes really did have the ability to deliver tantalizing views of planetary details at the limit of what was feasible with amateur instruments.

However, even as these wonderful telescopes were becoming more and more popular, the heyday of visual planetary observing was fast drawing to its sadly inevitable close. In December 1962, Mariner 2 would show the utter impossibility of lush jungles and exotic life forms on Venus, while two years later Mariner 4 would deal a blow to the Lowellian vision of Mars from which it would never recover. And most dramatically, a dozen astronauts would tread the lunar surface between July 1969 and December 1972. An army of amateurs equipped with their Astrolas, Unitrons, and Questars could not hope to compete.

▶ **TICKET TO RIDE** In the pre-aperture-fever era of the 1960s, an 8-inch telescope like this homebuilt instrument would have been regarded as "big." Coauthor Brasch's kid sister, Pat, poses next to the telescope she helped make. Says Klaus, "At the time she was able to squeeze inside the tube to paint it flat black!"

HEINZ BRASCH

Changing Times, Changing Telescopes

Today, Newtonian reflectors on heavy equatorial mounts like the Astrolas, Starliners, and the highly popular Criterion Dynascopes, are still cherished, but no longer occupy the pinnacle of commercial telescope manufacturing. During the 1970s and 1980s these classic telescopes were gradually displaced by Schmidt-Cassegrains, Dobsonian light-buckets, and superb apochromatic refractors.

Arguably, the turning point occurred in 1964 with the founding of Celestron Pacific by Tom Johnson. By modifying designs invented in the 1930s by Estonian optician Bernhard W. Schmidt, Johnson devised a process for mass-producing Schmidt-Cassegrain telescopes from 4- to 22-inches aperture. Although pricy at the time, these attractive and sophisticated instruments soon became highly sought-after. The company's now-iconic orange tube Celestron 8 was introduced to the world in a June 1970 advertisement in *S&T*. The C-8 ultimately became a runaway best seller around the world.

Mass production has made telescopes so affordable that few amateurs today bother building their own. It's fair to ask how the prices of modern telescopes stack up compared with those offered in the early days. In 1958 the very popular "standard" (as opposed to "De Luxe") 6-inch equatorially mounted Criterion Dynascope was priced at around $200, not including optional electric clock drive ($80) and setting circles ($60). Rounding the total to about $340, that equates to a whopping $3,200 in 2021 dollars. Today you can buy an 8-inch Dobsonian on a sophisticated Go To mount for around $1,500. There's no denying that amateurs in the 21st century get way more bang for their buck.

What observers can no longer buy, however, is the priceless sense of mystery that surrounded the Moon and planets in the 1950s and 1960s. It was a unique moment in history in which amateurs could realistically aspire to make important observations and discoveries that would be reported in the pages of *Sky & Telescope*.

As solar system exploration continues at a remarkable pace, we might one day soon finally answer the question of whether or not there was (or still is) life on Mars, or perhaps even on Venus or some of the tantalizing "water world" moons of the gas giant planets. At the same time, we can look back with satisfaction on what was for many of us truly a golden age of amateur astronomy.

■ **BILL SHEEHAN** became interested in astronomy in the 1960s, **KLAUS R. BRASCH** a decade earlier. In retirement, Brasch is an accomplished astrophotographer and authority on astrobiology, while Sheehan is a historian of the solar system whose new book (with Jim Bell), *Discovering Mars*, was published in October.

 by Paul H. Geithner

A generation in the making, the James Webb Space Telescope is the synthesis of scientific vision, technological advancement, and engineering achievement.

BUILDING THE JAMES WEBB SPACE TELESCOPE

Telescopes are powerful tools of exploration, enabling humans to probe far beyond where we can go ourselves or with robots. And arguably no instrument better embodies the advances spurred by our cosmic curiosity thus far than the James Webb Space Telescope. Scheduled to be ready for launch by October 31st when this article went to press, Webb is the long-awaited scientific successor to the Hubble Space Telescope and promises to be the world's premier space science observatory.

Even before the Hubble Space Telescope launched in 1990, scientists were considering what machine ought to follow it. Hubble "sees" primarily ultraviolet and visible light, with some capability to observe at the shortest near-infrared wavelengths. Scientists understood even then that, as mighty as Hubble would be, its 2.4-meter primary mirror and suite of instruments likely lacked the capability to explore the era when the first luminous objects formed. That era, called the *cosmic dark ages*, occurred in between the condensation of the primordial plasma into neutral hydrogen and helium (roughly 400,000 years after the Big Bang) and the ionization of those atoms by the first objects to emit visible and ultraviolet light (a few hundred million years later). This is the time when "the lights turned on" in the universe. But what exactly happened then? What were the first stars like, and how did they form in an environment so different from the one we think contemporary star formation requires? How did galaxies, which are the universe's large collections of ordinary matter and unseeable dark matter, assemble and evolve? How and when did the supermassive black holes that we observe at the hearts of most galaxies form? What came first: stars, black holes, galaxies . . . or something else?

Hubble can't answer these questions. Instead, to observe the end of the cosmic dark ages, we need a telescope exquisitely sensitive to infrared light. This is because the universe has been expanding since the Big Bang 13.8 billion years ago, which means that everything is moving away from everything else. The farther away something is, the faster it is receding. Light travels at a finite speed, so this expansion stretches light's wavelengths as the photons travel toward us, such that the farther away an object is, the redder it appears. The very first luminous objects to form after the Big Bang, whatever they were, are so distant that the ultraviolet and visible light they emitted more than 13 billion years ago reaches us today *redshifted* into the infrared spectrum.

CHRIS GUNN / NASA

OPTICS READY
The completed telescope looms above technicians at Northrop Grumman in this 2019 photo while awaiting integration with its spacecraft and sunshield.

So the goal was not only to gather enough light to reach back to the cosmic dark ages, but also to achieve a resolution at longer infrared wavelengths comparable to what Hubble provides at visible ones. To do this, Webb needed a primary mirror of at least 6 to 7 meters (about 20 feet) in diameter, and preferably a symmetrical one to reduce unnecessary image distortion. Such a mirror would also enable it to peer deeply at much closer targets, such as newborn stars and exoplanets sheathed in dusty gas clouds. The targeted wavelength and sensitivity ranges meant the telescope had to be space-based, above the interference from water vapor in Earth's atmosphere. And the telescope needed to be cold — below 60 kelvin (–213°C, or –352°F) — so that its own thermal emission didn't blind it to the infrared light coming from celestial sources.

This is how mission planners settled on creating a large, infrared telescope stationed in space and far from Earth's room-temperature glow — some 1.5 million kilometers (1 million miles) from Earth's nightside, at a gravitational balancing point in the Sun-Earth system called L_2 (see page 25). Building the envisioned telescope has been a feat of invention, ingenuity, and perseverance that makes it a milestone in the creation of space observatories.

Engineering Challenges

Several inventions and technological advances were necessary to make Webb feasible. Size, combined with the need to operate at cryogenic temperatures, conspired to present the greatest challenges. Webb's aperture exceeds the 5-meter diameter of standard, commercially available launcher fairings — in other words, there was no nose cone wide enough to carry the telescope to space if we built it with a symmetrical, one-piece mirror. Moreover, using the technology behind Hubble's lightweight, monolithic glass mirror would have required an impractically massive support structure.

Assembling the telescope in space wasn't an option, either: It would have added too much expense and risk. Thus, engineers developed *foldable* optics and structures so that the telescope could fold up to fit into a rocket fairing and withstand the rigors of launch, then deploy in space into a different, operational configuration. Instead of one big primary mirror, we built a segmented one of 18 hexagonal mirrors, each 1.3 meters across and about 40 kg (88 lbs). Together, they make a 6.5-meter-wide honeycomb.

Nor is unfolding the only transformation the telescope will undergo once in space. The challenge of operating at cryogenic temperatures is a daunting one that affects every aspect of design and testing. Materials change dimensions with temperature, typically expanding when warm and shrinking when cold. What's more, different materials behave in different ways, and we had to use more than one kind of material to build Webb, so we had to account for each part changing in its own way. This meant developing new processes to shape and polish optical surfaces "perfectly wrong" at room temperature, such that they become "precisely correct" at cryogenic operating temperature. The surfaces also had to attain that shape predictably, over and over again through repeated testing, and finally once launched and cooled down.

Beryllium became the mirror material of choice. Beryllium is light and stiff, and it virtually stops changing dimensions at temperatures below 100K. Ordinary beryllium is unpredictable, however, so technologists developed a new beryllium microsphere powder that the team then fused using intense pressure and heat into mirror blanks. Once the blanks were machined, ground, and polished, technicians coated each mirror in gold, which is excellent at reflecting infrared wavelengths.

The segmented mirror, along with the other optics and scientific instruments, are mounted on structures made of a special formulation of carbon graphite-epoxy that is very stiff, strong, and relatively stable over a wide range of temperatures, all the way from above room temperature down to cryogenic.

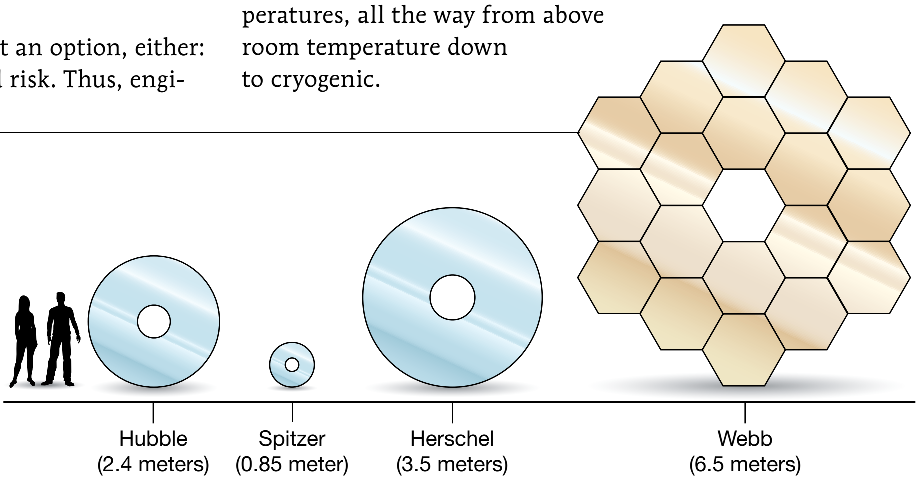
WEBB'S MISSION GOALS

Search for the universe's first galaxies

Study galaxies' evolution over cosmic time

Observe the formation of stars and planetary systems

Measure properties of the solar system and other planetary systems and investigate the potential for life



▶ **BIGGER IS BETTER** The larger a telescope's mirror, the more resolving power and sensitivity it can have: At a given wavelength, a telescope with an aperture twice as wide will resolve detail twice as fine and collect four times as much light. All four of these telescopes had (or have) infrared capabilities: Hubble can detect near-infrared wavelengths as well as visible and ultraviolet, while NASA's Spitzer covered only infrared. Europe's Herschel observed far-infrared wavelengths, much longer than those Webb will detect.

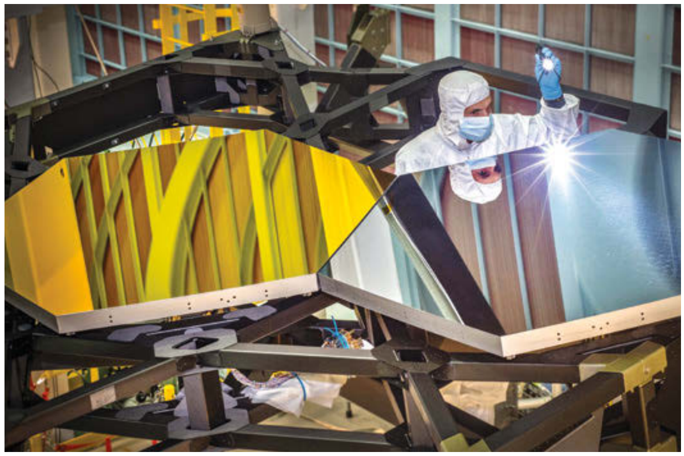
LEAH TISCIONE / S&T

The Origami Observatory

The sting of Hubble's spherical aberration was fresh in people's minds during Webb's early conceptual development, and naturally when thinking about a new space telescope one thinks of optics and how to make and test them. But there's more to Webb than its optics. Webb is a giant — and frigid — origami observatory, and the difficulties presented by a folding space observatory that will deploy in space by remote command and operate at cryogenic temperatures add to the challenge.

Virtually every modern spacecraft unfurls, deploys, or releases in some fashion, such as extending a solar array for power generation. By necessity, Webb takes on-orbit releases and deployments to the extreme:

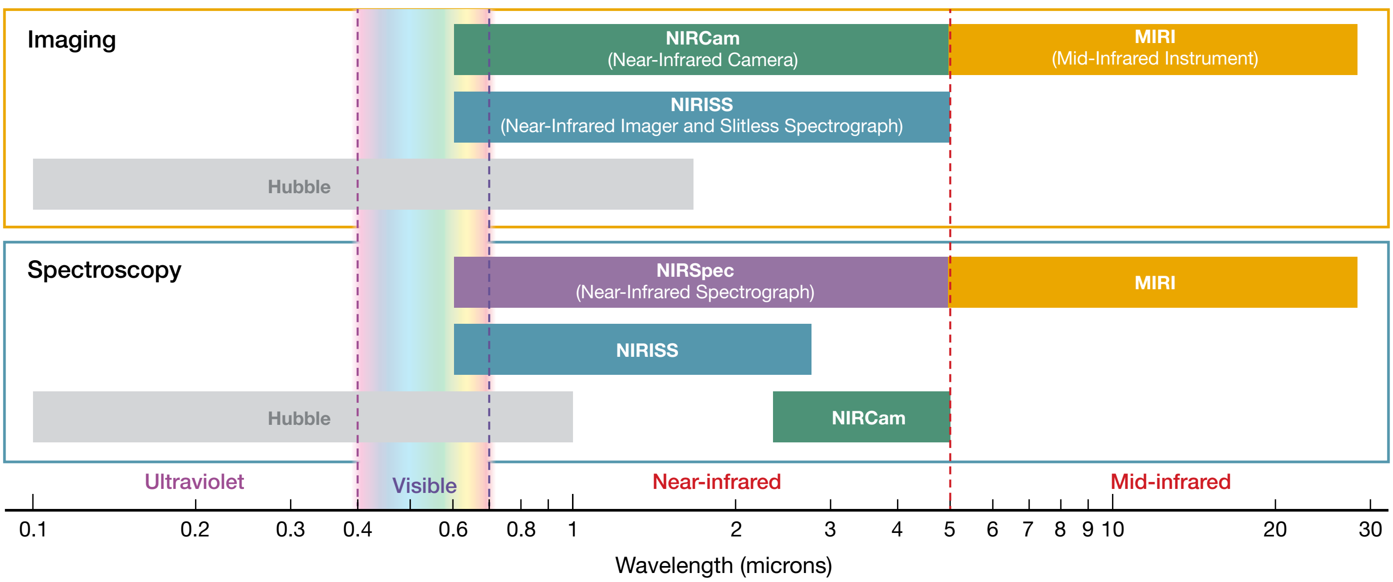
- The telescope primary mirror backplane structure has to fold up for launch and then deploy precisely.
- Primary mirror segments have to be movable in any direction so that they can correctly align to a few millionths of a millimeter and act as one.
- The secondary mirror must deploy on a hinged tripod (seen folded on page 21) and also move in any direction.
- The telescope structure is attached to the spacecraft bus when stowed for launch, but a telescoping tower must extend to separate the structure and bus, so that the telescope is isolated from any mechanical vibrations or heat from the spacecraft and sunshield.
- The star tracker, used to monitor the telescope's position in space, is attached to this extendable tower and must release from launch locks on the bus once in space.
- Various radiators must also release from launch locks and deploy to provide thermal and mechanical isolation.



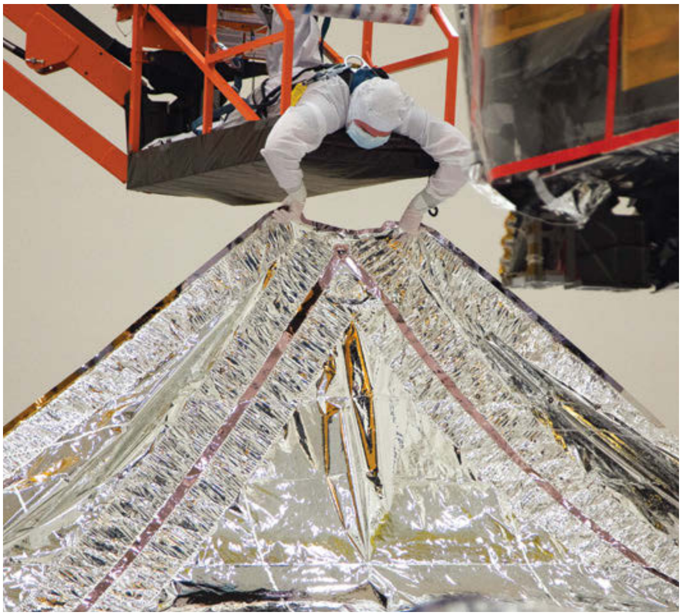
▲ **GO FOR GOLD** An optical engineer examines two test mirror segments, one coated in gold. The frame is a composite material designed to handle Webb's space environment.

The sunshield posed the grandest stowage and deployment engineering challenge of them all. The sunshield's job is to be an umbrella, shielding the telescope from the heat of the Sun as well as stray light from Earth and the Moon. This protection allows the telescope and instruments to radiate their own heat away and stay cool in the 7K deep space at L_2. The shield needs to let through a mere millionth of the total heat hitting it, attenuating more than 200 kilowatts of solar insolation down to a fraction of a watt. It also needs to span a much larger area than the telescope itself — roughly that of a tennis court — so that it provides adequate shadow for the telescope to access as much of the sky as possible. Lastly, it must weigh extremely little, stow compactly for launch, and

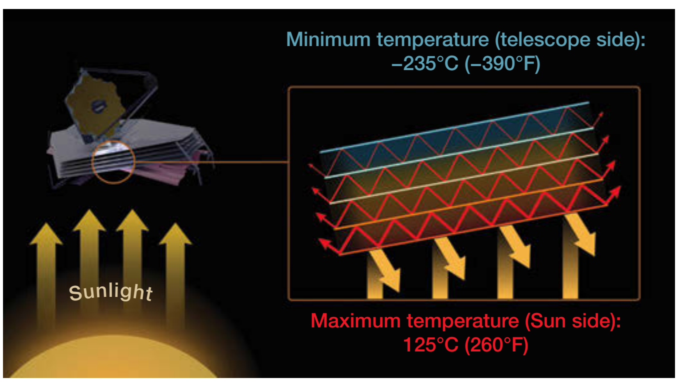
▼ **INFRARED EYE** Unlike Hubble's instruments, which focus primarily on ultraviolet and visible wavelengths, Webb's observe the near-infrared and mid-infrared parts of the spectrum. Each instrument is a specific combination of observing modes, wavelength range, field of view, and resolution, combining multiple instruments within themselves. NIRCam, NIRISS, and MIRI can do both imaging and spectroscopy, but the NIRCam and NIRISS spectrographs cover a smaller wavelength range than their cameras.



MIRRORS: CHRIS GUNN / NASA; INFRARED: LEAH TISCIONE / *S&T*; SOURCE: STSCI



▲ **SUNSHIELD** *Top:* This photo from 2014 shows the first time engineers stacked and unfurled a full-size test sunshield. *Above:* A technician carefully folds the real sunshield in 2020, in preparation for stowing the telescope into its launch configuration.



▲ **PARASOL** The five-layer design of Webb's sunshield protects its mirror and instruments from unwanted infrared radiation from the Sun, Earth, and Moon. Because none of the layers touch, heat doesn't conduct from one layer to another and instead flows to the layers' edges and into space.

deploy reliably, both on the ground multiple times for testing and in space for the one time it really counts.

These requirements are met by a design consisting of five kite-shaped, gossamer membranes stacked in layers. Each membrane is about 165 square meters (1,780 ft^2) in area and coated with vapor-deposited aluminum. When deployed, the space between each membrane gets progressively wider from the center to the edges. This allows heat that isn't reflected away and manages to pass to the next layer to then bounce its way out to the edges and overboard to space. Even the membrane edges are aligned to millimeter tolerances, to ensure no infrared photons from edges heated by the Sun will have a line of sight to telescope optics and become a source of stray light.

As the largest element of Webb, the sunshield will unfold in grand fashion. A graphite-epoxy frame will cradle the *Z*-folded membranes for launch and then extend to deploy the membranes in space. An elaborate system of motors, stem drives, pulleys, and cables will deploy the sunshield skeleton and pull the membranes taut. Because membranes and cables are non-rigid floppy things, hundreds of simple, ingenious straps and elastic clips must restrain them as they're deployed in the weightlessness of space to preclude snagging and entanglement.

In all, deployment of flight hardware involves 178 non-explosive release devices, more than 40 major deployments of 30 different types, 155 motors, more than 600 pulley assemblies, and nearly 100 cables totaling about one quarter mile in length.

Beyond the State of the Art

Then there are the advances spurred by Webb's instruments. To accomplish the science goals, infrared detectors had to become better than what existed when we began planning. Engineers had to adapt electronics so that the combination of any "noise" from the detectors with heat from the mirror itself would be less than the signal from the zodiacal light, the background glow from diffuse dust in the inner solar system. This is where the 60K requirement comes from.

But to observe mid-infrared wavelengths takes even more extreme measures. The mid-infrared instrument's detectors have to be colder than 7K to operate, which they won't achieve by simply sitting out in space at L_2. Instead, Webb needs its own cryocooler, which required more development.

From the invention of a new slit mask for the main spectrometer to advances in cryogenic testing, many technologies had to lurch forward to make Webb possible. Of course, we had to leap over various engineering hurdles throughout the long development, but tackling challenges is part of what makes this work rewarding.

Then there are the international hurdles. Science is a worldwide community, and contributors the world over wanted in on the mission from the beginning. The

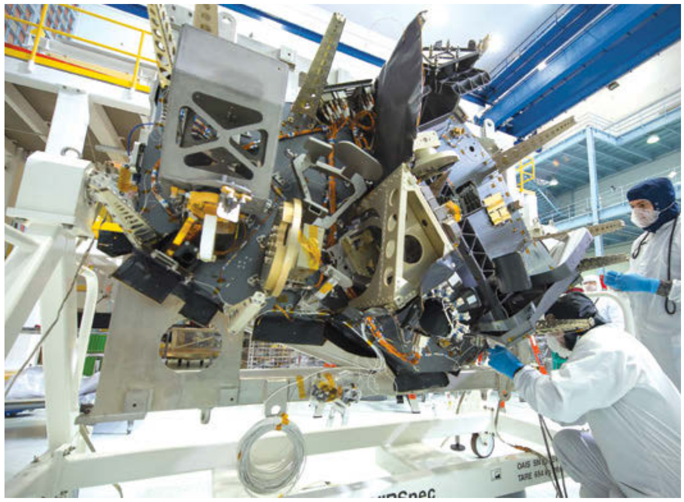
DEPLOYED SUNSHIELD: CHRIS GUNN / NASA; **SUNSHIELD** FOLDING: NORTHROP GRUMMAN; SUNSHIELD DIAGRAM: STSCI

European and Canadian space agencies are both providing instruments and operations support, and the European Space Agency (ESA) is also handling the launch. But there are laws regulating the sharing of information, even with friendly allies. Finding ways to collaborate with our partners and their contractors added a degree of difficulty to this process, but the return in scientific capability has been worth it.

Proving It Works

A major difference from some other spacecraft is that the entire Webb observatory cannot be tested faithfully as one fully assembled unit before launch: It's simply too big and complex. That may be nerve-wracking to readers who remember the blurred images Hubble returned when it first looked at the cosmos. To be clear, we've tested Webb's optical system in one piece end-to-end. What's impractical is creating on the ground the environment that Webb will unfurl in. We can't easily emulate weightlessness and perform deployments while in a vacuum chamber, nor is it feasible to replicate Webb's thermal condition — with intense sunlight heating one side and extreme cold chilling the other — and simultaneously run end-to-end optical tests on the complete, deployed observatory in the vacuum.

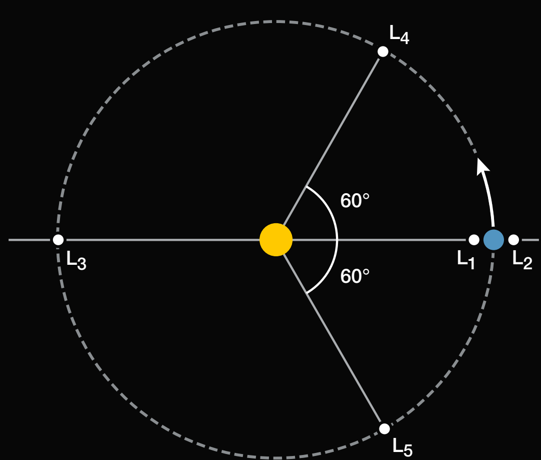
This led engineers to test the observatory in halves — the telescope and instruments as one unit, and the combined spacecraft bus and sunshield as the other. Each was shaken and blasted with sound and subsequently tested for performance in temperature-controlled vacuum chambers. Then once put together, the observatory was shaken some more to verify workmanship of the final assembly.



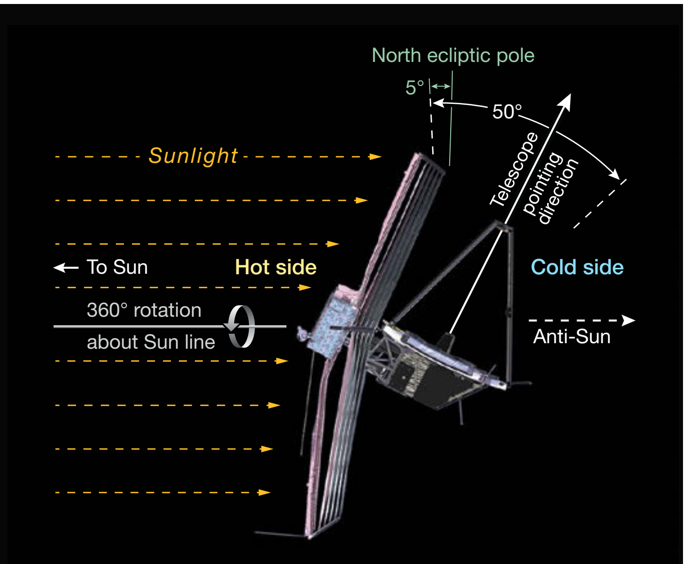
▲ **MEGASIZE INSTRUMENTS** Engineers prepare the Near-Infrared Spectrograph for acoustic tests.

We learned a crucial lesson from the Hubble spherical aberration experience: Don't rely on the same tools used to make the optics when you test them. This meant we had to build different devices to verify, crosscheck, and optically test the entire telescope and instrument assembly end-to-end. The testing required a vacuum chamber capable of cooling the entire telescope and instrument assembly to about 40K, suppressing background mechanical vibrations, and housing sophisticated testing equipment.

A relic of the Apollo era, the enormous Chamber A at NASA's Johnson Space Center, was refurbished and upgraded

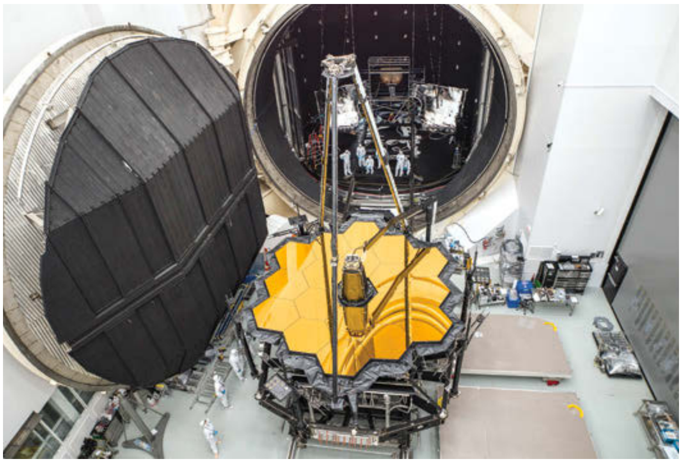


▲ **LAGRANGIAN POINTS** In a system of two massive bodies orbiting each other (such as the Sun and Earth), five gravitational "balance points" exist where a third, much smaller object can orbit in a constant pattern. A craft at L_2 can always keep the Sun, Earth, and Moon behind itself, making it a frequent choice for space missions. Previous denizens of L_2 include Europe's Planck and Herschel missions; the sky-scanning Gaia spacecraft is currently there.



▲ **THE VIEW** Webb's mirror is perpendicular to its sunshield, and the spacecraft can tilt to point the telescope within a 50° arc while still keeping the mirror and instruments safely in shadow. It can also rotate full circle. Over time, Webb will see the entire sky as it orbits the Sun.

INSTRUMENT: CHRIS GUNN / NASA; LAGRANGIAN POINTS: LEAH TISCIONE / *S&T*; TELESCOPE FIELD OF REGARD: STSCI



▲ **CHAMBER A** Webb emerges from months of cryogenic vacuum testing in 2017.

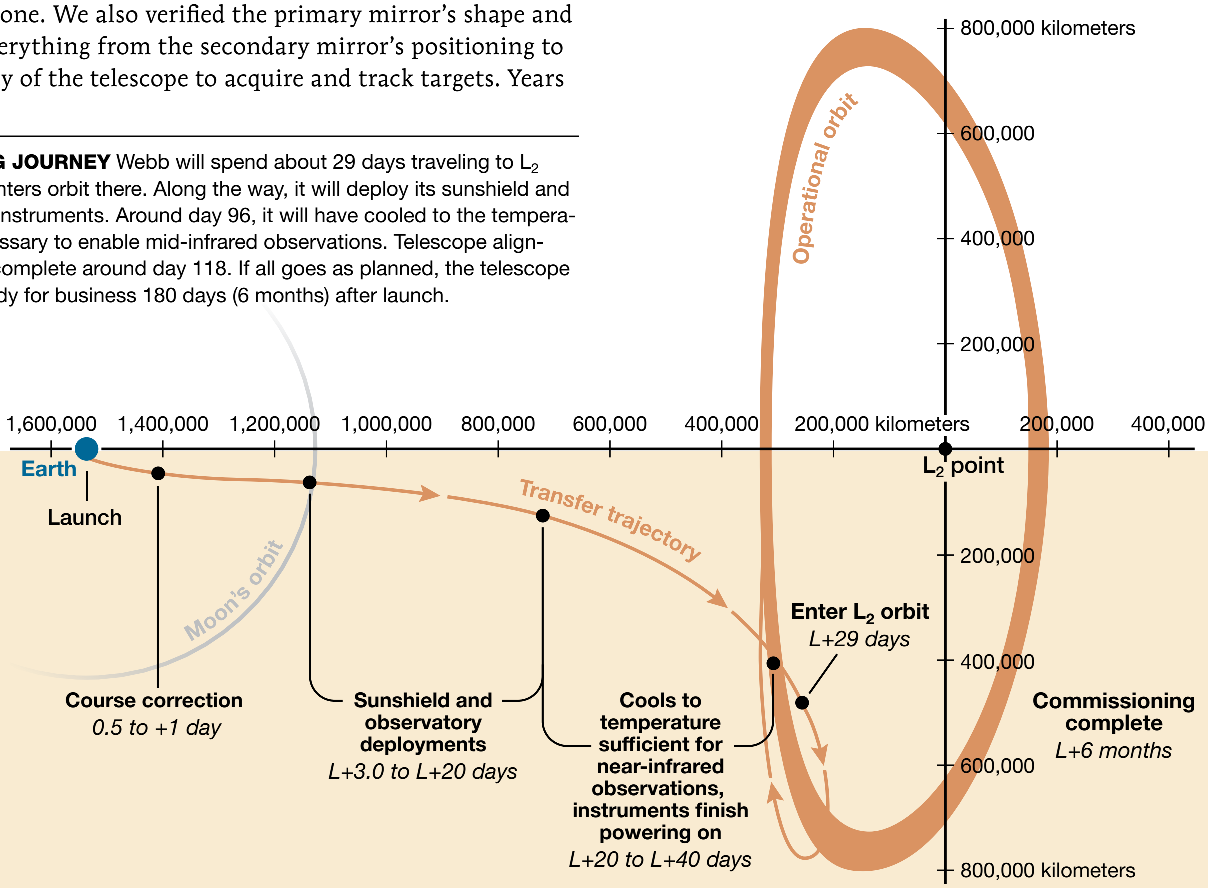
into the world's finest large cryo-vacuum optical test facility for the work. This chamber is about nine stories tall, taller than the Lincoln Memorial Building — so large that the air inside it weighs 12 tons (before all but 2 grams gets pumped out for testing). Engineers placed the deployed flight hardware on a truss structure platform and rolled it into the bottom of the chamber on rails, then connected it to long steel rods suspended from the ceiling. Using a combination of mirrors, cameras, and other carefully tested instruments positioned inside the chamber, we successfully aligned all 18 segments to act as one. We also verified the primary mirror's shape and tested everything from the secondary mirror's positioning to the ability of the telescope to acquire and track targets. Years of careful planning meant that even when Hurricane Harvey hit right in the middle of this 100-day-long cryo-vacuum test in 2017, we completed it without interruption.

Meanwhile, to prove that the observatory could properly manage heat not only from the Sun but also from its own electronics, we had to combine results from multiple tests. To check the sunshield design, we tested a ⅓-scale model of the deployed sunshield in a temperature-controlled vacuum chamber. To verify that the telescope and instruments would stay cool despite the heat the electronics give off, we built and tested a full-scale version of Webb's core section — the thermal Grand Central Station of the observatory — to confirm that heat moves around the way it needs to. Such tests required milliwatt-level precision. We then combined these results with those from the thermal-vacuum test of the bus-plus-sunshield assembly and the cryo-vacuum test of the assembled telescope and instrument package.

On top of all that, we've done exhaustive, iterative checks of the unfolding processes. All flight-deployable items have been unfolded multiple times; the flight sunshield, for example, has been stowed four times and deployed three times before flight. So much of the observatory can fold out that every stow operation was like reassembly, with a regimen of extra checks and precautions.

And after more than a decade of testing flight hardware, we'll soon be ready for the next step: launch.

▼ **A LONG JOURNEY** Webb will spend about 29 days traveling to L_2 before it enters orbit there. Along the way, it will deploy its sunshield and power up instruments. Around day 96, it will have cooled to the temperatures necessary to enable mid-infrared observations. Telescope alignment will complete around day 118. If all goes as planned, the telescope will be ready for business 180 days (6 months) after launch.



CHAMBER A TESTING: CHRIS GUNN / NASA; TRAJECTORY AND COMMISSIONING TIMELINE: GREGG DINDERMAN / *S&T*, SOURCE: NASA

Opening Webb's Eye on the Cosmos

Once it lifts off from French Guiana, Webb will undergo an action-packed six-month commissioning period. Moments after completing a 26-minute ride aboard ESA's Ariane 5 rocket, the spacecraft will separate and deploy its solar array automatically per a stored command. After that, we'll initiate all subsequent deployments over the next few weeks from the ground. This is in stark contrast to the "7 minutes of terror" for projects landing on distant Mars, for example. For them, every step of entry, descent, and landing is pre-programmed and autonomous because of Mars's distance — it's all over before engineers on Earth receive a signal that it has even begun. Webb, however, will be mere light-seconds away, so we will be able to control deployments carefully.

Webb will take one month to fly to L_2, slowly unfolding as it goes. Sunshield deployment starts at day 2.7 and will finish a few days later. Once the shield starts to deploy, the telescope and instruments will enter shade and cool rapidly. Over the ensuing weeks, the mission team will closely monitor the observatory's cooldown, managing it with heaters to prevent escaping moisture from freezing onto sensitive surfaces. In the meantime, the secondary mirror tripod will unfold, the primary mirror will unfold, instruments will slowly power up, and midcourse maneuvers will insert Webb into a prescribed orbit around L_2 on day 29.

Once the observatory has cooled to the necessary low, stable temperature, it'll take several months to align the optics and calibrate the scientific instruments. Assuming commissioning goes as planned, scientific operations will commence about six months after launch. Webb's mission lifetime is designed to be at least five years, but the observatory could last more than a decade depending on how much fuel we use to achieve and maintain orbit around L_2 and how quickly the telescope's components degrade in space.

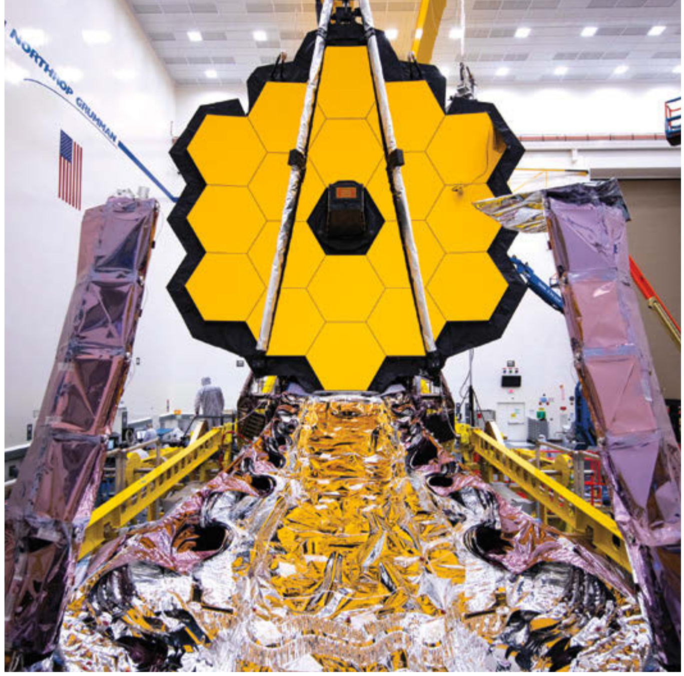
Flagship missions like Webb are generational. They take a long time because they are difficult, and they are expensive because they take a long time. Webb has built on both the legacy and the lessons of missions before it, such as the Hubble and Spitzer space telescopes. It will in turn provide the foundation upon which future large astronomical space observatories may one day be developed.

Webb is a marvelous machine. It is a remarkable engineering achievement full of scientific potential and promise. It has been built to explore the frontiers of cosmology and astronomy, from observing the end of the cosmic dark ages to "sniffing" the atmospheres of exoplanets around nearby stars to perhaps detecting the chemistry that makes life as we know it possible.

But its greatest discoveries will likely be answers to questions that we have yet to ask or imagine.

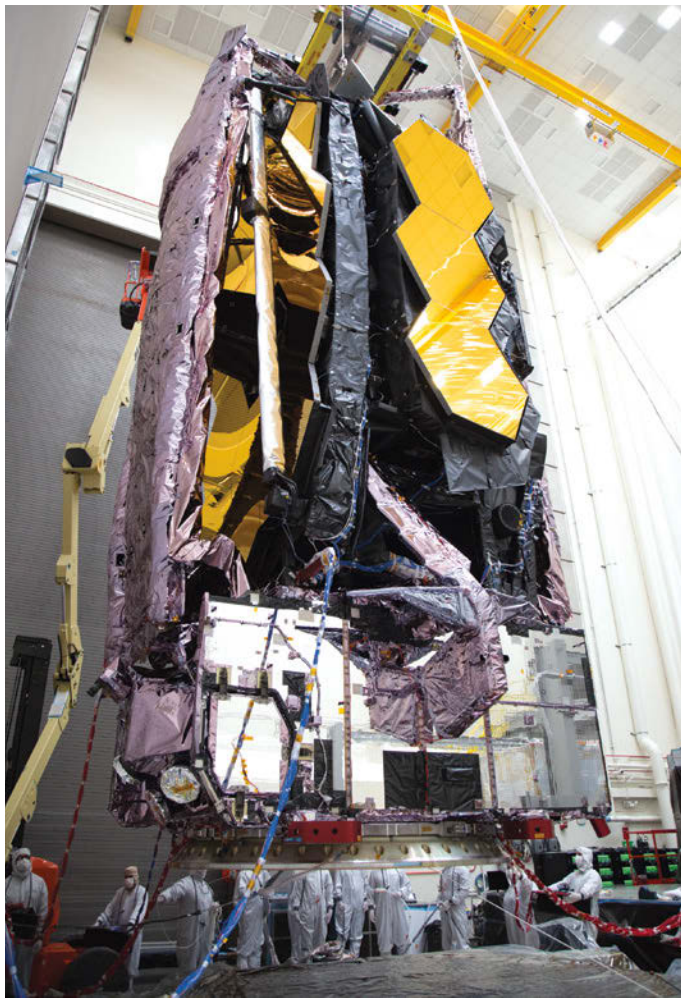
■ Deputy Project Manager **PAUL H. GEITHNER** has held several jobs on Webb since 1997 after coming to NASA in 1991 to help fix and upgrade Hubble. On the side, Paul rebuilds cars and houses and is borderline obsessed with golf.

NORTHROP GRUMMAN (2)



▲ **SEMI-DEPLOYED** The sunshield lies furled below the unfolded primary mirror. For launch, the shield will fold up and sandwich the mirror.

▼ **FOLDED FOR LAUNCH TEST** The telescope successfully endured deafening noise and jarring vibrations tuned to simulate conditions aboard the Ariane 5 rocket during launch. These 2020 tests were the last environmental tests before launch.



 by Camille M. Carlisle

The CUTTING Edge

EDUARD MUZHEVSKYY / SHUTTERSTOCK.COM

Welcome to the future.

In the following pages, we take a look at where astronomy research and exploration are (potentially) going. Prediction is a dangerous game, and *S&T* doesn't often engage in speculation. But there are amazing things on the horizon — technology and projects that will fundamentally change the landscape of astronomy and, ultimately, what we know about the universe.

First, we highlight four tech and mission concepts actively being explored. In choosing these examples, we've sought to show variety, not favoritism: While there are many great ideas under investigation, these four span a range of developments that will revolutionize the core technology we use in astronomy or change the scale on which we do it.

Then we step back for the long view. We polled several dozen astronomers in fields from planetary science to cosmology and asked them what advances they see coming down the pike, and when those advances might arrive. We then combined their responses with prognoses we've heard at science conferences and colloquia and weeded for likelihood and variety. The resulting timeline provides a forecast for what's coming between now and 2050.

Some of these predictions are likely wrong. Back in January 2013, for example, a physicist said in our pages, "The discovery of dark matter seems almost imminent. . . . I would be surprised if another 5 or 10 years pass without the appearance of signals from WIMPs." We're nearly nine years into that prediction, and scientists are wondering if *weakly interacting massive particles* (WIMPs) — once the favored candidate for dark matter — are a dead end.

And, of course, we can't predict the surprises, either. Will we find signs of microbes elsewhere in the solar system? Will we discover something new about how the universe works? And (we almost plead) will another supernova soon light up the Milky Way? We're long overdue: In a galaxy like ours, we should see a star go bang every 100 to 200 years, but it's been more than 400 years since one graced our skies. Will the next one blaze by 2050?

The biggest news in the next generation may well be something we can't even imagine yet. But that's no reason not to try.
—CAMILLE M. CARLISLE

LASERS IN SPACE NASA's Laser Communications Relay Demonstration will transmit data from the International Space Station to Earth using infrared lasers.

DAVE RYAN / NASA

Beam the Data Down, Scotty

Lasers will replace radio antennas as the interplanetary communications system.

Cassini. New Horizons. The Hubble Space Telescope. These spacecraft and so many others have given us mesmerizing views of the cosmos, expanding our knowledge and piquing our curiosity.

But it's no use sending instruments to space if we can't get the data back. Without a communications link, there is no exploration.

Throughout the Space Age, we've used radio wavelengths to transmit data to and from our space emissaries. Radio has major perks: It cuts through clouds above ground stations, and its wavelengths are so long that you don't have to aim too carefully in order to hit your antenna back on Earth.

But radio is also slow. Those same long wavelengths limit how much information a signal can carry. Take, for instance, the New Horizons spacecraft, which due to distance, bandwidth, and network sharing needed more than a year to send its 6.25 GB of Pluto flyby data back to antsy team scientists. That's similar to the file size of a single HD movie.

NASA and other spacefarers are thus developing an alternative: infrared laser communications.

Radio and laser communications operate on the same principle: Encode information by modulating a wavelength's properties, then transmit the signal to a receiver that can decode the modified stream. It's the same idea behind your Wi-Fi router, which uses microwaves to send information from the internet to devices around your home.

But infrared wavelengths are roughly 10,000 times shorter than the radio ones used to communicate with spacecraft, so lasers pack information into tighter waves. They can thus deliver more data in the same period of time than a radio signal can. Switching to infrared lasers — which go by the misnomer *optical communications* — would increase data transmission rates by a factor of 10 or more. That would boost the downlink rate from Mars — which is about 2 megabits per second (Mbps) when the planet is at its closest — to some 25 Mbps, the minimum uplink requirement for U.S. broadband.

There are downsides, however. First, infrared lasers can't pass through clouds, so ground stations need to be in clear-sky locations, such as Hawai'i and parts of California. Second, the signal beam is narrow. Electromagnetic waves spread out as they travel from their source; a radio beam transmitted from Mars is larger than Earth's diameter by the time it reaches our planet, making catching it easy. But a laser beam shot from that same distance would only be the size of California when it reached Earth, says Abhijit Biswas (Jet Propulsion Laboratory). Successfully hitting the ground station is like holding a meter-long soda straw so steady that the far end doesn't dip by a micron. "If we miss," he says, "there will be no one to catch the bits."

NASA successfully demonstrated laser communications from lunar orbit in 2013, achieving a downlink speed of 622 Mbps. Other experiments have followed. The European Space Agency now uses optical links to connect some of its low-orbit satellites with two geostationary relays (which then send the data down to Earth via radio), and the Starlink project has begun using inter-satellite lasers, too.

NASA's Laser Communications Relay Demonstration (LCRD) aims to be the first relay system based entirely on optical. From geosynchronous orbit, it will transmit data sent from the International Space Station at a rate of 1.2 Gbps, about double that of the 2013 lunar experiment. LCRD's June 2021 launch was delayed due to rocket concerns, however, and no revised launch date had been announced when this article went to press.

But explorers want to push beyond near-Earth space. Slated to launch in 2022, the Deep Space Optical Communications (DSOC) experiment will piggyback on NASA's Psyche asteroid mission to test how well laser links work beyond Mars. Using a setup similar to an off-axis telescope, DSOC will point a micron-wavelength laser at a 22-cm mirror and shoot it back to Earth, transmitting canned data that team members will check for accuracy. (They'll lock onto Earth thanks to a beacon beamed at a slightly different wavelength.)

DSOC's ground station will be the 5.1-meter Hale Telescope at Palomar Observatory in California — "which is on the skinny side for what we'd like for these distances," admits Biswas, who serves as DSOC project technologist. Ideally, he says, laser communications will utilize 8- to 10-meter telescopes in the future.

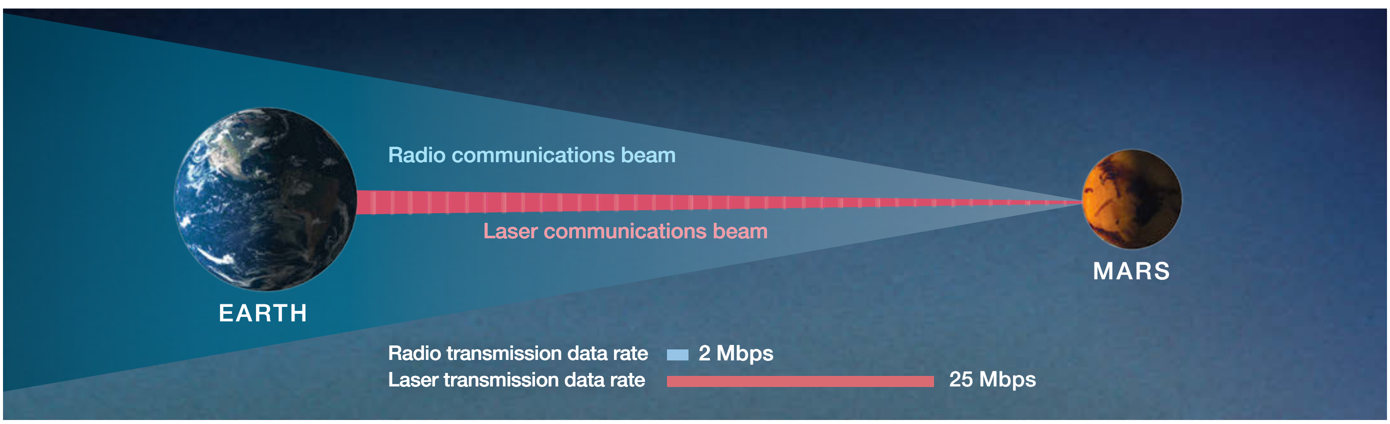
The DSOC team's goal is to downlink at 100 Mbps from a quarter of an astronomical unit away and about 2 Mbps from 2 a.u., which would be well into the asteroid belt. (For comparison, Psyche's main telecommunications system will probably achieve a rate one-tenth as fast.) Beyond 2 a.u., the spacecraft will be in the daytime sky and thus unobservable.

It may be 20 years before laser communications are routine on space missions, but routine they must become. The aging Hubble Space Telescope collects an average of 18 GB of science data each week. The Transiting Exoplanet Survey Satellite (TESS), launched in 2018, downloads 94 GB of compressed data on a 2-week cycle, and the new James Webb Space Telescope (see page 20) is expected to send about 30 GB over 4 hours, twice a day. But future flagship missions will likely collect *terabytes* of data each day, says astrophysics chief technologist Mario Perez (NASA). Radio networks cannot handle the data deluge.

▲ **TO DEEP SPACE** Team members test the Deep Space Optical Communications experiment in a JPL clean room. The 22-cm primary mirror (center, pointed at camera) will transmit and receive infrared lasers to and from ground stations on Earth. The aluminum base plate will bolt to the Psyche spacecraft.

Lasers can. In the future, laser communications may enable astronauts to send high-def videos from the Moon. We'll receive streaming imagery from Mars. A fleet of laser-enabled, TESS-like satellites could take exoplanet observations to a new level. And maybe we'll position our receivers in space, avoiding the cloud and daylight problems entirely.

■ Science Editor **CAMILLE M. CARLISLE** learned more about Wi-Fi and downlink speeds during the pandemic than she ever thought she'd need to know.



▲ **DOWNLINK** Laser beams arrive at Earth much narrower than radio beams do, making precise pointing crucial. But lasers also transmit data 10 times faster than radio does.

COMMUNICATIONS INFOGRAPHIC: LEAH TISCIONE / S&T, SOURCE: NASA; LAB: NASA / JPL-CALTECH by Javier Barbuzano

Through a Lens, Brightly

Will giant refractors make a comeback as space-based telescopes?

If lenses could be built as large as pick-up trucks and thinner than their windshields, then we would probably still find them in many big telescopes, including those in space. Lenses are more resilient to misalignment and small defects than mirrors are, making lens-based devices potentially simpler, sturdier, and more reliable — as well as cheaper to launch. But astronomers largely abandoned refractor designs for large telescopes early in the 20th century, mainly because of the lenses' massive weight.

However, a group of astronomers and engineers at the University of Arizona might have found the key to making large, lens-based space telescopes a reality. Led by Daniel Apai and Tom Milster, they have come up with a lens design that combines refractive and diffractive elements and can reach several meters in diameter — with a thickness of just three millimeters. Compare that to the Yerkes Great Refractor, the world's largest refractor, whose 40-inch convex lens is about 2½ inches thick at its center.

The team is developing ways of mass-producing these lenses cheaply and quickly with molds. In fact, researchers are already making plans for a space array with dozens of telescopes, which might cost less than the soon-to-be-launched James Webb Space Telescope (JWST, see page 20).

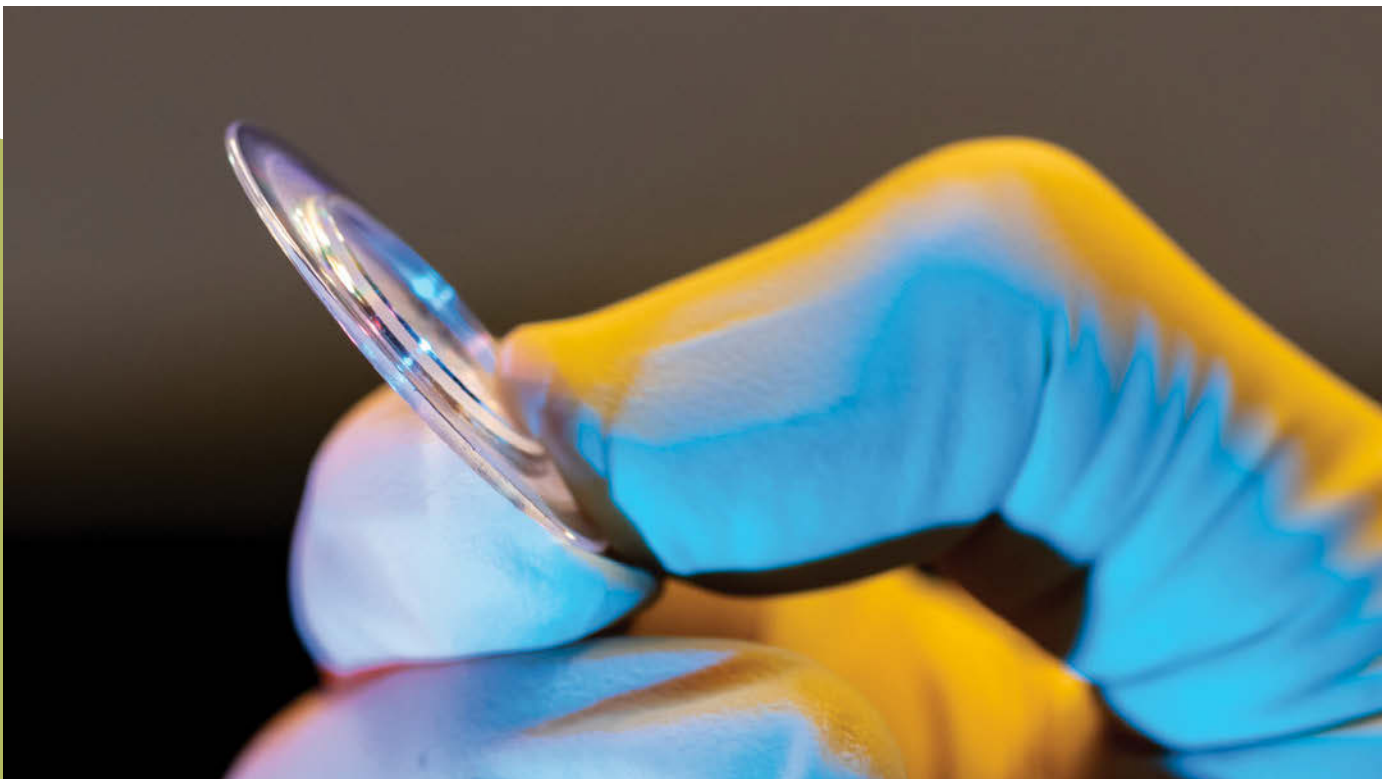
"This is potentially game-changing optics technology," says space telescope expert Garth Illingworth (University of California, Santa Cruz). Illingworth recently reviewed the array's progress for the Moore Foundation, which has granted the project $1.1 million. "Really lightweight optics will make a major difference in the size [of space telescopes] that can be built for a given cost."

A Fresh Look at Lenses

Called *multi-order diffractive engineered* (MODE) lenses, the new lenses are inspired by Fresnel lenses, like those typically found in lighthouses. Instead of being a thick, convex monolith, the surface of Fresnel lenses has a series of concentric circles. The pattern preserves the curvature of the lens while removing excess material from its back.

This flattened lens surface, however, produces terrible chromatic aberration — a shift in the focus of different wavelengths that distorts images. To fix it, the team adds a diffractive layer on the back of the lens, similar to gratings used to

▼ **À LA MODE** A prototype glass MODE lens. Unlike conventional, fully refractive lenses, MODE lenses combine diffractive and refractive properties to achieve high optical performance — one largely independent of the lens's thickness.



DANIEL APAI / UNIV. OF ARIZONA

disperse light in some optical applications. "The chromatic aberration is literally opposite between these two types of surfaces, so they cancel [each other] out," says team member Daewook Kim (University of Arizona), who leads the fabrication and testing of the lenses. "Overall, if you apply this technique, you can achieve a very thin, lightweight, compact lens while having good chromatic aberration control."

MODE lenses have an optical performance on par with apochromatic lens systems, Apai says, and "can come very, very close" to a perfect parabolic mirror over a broad range of wavelengths.

A Thousand Exoplanets

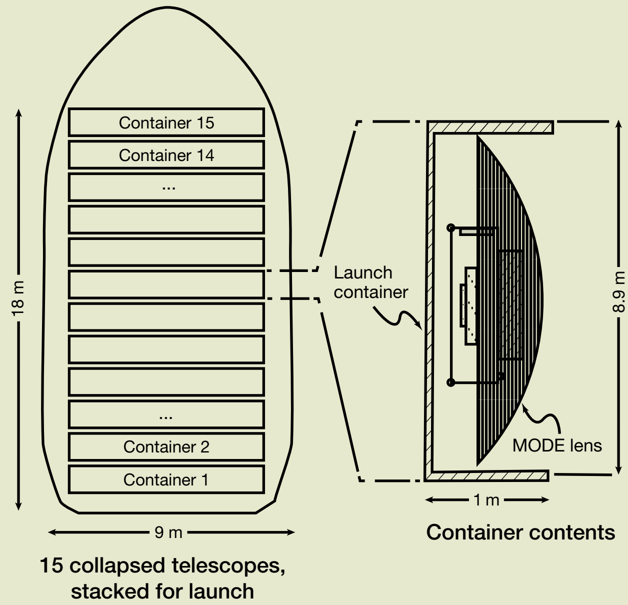
Exoplanets provide an excellent science case for MODE lenses. As detections of rocky planets in the habitable zones of their host stars pile up, astronomers are eager to search for chemical signatures of biological activity in their atmospheres. But JWST will only be able to characterize the atmospheres of a handful of these planets, likely not enough to understand exoplanets as a population.

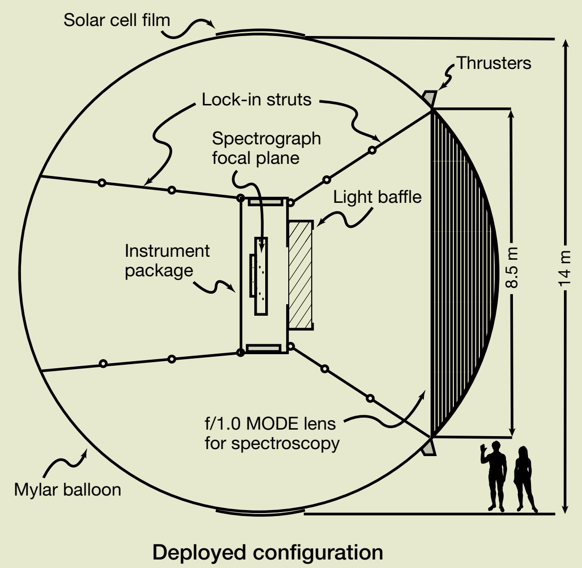
"If you have a very small sample it is going to be very difficult to understand really what you are looking at," Apai says. "What are really the trends, patterns, groups?" The only way of knowing is by looking at many more examples.

To do so, Apai and his team are developing a mission concept called Nautilus, an array of 35 space telescopes each equipped with an 8.5-meter MODE lens. Their goal is to achieve a combined light-collecting surface equivalent to a mirror 50 meters in diameter, or almost 10 times larger than that of JWST — all without exceeding JWST's $8.8 billion price tag. Such an array could characterize the atmospheres of exoplanets in their stars' habitable zones within 1,000 light-years of Earth. The telescopes could pick up faint changes in the stars' light as it filters through the atmospheres of planets crossing in front of them — a technique called *transit spectroscopy*. "We wanted to come up with a system that is capable of really making a leap," Apai says. "Not just a little bit better, but truly a significant leap."

Currently, Apai and his team are focused on building a molded 0.24-meter (10-inch) lens — the largest MODE lens to date — that will be installed on a telescope at the Mount Lemmon Observatory, near Tucson. Demonstrating the technology is a crucial step to securing more funding. If the tests are successful, the team plans to send a proposal to NASA to develop a probe-class mission (with a budget of around $800 million) in the second half of this decade. "It may take about eight to 12 years to then build a telescope," Apai says. "Right now, I'm quite optimistic."

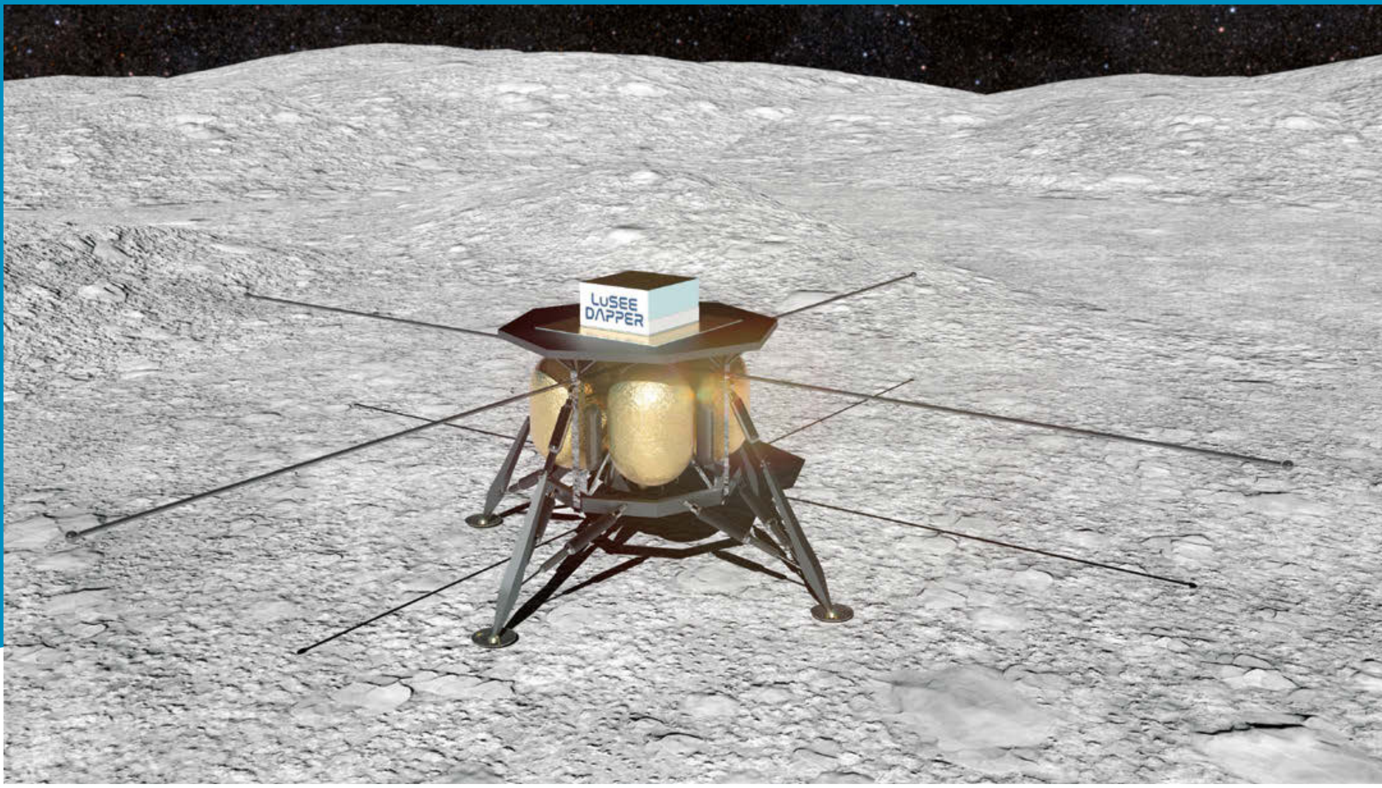
JAVIER BARBUZANO is a freelance science writer based in Barcelona, Spain. Find him on Twitter: **@javibarbuzano**.





▲ **NAUTILUS** In the proposed array, a fleet of space telescopes would launch together *(top)*, then inflate in space to become ball-shaped craft *(bottom)*. The prototype lenses are flat, but Nautilus may use curved ones — unlike with conventional lenses, a MODE lens's shape is relatively unimportant: The diffraction patterns on the lens's front and back surfaces are what focus the light. Thus the lens's shape can be adapted to what's most practical. A spherical surface has greater structural strength, making it a good choice for space deployment.

DANIEL APAI / UNIV. OF ARIZONA (2)



UNIVERSITY OF COLORADO AND TEND STUDIOS

▲ **COSMIC EXPLORER** From the Moon's farside, NASA's DAPPER will look for faint radio signals from the early universe.

The Lunar Frontier

By the late 2020s, we may have deployed multiple radio astronomy instruments on Earth's natural satellite.

Radio wavelengths give astronomers access to an unseen universe, from stellar flares to jets launched from supermassive black holes. But arguably, we have yet to take advantage of the best place in the inner solar system for low-frequency radio astronomy: the Moon.

The lunar farside always faces away from Earth and is thus radio-quiet, shielded by the Moon itself from radio-frequency interference coming from powerful Earth-based transmitters. The Moon also lacks a substantial ionosphere, whereas Earth's ionosphere absorbs and refracts cosmic radio sources. Furthermore, the lunar environment is dry and stable, leading to steadier radio observations.

Radio astronomy from the Moon is not a new idea — astronomers proposed a lunar radio observatory at a science symposium in 1965, before Apollo 11. In a separate endeavor, NASA's Radio Astronomy Explorer 2 orbited the Moon from 1973 to 1975, the first mission to gather radio data above the farside. It confirmed the radio-quiet environment and made low-frequency measurements of Jovian radio bursts and sources in the Milky Way.

But lack of access to the Moon meant that the next lunar radio mission didn't occur until 2018, when China launched its Chang'e 4 mission. After touching down on the lunar farside, the lander unfolded three 5-meter radio booms; another three 5-meter antennas, part of the Netherlands-China Low-frequency Explorer, orbit the Moon aboard the Queqiao satellite, which acts as a communications relay for the lander and rover.

As nations reestablish access, the Moon is open again to science and exploration. Using new rockets and technologies, spacecraft from China, the U.S., India, and Japan are surveying the Moon for water and other resources and assessing its potential as a platform for astrophysics. NASA's Commercial Lunar Payload Services (CLPS) program is to begin delivering science instruments on robotic landers starting in 2022. The public-private partnerships behind these missions have dramatically reduced their costs.

In recent years, several exciting science cases for farside radio telescopes have emerged. For example, low-frequency (below the FM band) observations of nearby exoplanet systems enable us to investigate stellar winds and planetary magnetic fields, which affect potential habitability.

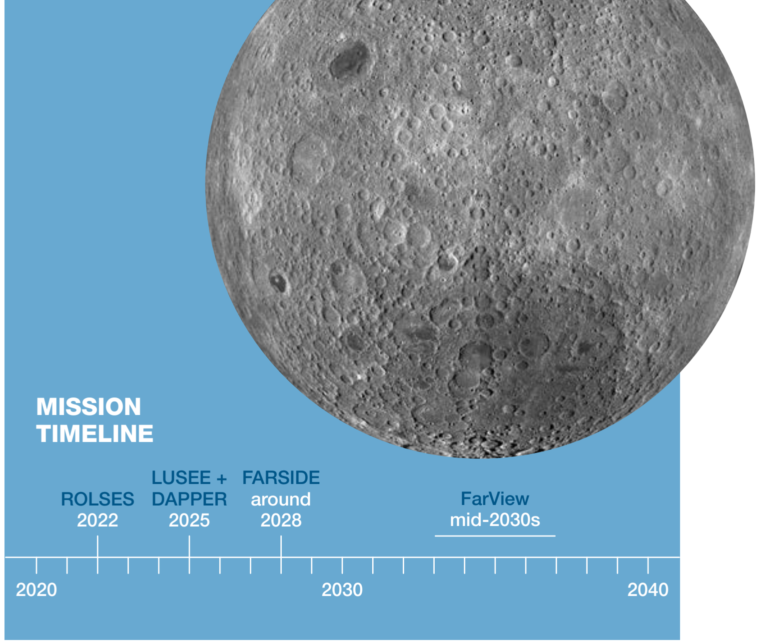
Meanwhile in cosmology, emission from neutral hydrogen in the early universe shifts into the low-frequency range as the photons traverse the expanding universe. These signals probe the dark ages of the universe's first few hundred million years, as well as the cosmic dawn when the first stars were born. Early-universe investigations will rigorously test the standard model of cosmology and may uncover new exotic physics involving dark matter, dark energy, and cosmic inflation (*S&T:* June 2019, p. 22).

Several U.S. missions to the Moon — both nearside and farside — are in the works. Intuitive Machines plans to place its NOVA-C lander on the lunar nearside in early 2022. This CLPS mission includes the ROLSES (Radio Wave Observations at the Lunar Surface of the Photoelectron Sheath) instrument, using simple single antennas. LUSEE (Lunar Surface Electromagnetics Experiment) will follow in 2025 and will land in Schrödinger Basin on the farside. Both radio instruments will investigate the thin, ionized plasma created when the solar wind slams into the lunar surface, as well as the charged dust and radio waves that come from solar eruptions.

I myself am involved with several endeavors. Stuart Bale (University of California, Berkeley), Richard Bradley (National Radio Astronomy Observatory), and I recently proposed that the Dark Ages Polarimeter Pathfinder (DAPPER) could fly with LUSEE to the lunar farside. The additional antennas and receiver on DAPPER would enable investigations of the low-frequency radio spectrum up to 110 MHz. Absorption troughs in this frequency range will reveal not only when the first stars and galaxies "turned on" but also what they looked like, including their typical masses and luminosities.

Together with Gregg Hallinan (Caltech) and my colleagues at the Jet Propulsion Laboratory, I have also proposed FARSIDE (Farside Array for Radio Science Investigations of the Dark Ages and Exoplanets), which would consist of 256 dipole antennas working together to act as a single, large radio antenna on the lunar surface. The mission could be ready for flight later this decade.

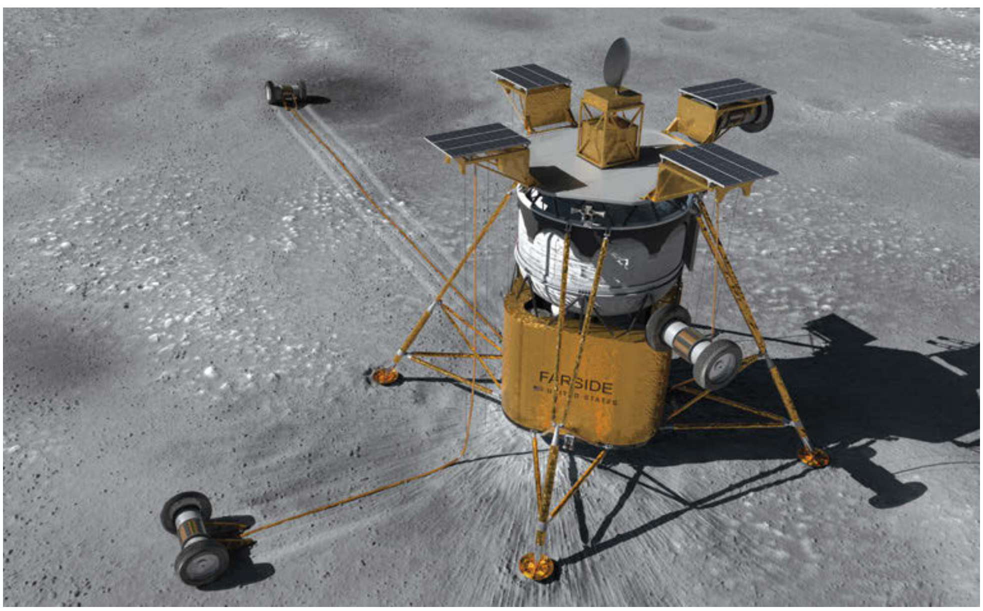
The NASA Innovative Advanced Concepts Program also recently funded the study of a 100,000-antenna array called FarView. These antennas, which would be manufactured onsite from lunar regolith, would map fluctuations in neutral hydrogen in the early universe, providing insights into the nature of the cosmic web, dark matter, and primordial gravitational waves. Ronald Polidan and Alex Ignatiev (Lunar Resources, Inc.) and I are proposing to place FarView on the Moon in the 2030s.



This ambitious road map for lunar radio astronomy, combined with renewed access to the Moon, will open a new window to the low-frequency cosmos.

■ **JACK BURNS** is a professor of astrophysics and physics at the University of Colorado, Boulder. He served on the Presidential Transition Team for NASA in 2016–17, helping to define NASA's new missions to the Moon — including low-frequency astrophysics from the lunar farside as well as what is now Project Artemis.

FURTHER READING: Burns, J.O., et al. "Low Radio Frequency Observations from the Moon Enabled by NASA Landed Payload Missions." *Planetary Science Journal* 2021.



▶ **THE FARSIDE** The FARSIDE lander would carry more than 200 radio antennas, strung together and deployed using four small, wheeled rovers.

TIMELINE: TERRI DUBÉ / *S&T*; MOON: NASA GSFC / ARIZONA STATE UNIVERSITY; LANDER: BLUE ORIGIN

To Boldly Go

By mid-century, we may have sent a craft to look back at ourselves from beyond the solar system.

In the last decade, the notion of interstellar travel went from fiction to reality. In 2012, after 35 years of interplanetary travel across 122 astronomical units, Voyager 1 left the solar system and crossed into interstellar space. In 2018, Voyager 2 did the same.

But the only other transmitting spacecraft on a trajectory to interstellar space, New Horizons, is not even halfway there. The scientific community's tenuous connection to this unexplored region therefore depends on the 44-year-old Voyagers staying alive or the New Horizons craft surviving another couple decades.

Unless we send a dedicated mission to interstellar space.

U.S. astronomers have proposed interstellar missions since 1960; since then, NASA and the European Space Agency (ESA) have entertained a couple dozen interstellar mission concepts, none coming to fruition. But a few ideas persist today. Interstellar Probe, a mission proposed by the Johns Hopkins University Applied Physics Laboratory and funded by NASA as a concept study, is one of them. Interstellar Probe could travel to 200 a.u. in 30 to 40 years — beyond where the Voyagers are now — and answer some of the biggest open questions about our star's relationship with the galaxy.

Seeing the Heliosphere

The Sun produces a wind, full of particles and magnetic fields, that carves out a magnetic bubble in space. This *heliosphere* envelops the solar system and protects us from high-energy galactic particles. But data from the Voyager spacecraft as they left the heliosphere raised more questions than answers (*S&T:* Sept. 2020, p. 16). What does the heliosphere look like? What is the material composition of interstellar space? And what happens at the boundary where these two meet?

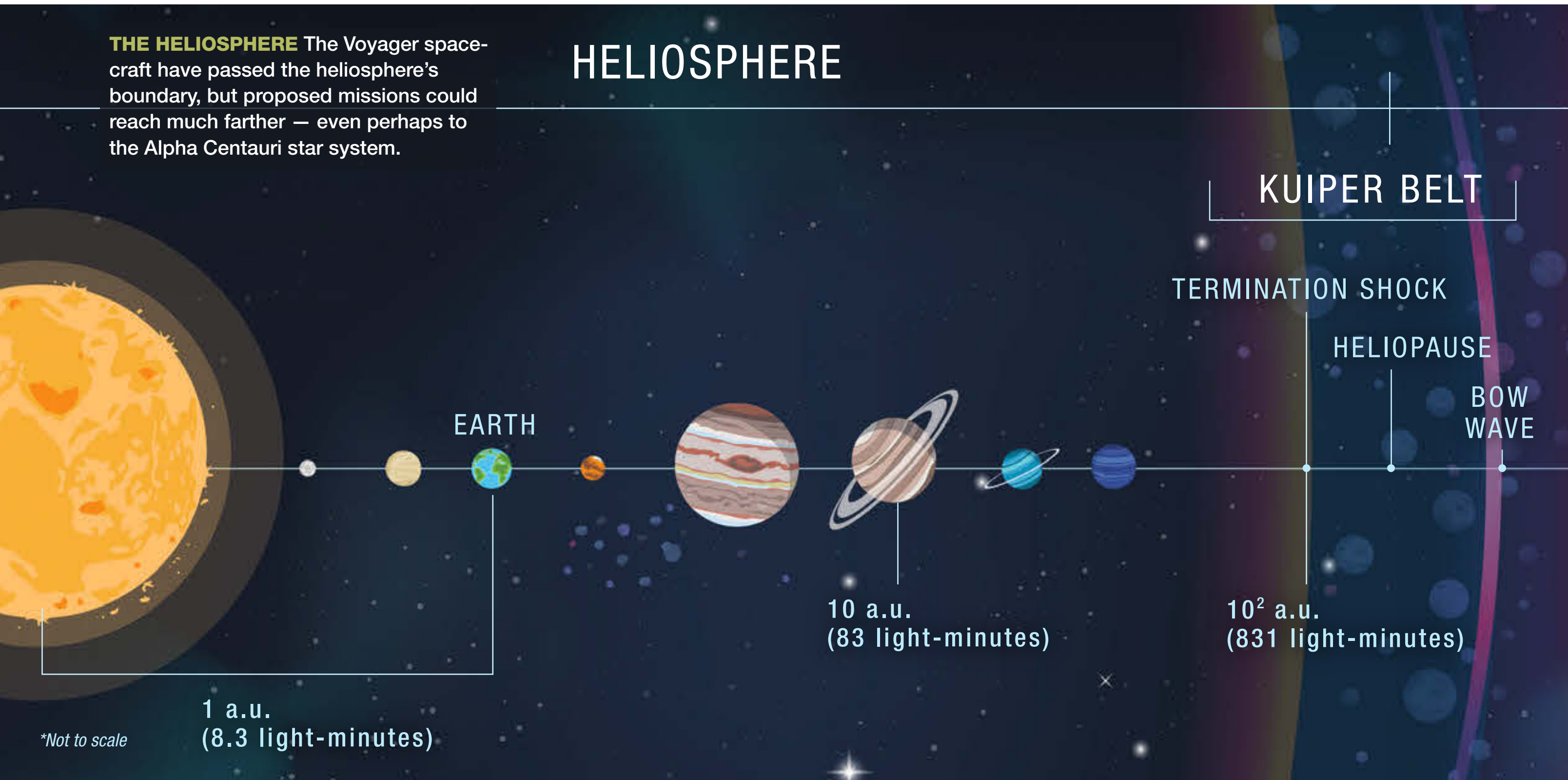
Interstellar Probe could answer these questions by turning around and taking a picture of our home star's heliosphere, like the dusty Pale Blue Dot image of Earth taken by Voyager 1. In fact, it could take three.

The first picture would show the heliosphere's shape. Astronomers know that the heliosphere shelters us from harmful, high-energy particles, and similarly protected environments may harbor life elsewhere. But what it actually looks like remains unclear.

To solve this mystery, astronomers can use *energetic neutral atoms*, particles that arise when the solar wind bumps into the interstellar medium, to map the boundary of the heliosphere. While the Interstellar Boundary Explorer (IBEX) is making these maps from vantage points near Earth, it measures atoms at energies too low to probe the entire heliosphere. The future Interstellar Mapping and Acceleration Probe (IMAP) will make similar maps with an even larger energy range and thus reach farther distances.

However, both these missions only measure energetic neutral atoms that travel within the heliosphere, not the ones

JOHNS HOPKINS APL



THE HELIOSPHERE The Voyager spacecraft have passed the heliosphere's boundary, but proposed missions could reach much farther — even perhaps to the Alpha Centauri star system.

◀ **LL ORIONIS** This young star in the Great Nebula in Orion is creating a bow shock around itself as it plows through the interstellar medium. The bow shock forms where the star's vigorous stellar wind hits the slower-moving gas in the nebula.

NASA / HUBBLE HERITAGE TEAM (STSCI / AURA)

from interstellar space. Mapping the heliosphere with these data is akin to determining the shape of a house by tracing the inside walls. Interstellar Probe could obtain the first complete view of the heliosphere from a vantage point in interstellar space. Together with IBEX and IMAP, these three probes will provide a definitive picture of the shape of the heliosphere.

The second picture would show how interstellar material piles up at the solar system's boundary. By measuring sunlight scattered off interstellar hydrogen, the Voyager and New Horizons craft detected a wall of hydrogen surrounding the heliosphere. Images from multiple space telescopes show similar walls surrounding the magnetic bubbles, or *astrospheres*, of other Sun-like stars. But astronomers don't know how similar the heliosphere is to these astrospheres. Interstellar Probe could make the first map of the hydrogen wall surrounding the heliosphere as seen from the outside. Then astronomers could compare this picture to other astrospheres to identify Sun-like stars that may, in turn, host habitable planets.

The third picture would show interstellar dust from the outside. Almost 30 years ago, the Ulysses satellite detected interstellar dust *inside* the heliosphere. Since then, the Cassini mission detected 36 grains, Stardust detected seven, and upcoming missions DESTINY+ and IMAP will detect some more. Along with the debris from interstellar visitors like Comet Borisov, these scant grains are the only particulate matter from other stars that astronomers can measure directly inside the solar system. By directly measuring and imaging dust outside the solar system, Interstellar Probe could illuminate where these particles come from and how they seep into the heliosphere.

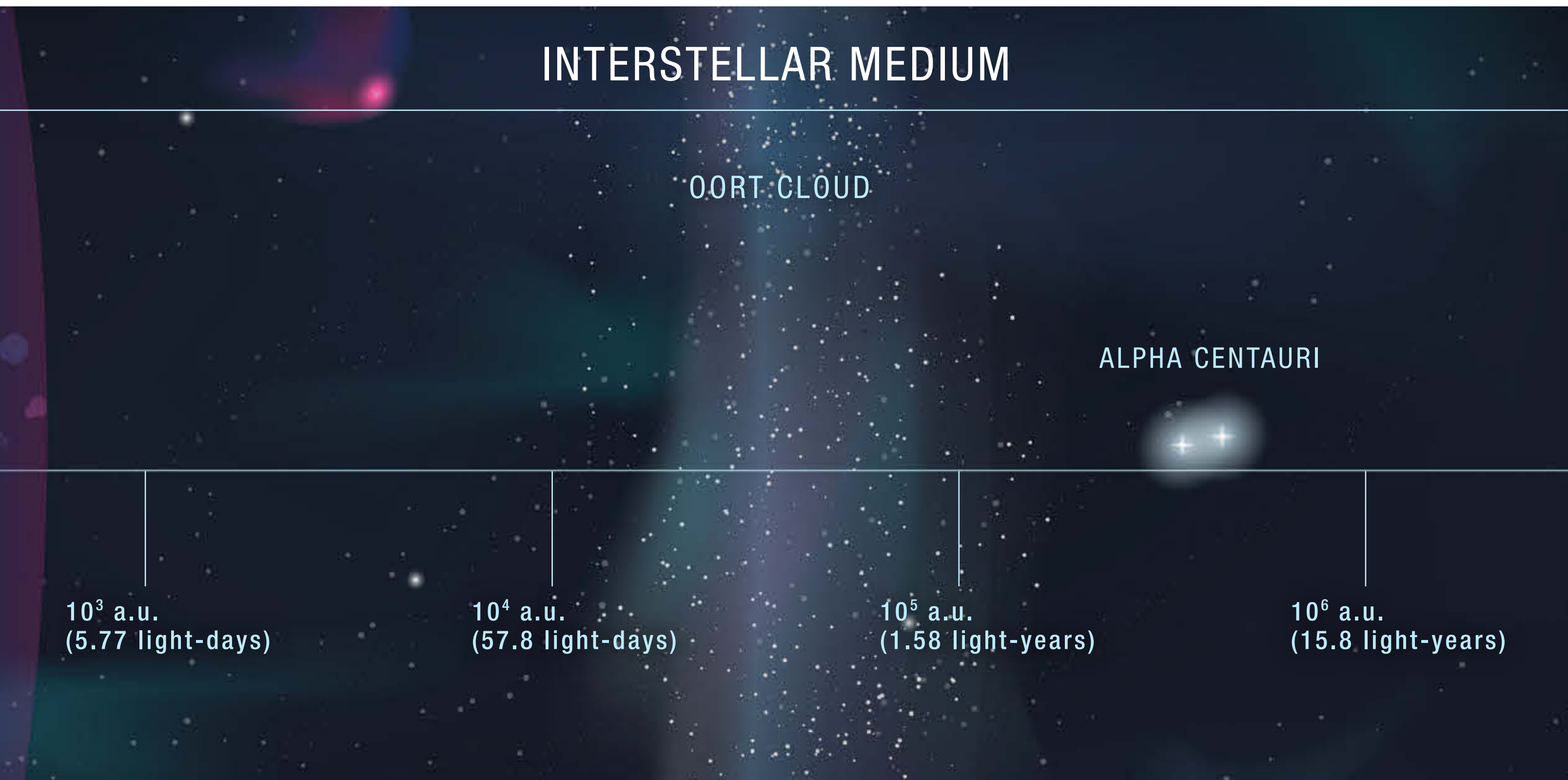
Daring Adventures

Interstellar Probe is not the only mission concept on the table. The Chinese Academy of Sciences is discussing Interstellar Heliosphere Probes, twin spacecraft that could travel to 100 a.u. by 2049. And the privately funded Breakthrough Initiative is proposing Breakthrough Starshot, which plans to go 3,000 times farther — to Alpha Centauri — in 20 years.

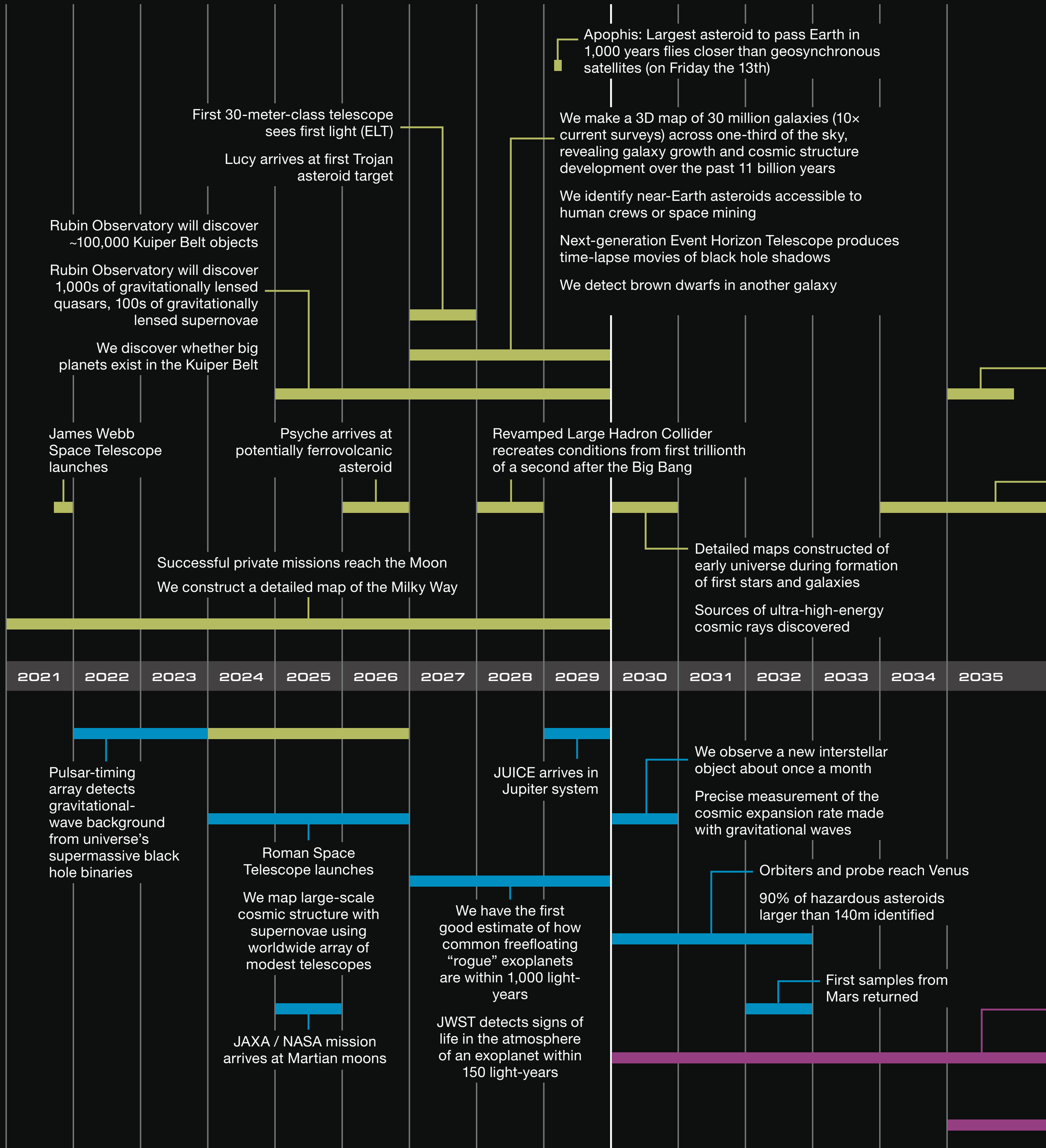
Regardless of which idea makes it to launch, a craft must travel quickly to get to interstellar space in our lifetime. One possible plan would employ the Sun as a gravitational slingshot to accelerate Interstellar Probe to about 110,000 kilometers per hour (70,000 miles an hour) — nearly twice as fast as the Voyagers. The Breakthrough Starshot team, on the other hand, plans to use a ground-based laser beam to propel an army of tiny spacecraft to more than *160 million* kph.

These plans are both risky and expensive. But the reward, the teams argue, is worth it.

■ Solar physicist **MONICA BOBRA** is a contributing editor for *Sky & Telescope*.



80 YEARS: WHERE WE'RE GOING by Camille M. Carlisle, Terri Dubé, and Lauren Sgro



Future Forecast

What can we expect in astronomy news between now and 2050?

We've arranged astronomers' predictions into a rough timeline, with probability rankings and approximate fulfillment dates. Many are safe bets; a few aren't. Things become more uncertain after 2030.

Science Editor Camille M. Carlisle and editorial intern Lauren Sgro pestered dozens of astronomers to amass this list. Art Director Terri Dubé reined everything in.

Possible | Highly likely | (Almost) certain

We directly image surfaces of Earth-like planets orbiting Sun-type stars

Dragonfly helicopter arrives at Titan

Close-ups of Europa reveal potential connections between subsurface ocean and surface, spurs sample lander planning

Spacecraft enters orbit around Uranus

Sources of high-energy neutrinos identified

We measure the acceleration of cosmic expansion in real time

2036 2037 2038 2039 2040 2041 2042 2043 2044 2045 2046 2047 2048 2049 2050

Spacecraft employ nuclear electric propulsion to explore solar system

Space-based LISA detects gravitational waves from binary supermassive black holes

Ground-based detectors measure gravitational waves from binary black holes in the universe's first 500 million years

We verify whether some of the fundamental physical constants are really constant or actually vary throughout space and time

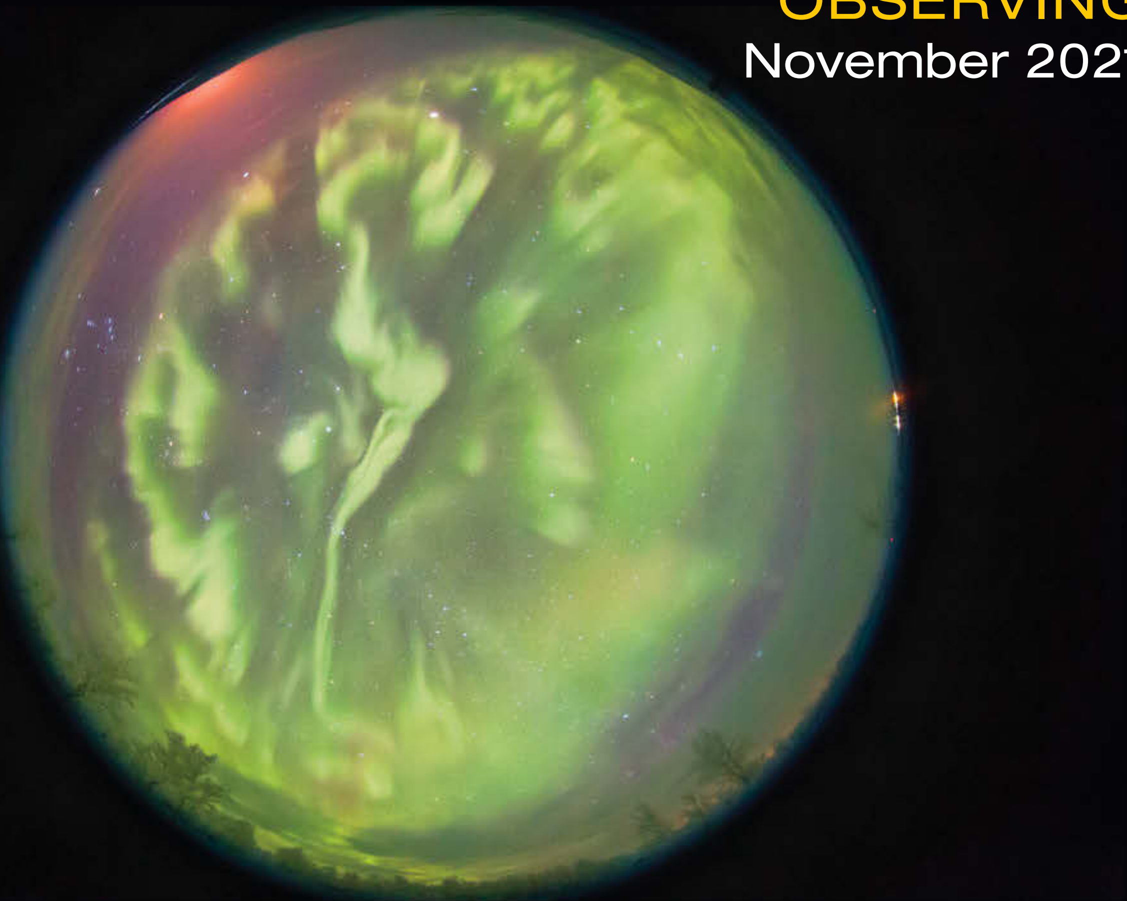
We determine how the first supermassive black holes formed

Earliest supernovae in the universe detected

We observe the universe's first quasar (>13.3 billion years ago?)

First crewed mission heads to Mars

EDUARD MUZHEVSKYI / SHUTTERSTOCK.COM



1 **DAWN:** Tiny Mercury and Virgo's lucida, Spica, rise together in the east-southeast; some 4° separates the pair. You'll have to be quick to catch this sight before dawn brightens the sky.

3 **DAWN:** The Moon (one day shy of new), Mercury, and Spica form a fetching triangle low in the east-southeast before the Sun rises (see page 46).

7 **DAYLIGHT-SAVING TIME ENDS** at 2 a.m. for most of the U.S. and Canada.

7 **DUSK:** Look toward the west-southwest to see the young Moon and Venus around 3½° apart, left of the Teapot of Sagittarius.

9 **DUSK:** The waxing crescent Moon, Jupiter, and Saturn are arranged in a line approximately 25° long above the southern horizon, while blazing Venus anchors the quartet of planets in the southwest.

10 **DUSK:** The Moon and the gas giants form a triangle in Capricornus.

11 **DUSK:** Above the southern horizon, the first-quarter Moon gleams some 5° lower left of Jupiter.

14 **EVENING:** Algol shines at minimum brightness for roughly two hours centered at 9:36 p.m. PST (see page 50).

17 **MORNING:** Viewing of the typically weak Leonid meteor shower will be severely hampered by the nearly full Moon.

17 **EVENING:** Algol shines at minimum brightness for roughly two hours centered at 9:25 p.m. EST.

19 **ALL NIGHT:** A deep partial lunar eclipse will be visible for almost all of North America (go to page 48 for more details).

19 **DUSK:** The Moon, just past full, rises in the east sandwiched by the Pleiades and the Hyades.

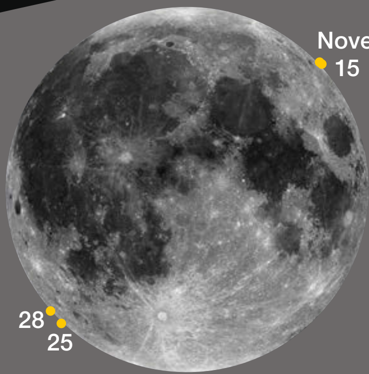
23 **EVENING:** Look to the east to see the waning gibbous Moon in Gemini around 3° from Pollux. Castor completes the triad.

24 **EVENING:** The Moon hangs in Cancer nearly 3° from the Beehive Cluster (M44).

27 **DAWN:** High above the southeastern horizon, the last-quarter Moon gleams in Leo a smidgen more than 5° from Regulus. The earlier you look, the narrower the gap will be.
— DIANA HANNIKAINEN

▲ The green shimmer of aurorae dominates the view in this fisheye image taken in Lapland in northern Sweden. Interest in this dazzling phenomenon has a long pedigree at *Sky & Telescope*: Eighty years ago, our very first issue featured readers' photos of the northern lights, as well as a glossary of terms describing auroral forms. P-M HEDÉNMI, SED

NOVEMBER 2021 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.

MOON PHASES

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

NEW MOON
November 4
21:15 UT

FIRST QUARTER
November 11
12:46 UT

FULL MOON
November 19
08:57 UT

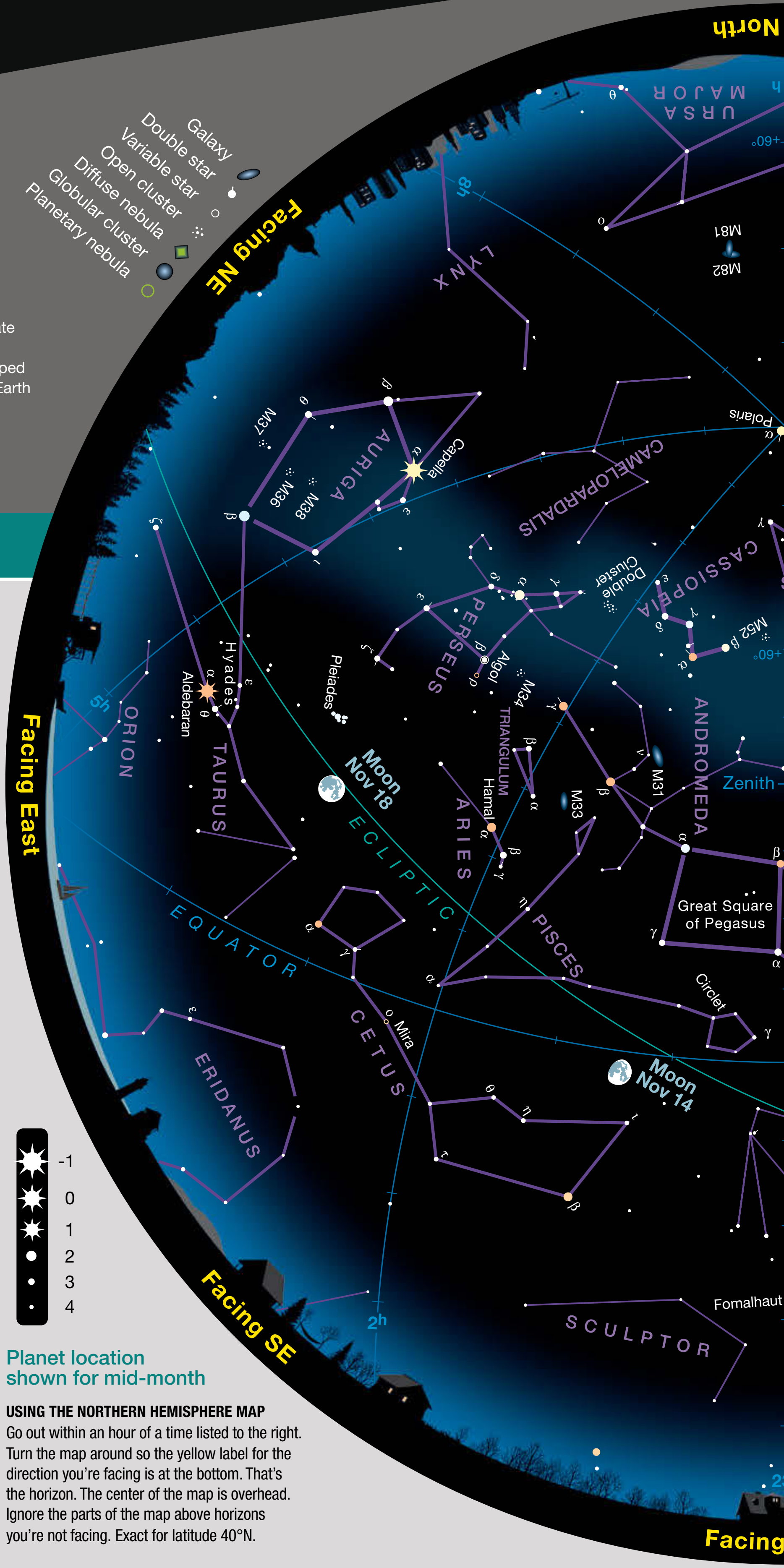
LAST QUARTER
November 27
12:28 UT

DISTANCES

Perigee	November 5, 22^h UT
358,844 km	Diameter 33′ 18″
Apogee	November 21, 02^h UT
406,279 km	Diameter 29′ 25″

FAVORABLE LIBRATIONS

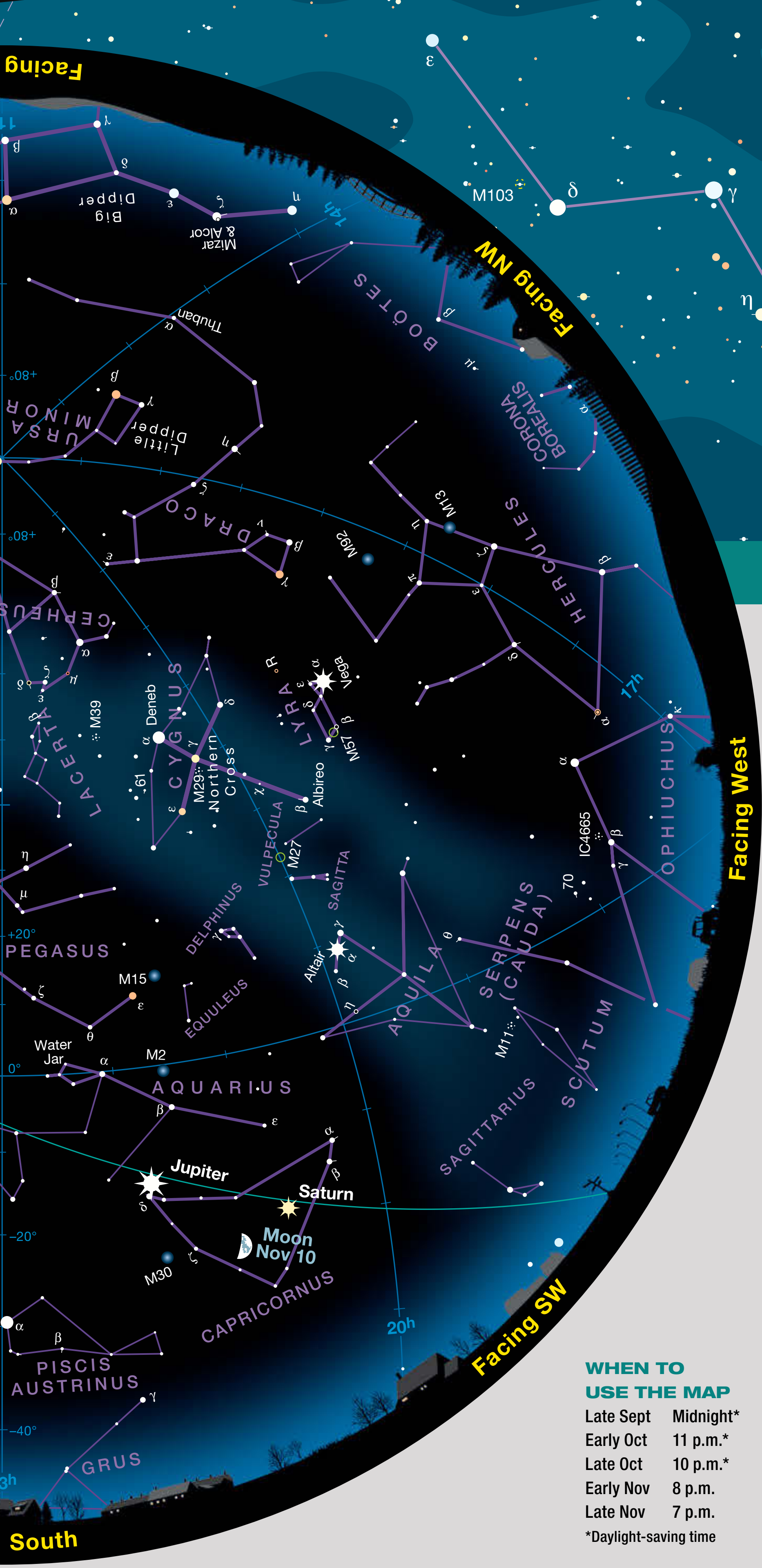
- Vashakidze Crater — November 11
- Mare Humboldtianum — November 15
- Andersson Crater — November 25
- Catalan Crater — November 28

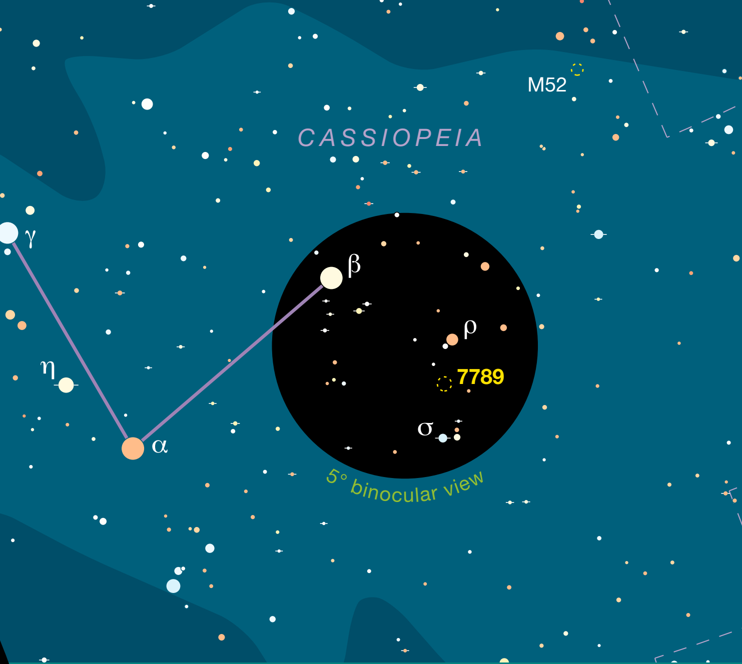


Planet location shown for mid-month

USING THE NORTHERN HEMISPHERE MAP

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





Binocular Highlight by Mathew Wedel

A Cluster Treat in Cass

Most new observers assume that the famed Messier catalog contains the best and brightest deep-sky objects in the night sky. That's mostly true, but there are many notable exceptions. The Double Cluster in Perseus is perhaps the most conspicuous omission. (What *was* Messier thinking?) But there are also a bunch of lesser-known bino targets that Messier overlooked, and most have NGC designations. One of the most appealing clusters for November evenings is **NGC 7789** in Cassiopeia.

Caroline Herschel discovered the cluster in 1783, hence its nickname Caroline's Rose. You can discover it yourself: It's an easy star-hop from the western half of Cassiopeia's W. Start from 2.2-magnitude Alpha (α) Cassiopeiae, zip up to 2.3-magnitude Beta (β), and make a right-angle turn west to 4.5-magnitude Rho (ρ). Caroline's Rose lies between the yellow hypergiant Rho and 5.0-magnitude Sigma (σ).

You'll have to look carefully and adjust your expectations to appreciate NGC 7789. The cluster is rich, but its stars are uniformly faint. So, instead of a collection of sparkles, you're going to see a small, misty patch of starlight. The cluster stands out well in a dark sky but is a challenge in light-polluted conditions. My 10×50s reveal a reasonably large, round haze set in a very pretty, rich star field. The view improves slightly in my 15×70s, which allow the brightest cluster members to pop in and out of view.

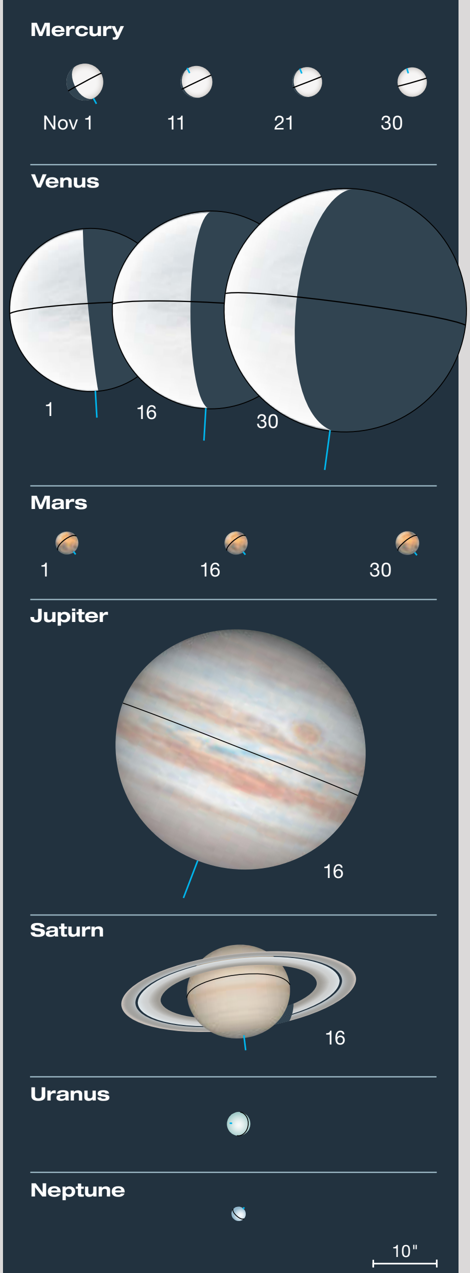
NGC 7789 is a respectable 1.6 billion years old, and as such its brighter and more massive stars have already evolved off the main sequence and are now red giants. You won't be able to detect their hue in your binos — but knowing this might help evoke a rose as you contemplate this misty patch.

■ **MATT WEDEL** enjoys both the famous and the obscure when it comes to star clusters.

WHEN TO USE THE MAP

Late Sept	Midnight*
Early Oct	11 p.m.*
Late Oct	10 p.m.*
Early Nov	8 p.m.
Late Nov	7 p.m.

*Daylight-saving time

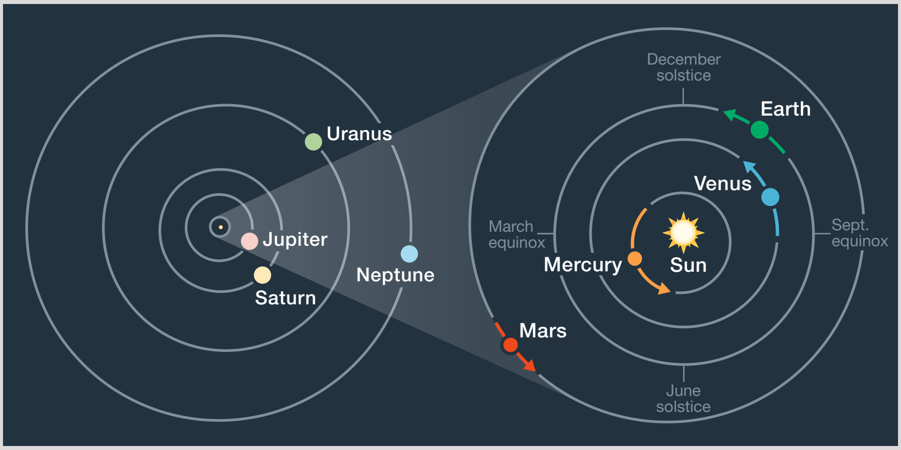


PLANET VISIBILITY (40°N, naked-eye, approximate) **Mercury** visible at dawn to the 11th • **Venus** shines brightly at dusk all month • **Mars** emerges at dawn on the 23rd • **Jupiter** and **Saturn** transit at dusk and set late at night.

November Sun & Planets

	Date	Right Ascension	Declination	Elongation	Magnitude	Diameter	Illumination	Distance
Sun	1	14^h 24.4^m	–14° 20′	—	–26.8	32′ 14″	—	0.993
	30	16^h 23.6^m	–21° 35′	—	–26.8	32′ 26″	—	0.986
Mercury	1	13^h 24.8^m	–6° 41′	17° Mo	–0.8	5.8″	79%	1.153
	11	14^h 23.6^m	–12° 53′	11° Mo	–0.9	5.0″	94%	1.331
	21	15^h 26.3^m	–18° 34′	5° Mo	–1.1	4.7″	99%	1.424
	30	16^h 25.0^m	–22° 27′	1° Ev	—	4.6″	100%	1.451
Venus	1	17^h 39.4^m	–27° 04′	47° Ev	–4.6	25.6″	48%	0.651
	11	18^h 21.8^m	–27° 10′	46° Ev	–4.7	29.0″	43%	0.575
	21	18^h 59.3^m	–26° 21′	45° Ev	–4.8	33.3″	36%	0.501
	30	19^h 26.7^m	–25° 01′	42° Ev	–4.9	38.2″	30%	0.437
Mars	1	13^h 54.8^m	–11° 16′	8° Mo	+1.7	3.6″	100%	2.585
	16	14^h 33.9^m	–14° 45′	13° Mo	+1.6	3.7″	100%	2.542
	30	15^h 12.0^m	–17° 39′	17° Mo	+1.6	3.8″	99%	2.490
Jupiter	1	21^h 40.3^m	–15° 07′	104° Ev	–2.5	42.2″	99%	4.675
	30	21^h 50.4^m	–14° 12′	77° Ev	–2.3	38.5″	99%	5.124
Saturn	1	20^h 38.2^m	–19° 20′	88° Ev	+0.6	16.8″	100%	9.909
	30	20^h 45.0^m	–18° 54′	61° Ev	+0.7	16.0″	100%	10.369
Uranus	16	2^h 38.9^m	+15° 02′	168° Ev	+5.7	3.8″	100%	18.759
Neptune	16	23^h 25.7^m	–4° 58′	117° Ev	+7.9	2.3″	100%	29.465

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.



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

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

A Is for Andromeda

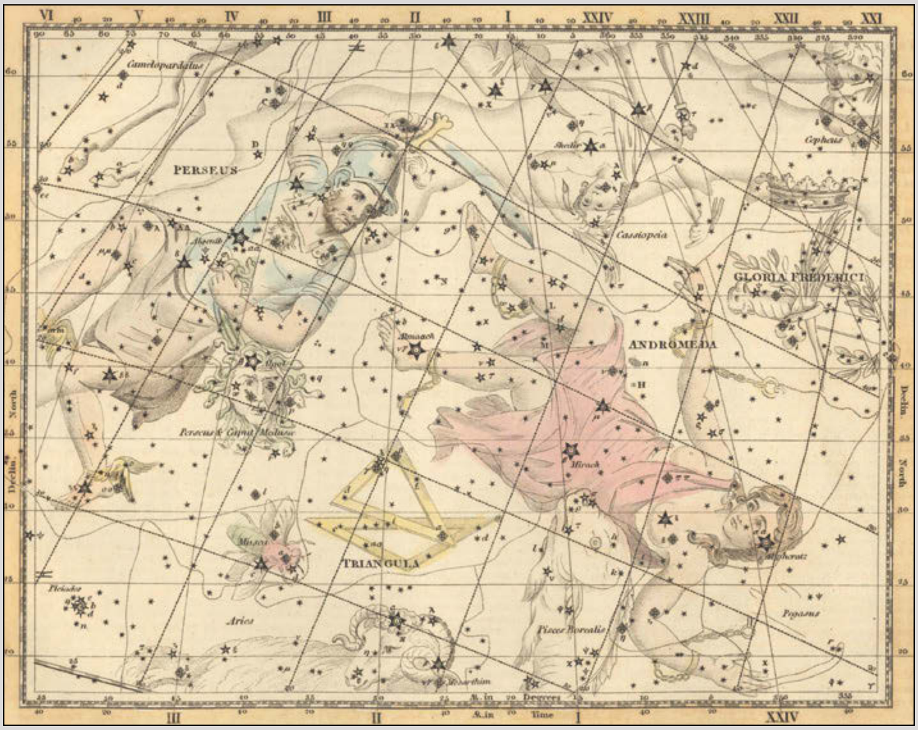
This ancient constellation leads in more ways than one.

"A is for Andromeda." It's a catchy phrase that suggests that the constellation comes first — and it does in a couple of interesting ways. Most obviously, Andromeda leads the way in the alphabetical listing of the 88 official constellations. Let's be glad that the roll call didn't begin with a faint and obscure figure like Antlia, the Air Pump. In constellation-by-constellation star guides, like the classic *Burnham's Celestial Handbook*, it's wonderful to get off to a smashing start with essays detailing Andromeda's marvelous galaxy, color-contrasting double star, and its many other highlights.

Andromeda also leads the way on the celestial sphere by virtue of the fact that its main pattern is dominated by three 2nd-magnitude stars that stretch in right ascension from 0^h to just past 2^h. The only other bright constellation occupying this right ascension range is Cassiopeia. But for observers at mid-northern latitudes, Cassiopeia is circumpolar and visible all year round, so it doesn't quite have the strong seasonal association that Andromeda does.

One practical advantage of being located near the 0^h line is that most star atlases order their charts from north to south, starting at 0^h right ascension and proceeding eastward. From the classic *Norton's Star Atlas* to the modern *Sky & Telescope's Pocket Sky Atlas*, you can count on finding Andromeda in the first set of non-circumpolar star maps.

For many skywatchers, the constellation's name is closely associated with M31, the famed Andromeda Galaxy. The object was first described around AD 964 as "the Little Cloud" by the Persian astronomical writer Abd al-Rahman al-Sufi. Until the early part of the 20th century, astronomers referred to M31 as the Andromeda Nebula and thought it was located within the Milky Way. In reality, the imposing spiral is even larger and populated with more stars than our own galaxy. At a distance of more than 2 million light-years, the Andromeda Galaxy is the most distant object readily visible to the naked eye.



▲ **HEROIC RESCUE** In Greek mythology, Andromeda was chained to a rock, having been sentenced to death by sea monster (Cetus). Just in the nick of time, the hero Perseus saves her.

How bright is M31? The usual figure given is around magnitude 3.4. But because the galaxy is an extended object whose light is spread over a large area, it's certainly not as easy to detect as a star of the same brightness. Most sources suggest that M31 appears as an elongated smear of radiance about 1° wide and 3° long. But talented observer Walter Scott Houston was, under excellent conditions, able to trace M31 out to a length of 4° with his unaided eyes and 5° with large binoculars.

Let's return to the constellation's three brightest stars mentioned earlier. As shown on the Sky Chart presented on pages 42 and 43, the trio are arranged in an appealing line. Working eastward, they are Alpha (α) Andromedae (Alpheratz or Sirrah), Beta (β) Andromedae (Mirach), and Gamma (γ) Andromedae (Alma). Remarkably, each star is spaced almost exactly 1^h of right ascension from its neighbor: Alpheratz is at $0^h\ 08^m$, Mirach at $1^h\ 10^m$, and Almak at $2^h\ 04^m$. Even more amazingly, their magnitudes are virtually identical, with Alpheratz and Mirach both shining at magnitude 2.07 and Almak at magnitude 2.10. Another interesting twist is that each star is also at double the distance of its neighbor. Alpheratz is 97 light-years away, Mirach is 200 light-years, and Almak is 400 light-years.

Each star also has at least one notable trait all its own. Alpheratz performs double duty by marking the northeast corner of the Great Square of Pegasus; Mirach is a striking orange-red star of spectral type *M*0; and Almak is a lovely telescopic double star with component suns shining gold and blue respectively. All good reasons to make Andromeda your first stop on autumn evenings.

■ As a young boy, **FRED SCHAAF** read *A for Andromeda*, written by astronomer Fred Hoyle and novelist John Elliot.

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

Mars Meekly Returns

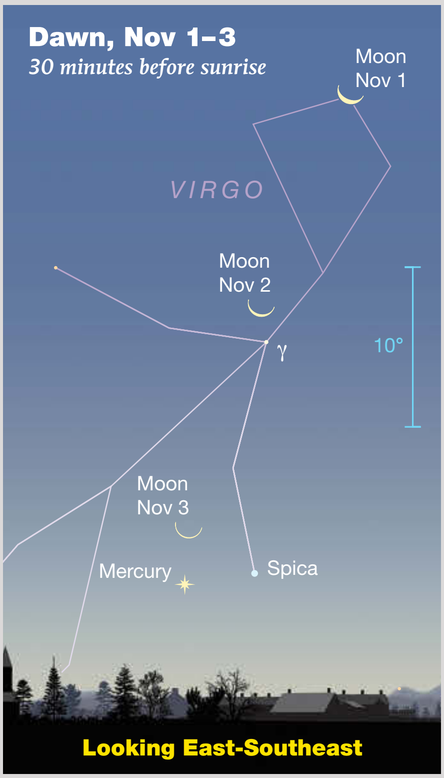
The Red Planet slowly re-emerges at dawn while Mercury slips away.

WEDNESDAY, NOVEMBER 3

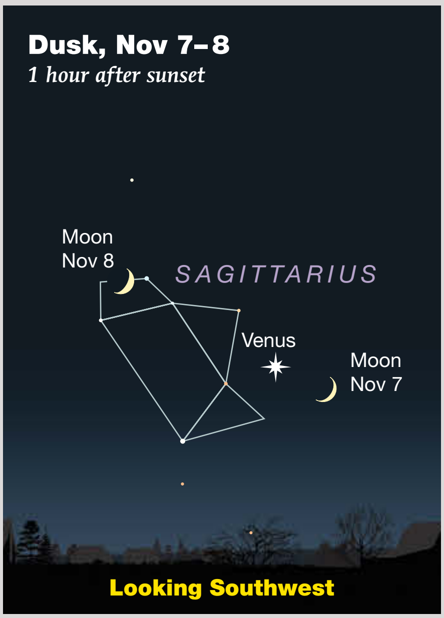
The month gets under way with an attractive dawn scene that includes the waning crescent **Moon**, **Mercury**, and **Spica**. The trio is arranged in a tidy triangle low in the east-southeast, with the Moon above Mercury and Spica off to the right. The Moon will be easy to spot and, at magnitude –0.8, so will Mercury. But you might need to dig out your binoculars to catch Spica in brightening twilight. Binoculars will also help you appreciate earthshine on the razor-thin Moon's "dark" side. As for Mercury, it's finishing off its most favorable morning apparition of the year, which peaked as last month drew to a close. Although the swift little planet brightens slightly as it continues its plunge sunward, Mercury will become progressively more difficult to see with each passing day as it nears its meeting with the Sun on November 28th. By late next week, Mercury will be a tough naked-eye find. Don't fret if you miss out though — another chance to catch it will come along in December at dusk.

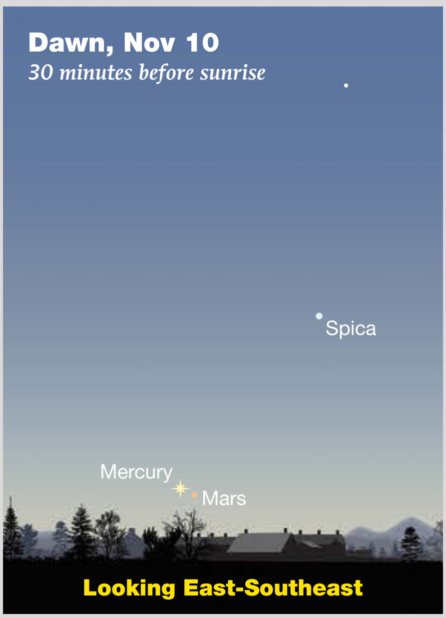
SUNDAY, NOVEMBER 7

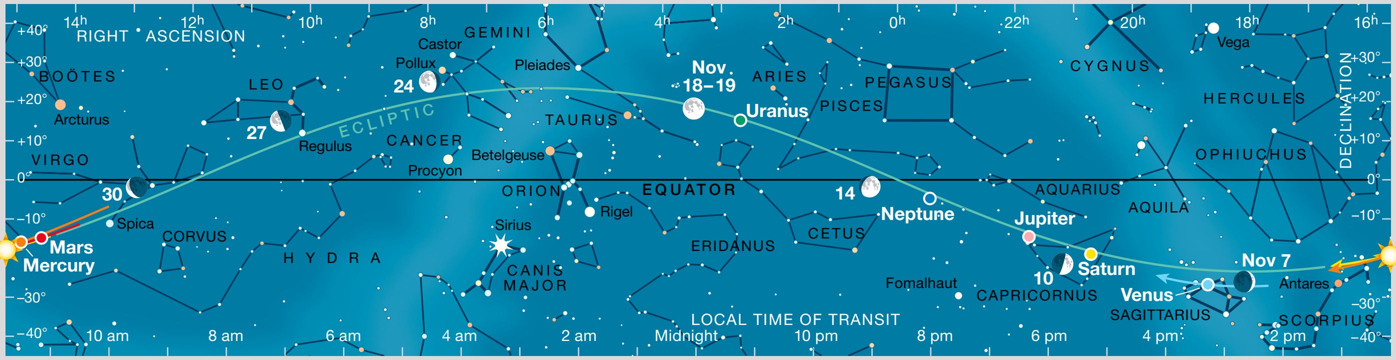
The once-a-month meeting between the crescent **Moon** and **Venus** takes place at dusk today. This time, the eye-catching duo are around 4° apart — perhaps a little more, perhaps a little less, it all depends on where you are and when you look. That's because the Moon moves against the background sky at a rate of roughly one lunar diameter per hour. Or, to put it another way, that means that the three-hour difference between twilight's arrival in New York and San Francisco gives the Moon plenty of extra time to approach closer to Venus. And sure enough, for New Yorkers the Moon is a little more than 4° from Venus at dusk, but three hours later for observers in San Francisco, there's just 2½° between the two objects. As a result, West Coast observers will see a noticeably more appealing version of this conjunction than skywatchers on the East Coast. Of course, it's not *always* the case that the West Coast gets the better view. Last month, for



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







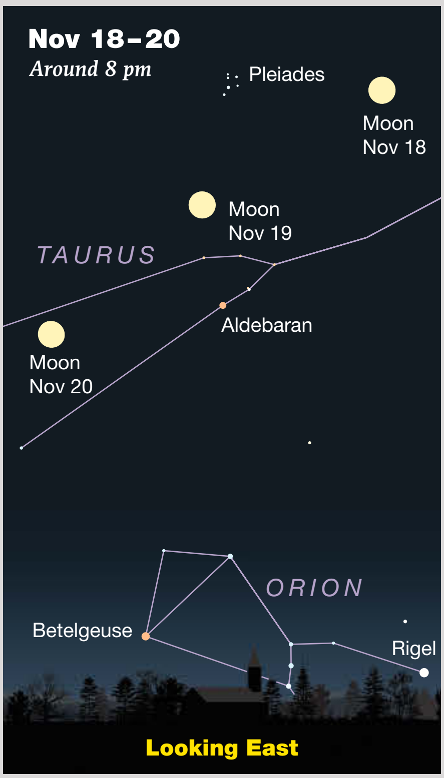
▲ The Sun and planets are positioned for mid-November; the colored arrows show the motion of each during the month. The Moon is plotted for evening dates in the Americas when it's waxing (right side illuminated) or full, and for morning dates when it's waning (left side illuminated). "Local time of transit"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

example, the Moon was east of Venus when the two paired up, so the earlier view (favoring the East Coast) was the more striking one.

WEDNESDAY, NOVEMBER 10

Here's one for binocular and small-scope enthusiasts. As **Mercury** sinks lower and lower at dawn it passes **Mars**, which is only now slowly climbing away from the Sun's glare, having had its solar conjunction a little more than one month ago. During morning twilight today, the two planets meet very low in the east-southeast. At magnitude –0.9, Mercury shouldn't present too much difficulty if you have an unobstructed horizon. Mars, however, is a different story, glowing dimly at magnitude 1.6. So, your strategy is clear: First find Mercury, then hunt very carefully 1° to the lower right for Mars. This will be a difficult observation to make, but if you succeed, you'll get an early look at the Red Planet as it begins a fresh apparition. Thirteen months from now when it's gleaming brilliantly in a midnight sky, you'll recall this morning with satisfaction and tell your friends, "I remember back when Mars was a sad little speck you could hardly see."

If you're in the mood for something less challenging (and at a more convenient hour), look to the southwest this evening to catch the first-quarter **Moon** between **Saturn** and **Jupiter**, in Capricornus. The Moon is roughly 6½° lower left of Saturn tonight. By tomorrow night, however, the Moon's eastward motion will place it slightly more than 5° lower left of brilliant Jupiter.



FRIDAY, NOVEMBER 19

Less than 24 hours after undergoing a nearly total eclipse (see page 48 for details) the **Moon** puts on another (albeit far more modest) show. This evening it rises bracketed by the **Pleiades** and **Hyades** clusters in Taurus. Given that the Moon is not yet 24 hours past full, its glare will rob most of the cluster stars of their prominence. But you can be sure that 1st-magnitude Aldebaran will shine through even though it sits less than 7° below the Moon as they clear the east-northeastern horizon together. Ironically, **Aldebaran** doesn't belong to the Hyades — it's simply an attractive foreground star that only appears to be a member of the cluster.

MONDAY, NOVEMBER 22

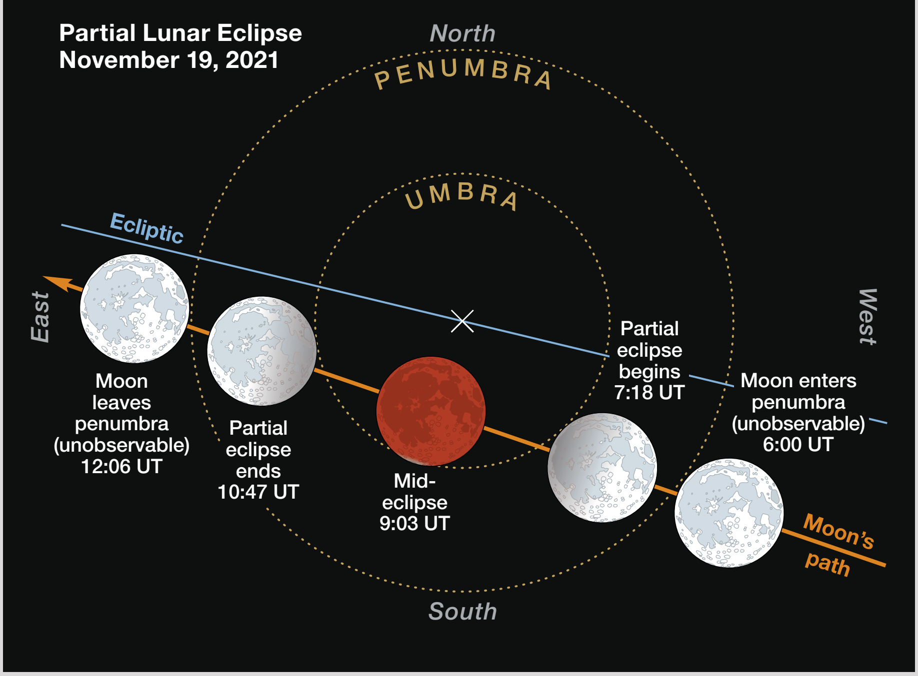
Here's another one for the binocular and small-scope crowd. Once again, it's **Mars** that's calling attention to itself — this time by partnering up with 2.7-magnitude Alpha (α) Librae, also known as **Zubenelgenubi**. Although less than two weeks have elapsed since its encounter with Mercury, the Red Planet should be easier to spot now, having gained roughly 2½° (five Moon diameters) of altitude. Once you've located Mars, look for the star appearing like a stray Martian moon sitting just 11′ above the planet.

Alpha Librae is best known for its fun-to-say name and for being a lovely double star in small telescopes. Zubenelgenubi has a 5.2-magnitude companion just a hair less than 4′ away. Indeed, the two stars and Mars form a wildly unequal three-in-a-row string if you can spot them all. The key is to find an unobstructed east-southeastern horizon and to look as early as possible, before brightening twilight completely washes out the sky.

■ Consulting Editor **GARY SERONIK** has looked forward to each Martian opposition since enjoying his first one in 1971.

An Almost Total Lunar Eclipse

Observers across North America get to watch the Moon slip through Earth's shadow.

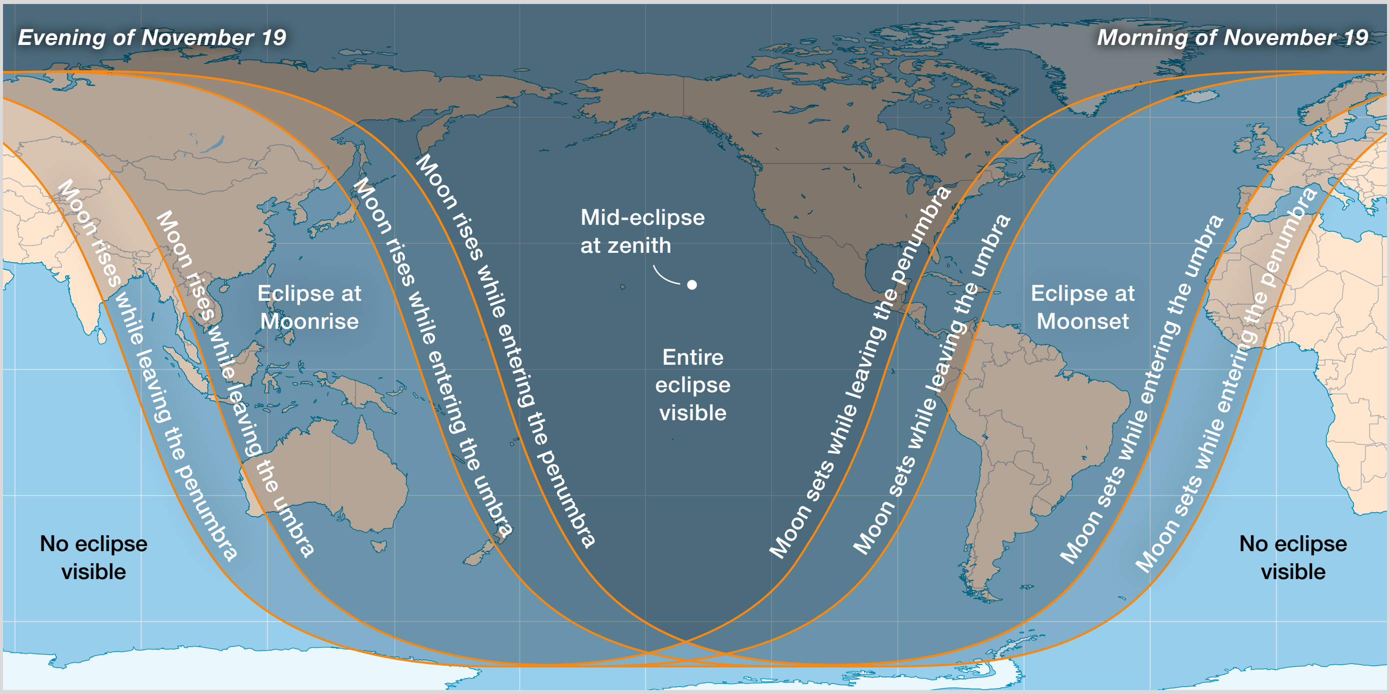


Yes, it's November, and yes, the weather's getting colder — but don't put your telescope away just yet. It's going to be a busy month.

Topping the list is a very deep partial lunar eclipse on the night of November 18–19, visible across the Americas, northern Europe, eastern Asia, Australia, and the Pacific. The partial phase — when the Moon enters Earth's umbral shadow — begins at 2:18 a.m. EST (7:18 UT) on November 19th, and greatest eclipse is at 4:03 a.m. EST (9:03 UT).

At maximum, 97% of the lunar disk will squeeze into the umbra, leaving just a narrow sliver of the southern limb poking out. The Moon will be just 1.7 days shy of apogee, so its apparent size will be slightly smaller than usual. This helps increase both the depth of the eclipse and its duration. The Moon exits the umbra at 5:47 a.m. EST (10:47 UT), nearly 3½ hours after it entered.

Depending on volcanic activity and other atmospheric factors, the lunar disk's color may range from yellow-orange to coppery red or even



MOON PATH: GREGG DINDERMAN / S&T; SOURCE: USNO; ECLIPSE MAP: LEAH TISICONE / S&T; SOURCE: USNO

DEBRA CERAVOLO

▲ The partially eclipsed Moon sets at sunrise on May 26, 2021, as seen from Anarchist Mountain, east of Osoyoos, British Columbia, Canada.

ruddy brown. Whatever the hue, the near-total aspect of the eclipse guarantees a colorful and beautiful sight, with the Moon floating some 5½° south-southwest of the Pleiades cluster around the time of maximum eclipse.

You might try your hand at carefully noting the Moon's appearance so that you can compare one eclipse with another. The Danjon scale is typically used to estimate the Moon's brightness and color during a total eclipse. But there's no reason you can't put it to use during this near-total event by hiding the Moon's uneclipsed edge behind a building. The scale ranges from L=0 for a very dark eclipse to L=4 for a bright, copper-red or orange eclipse.

Another fun project is to carefully time when the umbral shadow crosses prominent craters. Such crater timings help gauge the size of Earth's shadow, which can vary depending on the state of our planet's atmosphere. Roger Sinnott, a *Sky & Telescope* Senior Contributing Editor, plans to update predictions for umbral immersion and emersion times for selected craters on the magazine's website (**skyandtelescope.org**) prior to the eclipse. He'd be happy to receive your observations at **roger.sinnott@verizon.net**.

Two November Oppositions

BOTH URANUS AND CERES reach opposition this month. Uranus does so on the 5th (0^h UT), and Ceres on the 27th (4^h UT).

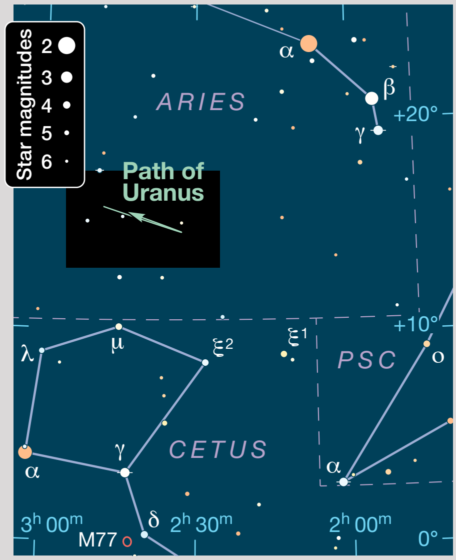
On opposition night, Uranus shines at magnitude 5.7 in southern Aries, 5.1° north-northwest of 4.3-magnitude Mu (μ) Ceti. Typical of outer planets around opposition, Uranus spends the month moving westward in retrograde motion. The nearly full Moon passes less than 2° south of the planet on the 17th.

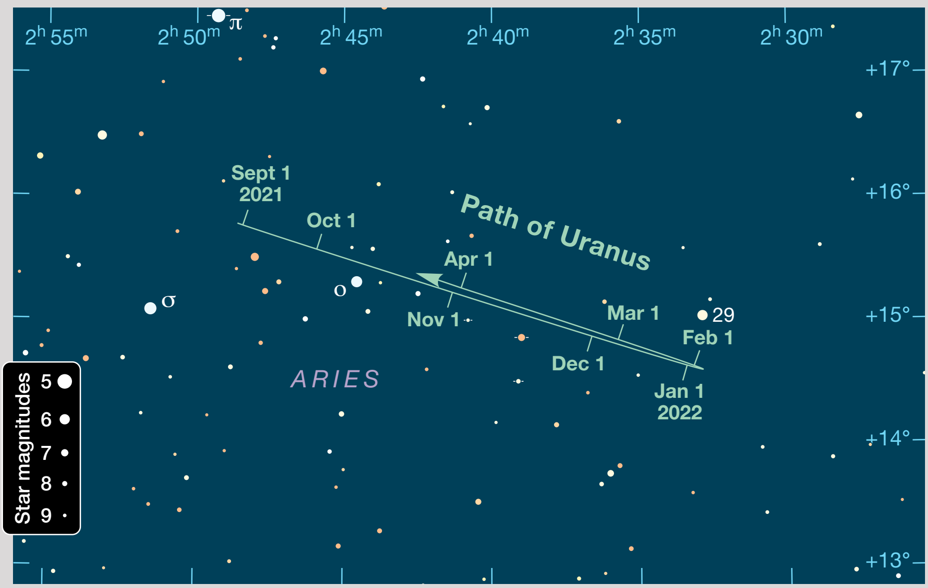
Uranus is slowly brightening as it approaches its August 2050 perihelion. Dimly visible to the naked eye under moonless rural skies, it will reach magnitude 5.4 at oppositions from 2048 to 2052. If light pollution and satellites haven't overrun the sky by then, more people than ever might see the distant planet without optical aid.

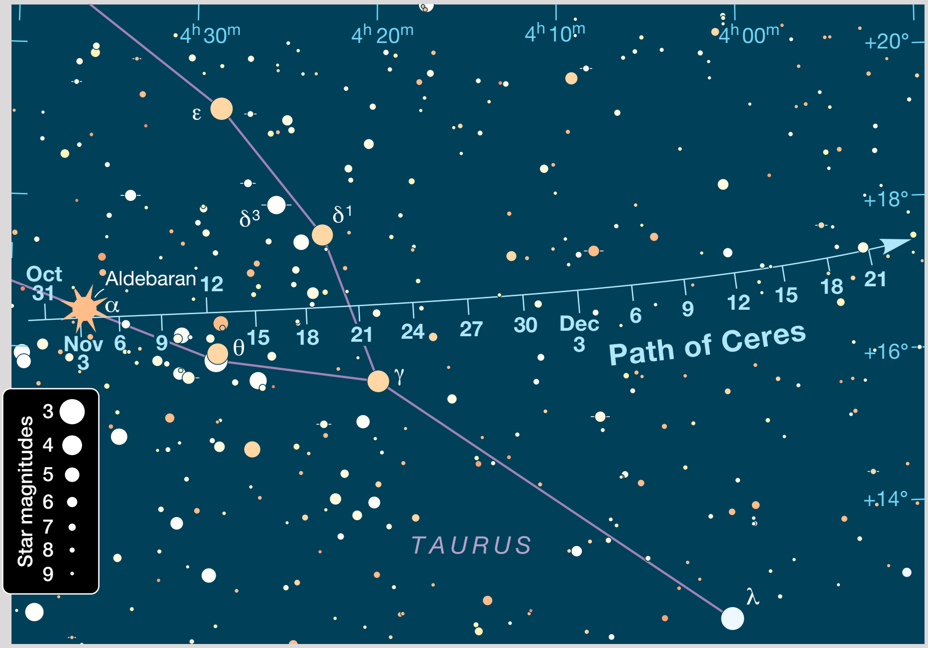
Uranus is a pretty sight in a telescope. A 3-inch refractor magnifying at 75× will reveal its tiny, aqua disk. However, even in larger instruments, the planet remains stubbornly small. With an apparent diameter of 3.8″ this month, discerning any detail requires excellent seeing and careful scrutiny. Some amateurs have occasionally sighted faint bands with 14-inch and larger instruments at magnifications of 400× and greater.

If you have an 8-inch or larger scope, you can hunt for the two brightest Uranian moons, Titania and Oberon. Titania, at magnitude 13.9, is very slightly brighter than Oberon at 14.1, but it's also closer to the planet. At maximum northern and southern elongations, Titania is a faint speck about 30″ from Uranus's limb compared to Oberon's 40″. Use the highest magnification seeing will allow and position Uranus just outside the field of view to reduce glare from the planet's disk.

To check the positions of the these satellites on any given night, visit the







Tools page of **skyandtelescope.org** for our handy "Moons of Uranus" interactive observing aid.

Compared to Uranus, finding the dwarf planet Ceres will prove relatively easy. On the night of November 2–3, it shines at magnitude 7.6 as it passes just 7′ south of 1st-magnitude Aldebaran in Taurus. For much of the rest of the month, Ceres crosses the familiar Hyades cluster as it brightens to a maximum of magnitude 7.0 at opposition on the 27th. From the outer suburbs or the countryside, a pair of 10×50 binoculars should suffice to spot Ceres and track its passage across Taurus.

Minima of Algol

Oct.	UT	Nov.	UT
3	5:24	3	18:21
6	2:13	6	15:10
8	23:02	9	11:58
11	19:50	12	8:47
14	16:39	15	5:36
17	13:28	18	2:25
20	10:17	20	23:14
23	7:05	23	20:03
26	3:54	26	16:52
29	0:43	29	13:41
31	21:32		

These geocentric predictions are from the recent heliocentric elements Min. = JD 2445641.554 + 2.867324*E*, where *E* is any integer. For a comparison-star chart and more info, see **skyandtelescope.org/algol**.

▲ Perseus climbs high in the northeastern sky during evening hours in November. 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).

Action at Jupiter

AT THE START OF NOVEMBER, Jupiter is well positioned for early evening viewing as it transits the meridian at about 8 p.m. local daylight-saving time. From its perch in eastern Capricornus, the gas giant shines at magnitude –2.5 and presents a disk 42″ across.

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

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

Features on Jupiter appear closer to the central meridian than to the limb for 50 minutes before and after transiting. Here are the times, in Universal Time, when the Great Red Spot should cross Jupiter's central meridian. The dates, also in UT, are in bold. (Eastern Standard Time is UT minus 5 hours.)

October 1: 6:03, 15:58; **2**: 1:54, 11:50, 21:45; **3**: 7:41, 17:37; **4**: 3:32, 13:28, 23:24; **5**: 9:19, 19:15; **6**: 5:11, 15:07; **7**: 1:02, 10:58, 20:54; **8**: 6:49, 16:45; **9**: 2:41, 12:36, 22:32; **10**: 8:28, 18:24; **11**: 4:19, 14:15; **12**: 0:11, 10:06, 20:02; **13**: 5:58, 15:54; **14**: 1:49, 11:45, 21:41; **15**: 7:36, 17:32; **16**: 3:28, 13:24, 23:19; **17**: 9:15, 19:11; **18**: 5:07, 15:02; **19**: 0:58, 10:54, 20:49; **20**: 6:45, 16:41; **21**: 2:37, 12:32, 22:28; **22**: 8:24, 18:20; **23**: 4:15, 14:11; **24**: 0:07, 10:03, 19:58; **25**: 5:54, 15:50; **26**: 1:46, 11:41, 21:37; **27**: 7:33, 17:29; **28**: 3:24, 13:20, 23:16; **29**: 9:12, 19:07; **30**: 5:03, 14:59; **31**: 0:55, 10:50, 20:46

November 1: 6:44, 16:39; **2**: 2:35, 12:31, 22:27; **3**: 8:22, 18:18; **4**: 4:14, 14:10; **5**: 0:06, 10:01, 19:57; **6**: 5:53, 15:49; **7**: 1:44, 11:40, 21:36; **8**: 7:32, 17:27; **9**: 3:23, 13:19, 23:15; **10**: 9:11, 19:06; **11**: 5:02, 14:58; **12**: 0:54, 10:49, 20:45; **13**: 6:41, 16:37; **14**: 2:33, 12:28, 22:24; **15**: 8:20, 18:16; **16**: 4:12, 14:07;

17: 0:03, 09:59, 19:55; **18**: 5:51, 15:46; **19**: 1:42, 11:38, 21:34; **20**: 7:30, 17:25; **21**: 3:21, 13:17, 23:13; **22**: 9:09, 19:04; **23**: 5:00, 14:56; **24**: 0:52, 10:48, 20:43; **25**: 6:39, 16:35; **26**: 2:31, 12:27, 22:22; **27**: 8:18, 18:14; **28**: 4:10, 14:06; **29**: 0:02, 09:57, 19:53; **30**: 5:49, 15:45

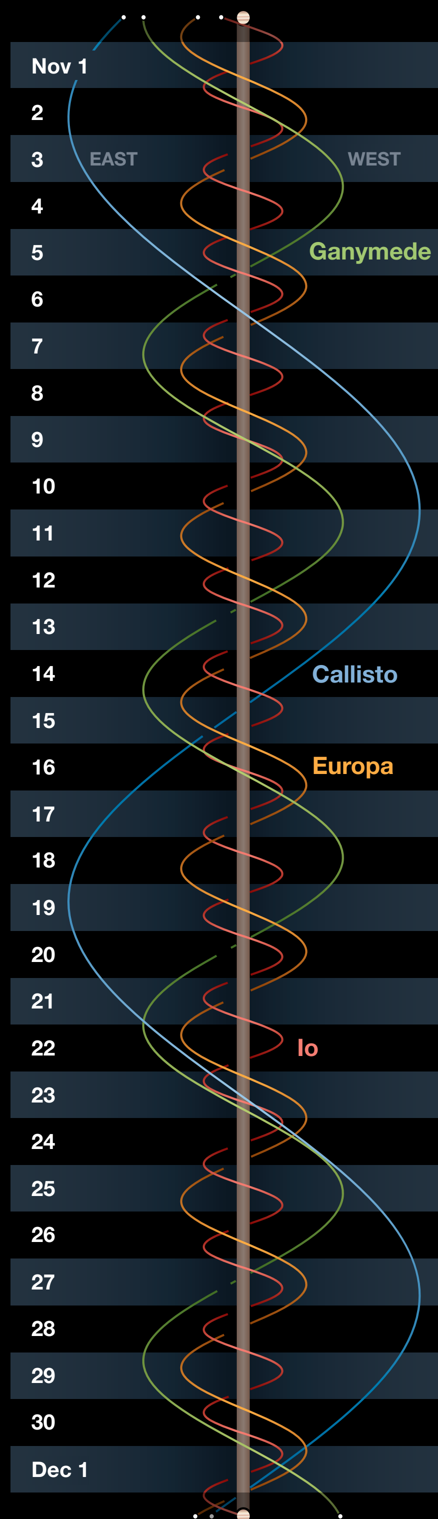
These times assume that the spot will be centered at System II longitude 8° on November 1st. If the Red Spot has moved elsewhere, it will transit 1⅔ minutes earlier for each degree less than 8° and 1⅔ minutes later for each degree more than 8°.

Phenomena of Jupiter's Moons, November 2021

Nov. 1	11:25	I.Oc.D
	15:00	I.Ec.R
	17:13	II.Tr.I
	19:49	II.Sh.I
	20:02	II.Tr.E
	22:36	II.Sh.E
Nov. 2	5:41	III.Tr.I
	8:45	I.Tr.I
	9:17	III.Tr.E
	10:03	I.Sh.I
	11:02	III.Sh.I
	11:02	I.Tr.E
	12:20	I.Sh.E
	14:34	III.Sh.E
Nov. 3	5:53	I.Oc.D
	9:29	I.Ec.R
	12:13	II.Oc.D
	17:46	II.Ec.R
Nov. 4	3:14	I.Tr.I
	4:32	I.Sh.I
	5:31	I.Tr.E
	6:49	I.Sh.E
Nov. 5	0:21	I.Oc.D
	3:58	I.Ec.R
	6:29	II.Tr.I
	9:07	II.Sh.I
	9:19	II.Tr.E
	11:55	II.Sh.E
	19:34	III.Oc.D
	21:42	I.Tr.I
	23:01	I.Sh.I
	23:12	III.Oc.R
	23:59	I.Tr.E
Nov. 6	0:58	III.Ec.D
	1:18	I.Sh.E
	4:32	III.Ec.R
	16:40	IV.Tr.I
	18:50	I.Oc.D
	21:16	IV.Tr.E
	22:27	I.Ec.R
Nov. 7	1:31	II.Oc.D
	5:33	IV.Sh.I
	7:04	II.Ec.R
	9:49	IV.Sh.E
	16:11	I.Tr.I
	17:30	I.Sh.I
	18:28	I.Tr.E
	19:47	I.Sh.E
Nov. 8	13:19	I.Oc.D
	16:56	I.Ec.R
	19:46	II.Tr.I
	22:26	II.Sh.I
	22:36	II.Tr.E
Nov. 9	1:13	II.Sh.E
	9:37	III.Tr.I
	10:40	I.Tr.I
	11:59	I.Sh.I
	12:56	I.Tr.E
	13:13	III.Tr.E
	14:15	I.Sh.E
	15:04	III.Sh.I
	18:36	III.Sh.E
Nov. 10	7:47	I.Oc.D
	11:25	I.Ec.R
	14:49	II.Oc.D
	20:23	II.Ec.R
Nov. 11	5:08	I.Tr.I
	6:28	I.Sh.I
	7:25	I.Tr.E
	8:44	I.Sh.E
Nov. 12	2:16	I.Oc.D
	5:54	I.Ec.R
	9:04	II.Tr.I
	11:44	II.Sh.I
	11:53	II.Tr.E
	14:31	II.Sh.E
	23:32	III.Oc.D
	23:37	I.Tr.I
Nov. 13	0:57	I.Sh.I
	1:54	I.Tr.E
	3:10	III.Oc.R
	3:13	I.Sh.E
	5:00	III.Ec.D
	8:33	III.Ec.R
	20:45	I.Oc.D
Nov. 14	0:23	I.Ec.R
	4:08	II.Oc.D
	9:42	II.Ec.R
	18:06	I.Tr.I
	19:26	I.Sh.I
	20:23	I.Tr.E
	21:42	I.Sh.E
Nov. 15	2:56	IV.Oc.D
	7:34	IV.Oc.R
	15:14	I.Oc.D
	15:43	IV.Ec.D
	18:51	I.Ec.R
	19:58	IV.Ec.R
	22:22	II.Tr.I
Nov. 16	1:02	II.Sh.I
	1:12	II.Tr.E
	3:50	II.Sh.E
	12:35	I.Tr.I
	13:38	III.Tr.I
	13:55	I.Sh.I
	14:52	I.Tr.E
	16:11	I.Sh.E
	17:14	III.Tr.E
	19:06	III.Sh.I
	22:38	III.Sh.E
Nov. 17	9:42	I.Oc.D
	13:20	I.Ec.R
	17:27	II.Oc.D
	23:01	II.Ec.R
Nov. 18	7:04	I.Tr.I
	8:24	I.Sh.I
	9:21	I.Tr.E
	10:40	I.Sh.E
Nov. 19	4:11	I.Oc.D
	7:49	I.Ec.R
	11:41	II.Tr.I
	14:21	II.Sh.I
	14:30	II.Tr.E
	17:08	II.Sh.E
Nov. 20	1:33	I.Tr.I
	2:53	I.Sh.I
	3:35	III.Oc.D
	3:50	I.Tr.E
	5:09	I.Sh.E
	7:13	III.Oc.R
	9:02	III.Ec.D
	12:35	III.Ec.R
	22:41	I.Oc.D
Nov. 21	2:18	I.Ec.R
	6:46	II.Oc.D
	12:19	II.Ec.R
	20:02	I.Tr.I
	21:22	I.Sh.I
	22:19	I.Tr.E
	23:38	I.Sh.E
Nov. 22	17:10	I.Oc.D
	20:47	I.Ec.R
Nov. 23	1:00	II.Tr.I
	3:40	II.Sh.I
	3:50	II.Tr.E
	6:27	II.Sh.E
	10:56	IV.Tr.I
	14:32	I.Tr.I
	15:31	IV.Tr.E
	15:51	I.Sh.I
	16:48	I.Tr.E
	17:43	III.Tr.I
	18:07	I.Sh.E
	21:19	III.Tr.E
	23:08	III.Sh.I
	23:52	IV.Sh.I
Nov. 24	2:39	III.Sh.E
	4:03	IV.Sh.E
	11:39	I.Oc.D
	15:16	I.Ec.R
	20:07	II.Oc.D
Nov. 25	1:38	II.Ec.R
	9:01	I.Tr.I
	10:20	I.Sh.I
	11:18	I.Tr.E
	12:36	I.Sh.E
Nov. 26	6:08	I.Oc.D
	9:45	I.Ec.R
	14:20	II.Tr.I
	16:58	II.Sh.I
	17:09	II.Tr.E
	19:45	II.Sh.E
Nov. 27	3:30	I.Tr.I
	4:49	I.Sh.I
	5:47	I.Tr.E
	7:05	I.Sh.E
	7:43	III.Oc.D
	11:21	III.Oc.R
	13:04	III.Ec.D
	16:37	III.Ec.R
Nov. 28	0:37	I.Oc.D
	4:14	I.Ec.R
	9:27	II.Oc.D
	14:57	II.Ec.R
	22:00	I.Tr.I
	23:18	I.Sh.I
Nov. 29	0:16	I.Tr.E
	1:34	I.Sh.E
	19:07	I.Oc.D
	22:43	I.Ec.R
Nov. 30	3:40	II.Tr.I
	6:17	II.Sh.I
	6:30	II.Tr.E
	9:04	II.Sh.E
	16:29	I.Tr.I
	17:47	I.Sh.I
	18:46	I.Tr.E
	20:02	I.Sh.E
	21:51	III.Tr.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 4 hours ahead of Eastern Daylight Time). Next is the satellite involved: **I** for Io, **II** Europa, **III** Ganymede, or **IV** Callisto. Next is the type of event: **Oc** for an occultation of the satellite behind Jupiter's limb, **Ec** for an eclipse by Jupiter's shadow, **Tr** for a transit across the planet's face, or **Sh** for the satellite casting its own shadow onto Jupiter. An occultation or eclipse begins when the satellite disappears **(D)** and ends when it reappears **(R)**. A transit or shadow passage begins at ingress **(I)** and ends at egress **(E)**. Each event is gradual, taking up to several minutes. Predictions courtesy IMCCE / Paris Observatory.

Jupiter's Moons



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

The Ever-changing Great Red Spot

Jupiter's famous storm is the focus of a rich tradition of discovery by amateur astronomers.

▲The gradually diminishing length of the Great Red Spot is striking when comparing these images sent back by NASA's Voyager I spacecraft in 1979 (left), Galileo in 1996 (center), and Juno in 2020 (right).

VOYAGER: NASA / JPL, GALILEO: NASA / JPL / CORNELL UNIVERSITY, JUNO: NASA / JPL-CALTECH / SWRI / MSSS

The first unambiguous record of the Great Red Spot (GRS) dates from 1831, when German astronomer Samuel Heinrich Schwabe glimpsed a portion of its outline as a pale "bay" indenting the southern edge of the dusky South Equatorial Belt. This muted appearance attracted scant attention until 1878, when the feature suddenly took the form of a vivid brick red ellipse measuring 40,000 km long by 12,000 km wide (25,000 by 7,500 mi). It dominated the face of the planet until 1882 when it abruptly faded.

Although it has slowly but steadily diminished in size and its ruddy color has waxed and waned many times during the past 140 years, the GRS remains Jupiter's most iconic feature and the subject of intensive study. Two exceptionally talented amateur astronomers spearheaded efforts to understand its nature and evolution.

The first was Percival Braybrooke Molesworth (1867-1908), an officer in the British Army's Corps of Royal Engineers posted to the harbor city of Trincomalee in the colony of Ceylon (known today as Sri Lanka). While there, he installed a superb 12.5-inch Newtonian reflector made by one of the era's foremost telescope makers, George Calver, on the front lawn of his bungalow on a high bluff overlooking the Indian Ocean. From the site's latitude of only 8.6° north, the planets ride high in the sky, and the laminar coastal airflow frequently results in superb seeing conditions.

Molesworth soon emerged as the leading Jupiter observer of the era. He employed a powerful technique recently devised by another British amateur, Arthur Stanley Williams. Williams recorded the precise times that well-defined features in Jupiter's turbulent and seemingly chaotic atmosphere passed through the central meridian, an imaginary line running from pole to pole, bisecting the planet's disc. By referring to an ephemeris, he determined the longitude of features from their central meridian transit times. Equipped with an accurate timepiece, a practiced eye can achieve an accuracy of one or two minutes, corresponding to about 1° of Jovian longitude. Williams discerned the presence of nine discrete, persistent currents at various latitudes on Jupiter, all running parallel to the equator.

Possessing keen eyesight and seemingly boundless energy, Molesworth recorded a whopping 6,758 central meridian transit timings during the 1900 apparition alone! Not only did he accumulate this vast amount of observational data in neat ledgers supplemented by beautifully tinted watercolor renderings of the planet, but he also performed the tedious manual calculations required to make sense of it. By 1901 he was able to identify all the principal currents that control large-scale circulations in the Jovian atmosphere.

The GRS is sandwiched between a westward jet stream located along the southern edge of the South Equatorial Belt (SEBs) and an eastward jet stream that runs along the northern edge of the South Temperate Belt (STBn). It rolls counterclockwise between these opposing atmospheric currents like an enormous ball bearing.

In 1905 Molesworth reported his strong suspicion that the GRS was oscillating in longitude with a period of 90 days. These strange accelerations and decelerations with a roughly 1° amplitude were confirmed during the 1960s by New Mexico State University Observatory astronomer Gordon Solberg, who measured high-resolution photographs of Jupiter taken with a 24-inch reflector on 469 nights over a 5-year period.

This 90-day cycle has remained remarkably constant for well over a century. Despite the dramatic changes in the size and appearance of the GRS, the cycle varies by less than two days from year to year and by less than 24 hours over longer intervals. Although features in the SEBs jet stream circle the planet every 90 days, the speed of this current fluctuates considerably. The immutability of the 90-day GRS oscillation remains a mystery to this day.

As early as 1902, observers witnessed encounters between the GRS and spots in the adjoining currents, which were swept by the periphery of the GRS like flotsam around an island. The first hint of internal circulation within the GRS that revealed its true nature as a huge anticyclone was reported in 1949 by Elmer Reese (1919-2010), an accomplished observer who worked in his family's Uniontown, Pennsylvania grocery store during much of his observing career (see page 14).

Like Molesworth, Reese was a prolific recorder of Jovian transit timings and an adept interpreter of data. Examining five drawings made by three members of the Association of Lunar and Planetary Observers in October and November of 1949, Reese noticed that all of the drawings depicted "a pair of thin, parallel streaks" within the GRS. "The position and orientation of these streaks on various dates," he reported, "suggest that the Red Spot region is a vortex in the Jovian atmosphere rotating in a counterclockwise direction in a period of 10.7 days."

In 1963, New Mexico State University recruited Reese to join its Planetary Patrol and Study Project, on which he collaborated with Gordon Solberg and Bradford Smith on a NASA-funded program to photographically monitor Jupiter. By the early 1970s, the NMSU team established an internal circulation period for the GRS of 6 days. In 1979, images recorded by NASA's Voyager I spacecraft confirmed their findings.

H. GORDON SOLBERG, JR.

▲The son of a Uniontown, Pennsylvania grocer, Elmer Reese was a founding member of the Association of Lunar and Planetary Observers.

As the width of the GRS has diminished at an average rate of 240 km per year, its internal circulation has sped up appreciably (see the July issue, page 10). This conservation of angular momentum is similar to a figure skater spinning on the tip of one skate and retracting outstretched arms in order to rotate faster.

For roughly two decades, backyard astronomers equipped with high-speed video cameras and powerful image-processing software have routinely recorded delicate features within the GRS. These images help monitor its internal circulation rate with a high degree of precision. Amateur images played a vital role in determining that the internal circulation rate of the solar system's most powerful storm has shortened an average of 1.2 days per decade since 1949.

Well into the 21st century, Jupiter continues to provide rewarding opportunities for amateurs to participate in a rich tradition of discovery.

■ Contributing Editor **TOM DOBBINS** has witnessed the changing appearance of the GRS over five decades.

Amateur planetary observers today routinely record sub-arcsecond features, providing valuable data on the state of the Jovian atmosphere. This September 6, 2020 image by Christopher Go clearly resolves the cyclonic clouds within the GRS.

BERNHARD HUBL

Water Carrier Line Dance

Tiptoeing along the celestial equator in Aquarius has its rewards.

Bully for you, Aquarius — your Water Carrier persona fits. When you culminate on November evenings, my suburban home in southwest British Columbia is usually getting drenched. On the rare occasions a November night is clear, I gaze up at your Water Jar asterism and shake my fist at it.

Just kidding!

In truth, I enjoy poking around the entire expanse of Aquarius. In my previous column on page 54 of the September issue, I toured through the southwestern part of this sprawling resident of the zodiac, but northern Aquarius is also worth exploring. Join me for another Aquarian adventure, starting in (uh oh!) the Water Jar.

Taking a Dip

I live at the north end of town, so my south sky is bad. Real bad. Even though ye olde Water Jar straddles the celestial equator well above my local streetlights, it's a prisoner of the massive light dome blighting my south.

The asterism's midpoint, 3.6-magnitude Zeta (ζ) Aquarii, shines gamely within a 3.6°-wide triangle formed by 3.8-magnitude Gamma (γ), 4.0-magnitude Eta (η), and 4.8-magnitude Pi (π). In my citified sky, the faint foursome is often reduced to a trio (bye-bye Pi) unless I use binoculars. Even then, I can't picture any kind of jar. A perceptive colleague of mine imagines a three-bladed propeller with its hub marked by Zeta. Several stargazing friends tell me the wedgelike grouping makes a crooked Y. I see a martini glass — full, of course.

The olive in my martini is Zeta — the brightest Jar star is an excellent binary to boot. Known to double-star enthusiasts as **Struve (Σ) 2909**, its 4.3- and 4.5-magnitude yellow-white suns are just 2.4″ apart. Resolving them is a treat for amateur astronomers, me included. I've Zeta-tested my three fave backyard scopes: a 120-mm (4.7-inch) f/7.5 apochromatic refractor, a 180-mm f/15 Maksutov-Cassegrain reflector, and my workhorse 10-inch f/6 Dobsonian reflector. All three split Zeta comfortably at magnifications in the range of 110× to 130×.

During last November's allotted clear night, I inserted a low-power eyepiece in my 10-inch Dob and centered Zeta in the field of view. Then, in a deft-to-daft instant, I clumsily bumped the scope a couple of degrees downward. To my audible displeasure, Zeta had been replaced by 5.9-magnitude **60 Aquarii**. But my mumble-grumble swiftly turned to a quiet grin. My accidental catch was — ta-da! — a second, *really* small martini glass. In this tiny version, an asymmetrical crescent of five stars outlines the top of the glass while yellowish 60 Aquarii adorns a crooked stem, and three unaligned stars make an off-kilter base. I love it.

I proceeded to make a sober assessment of the glassware with the 10-inch cruising at 169×. Within the crescent portion is a row of three very faint stars — tiny olives for my mini-martini. I noted that 6th-magnitude 60 Aquarii is accompanied by two feeble outliers, a loose combo that the Washington Double Star Catalog lists as **BU1515**. South of 60, a double-dot caught my eye. Called **BU77**, it features 9.3- and 9.9-magnitude stars 2.8″ apart (an

▲ **MAGNIFICENT MESSIER** It's hard to believe that when Charles Messier observed this gorgeous globular cluster in 1760, he described it as a "nebula without a star." At a distance of 40,000 light-years, M2 is more remote than most Milky Way globulars. Even so, it's among the finest specimens visible from mid-northern latitudes.

11th-magnitude winger is 23″ farther out). Finally, cupping my hands around the eyepiece to help block out stray light, I took in the entire field and counted at least 20 stars down to about magnitude 11.5. Nice!

I Walk the Line

Returning to Zeta, which lies a tad north of the celestial equator, I pushed the Dobsonian westward a little less than 6° to 3.0-magnitude Alpha (α) Aquarii, barely south of the equator line. Yellowy Alpha guards a noticeably reddish, 8.4-magnitude star 13′ northwest. Of greater interest to me was the tight tandem **Σ2862**, which anchors the eastern end of a ½°-wide triangle 1° north-northeast of Alpha. The 8.0- and 8.4-magnitude stars, 2.5″ apart, resolved cleanly at 120×.

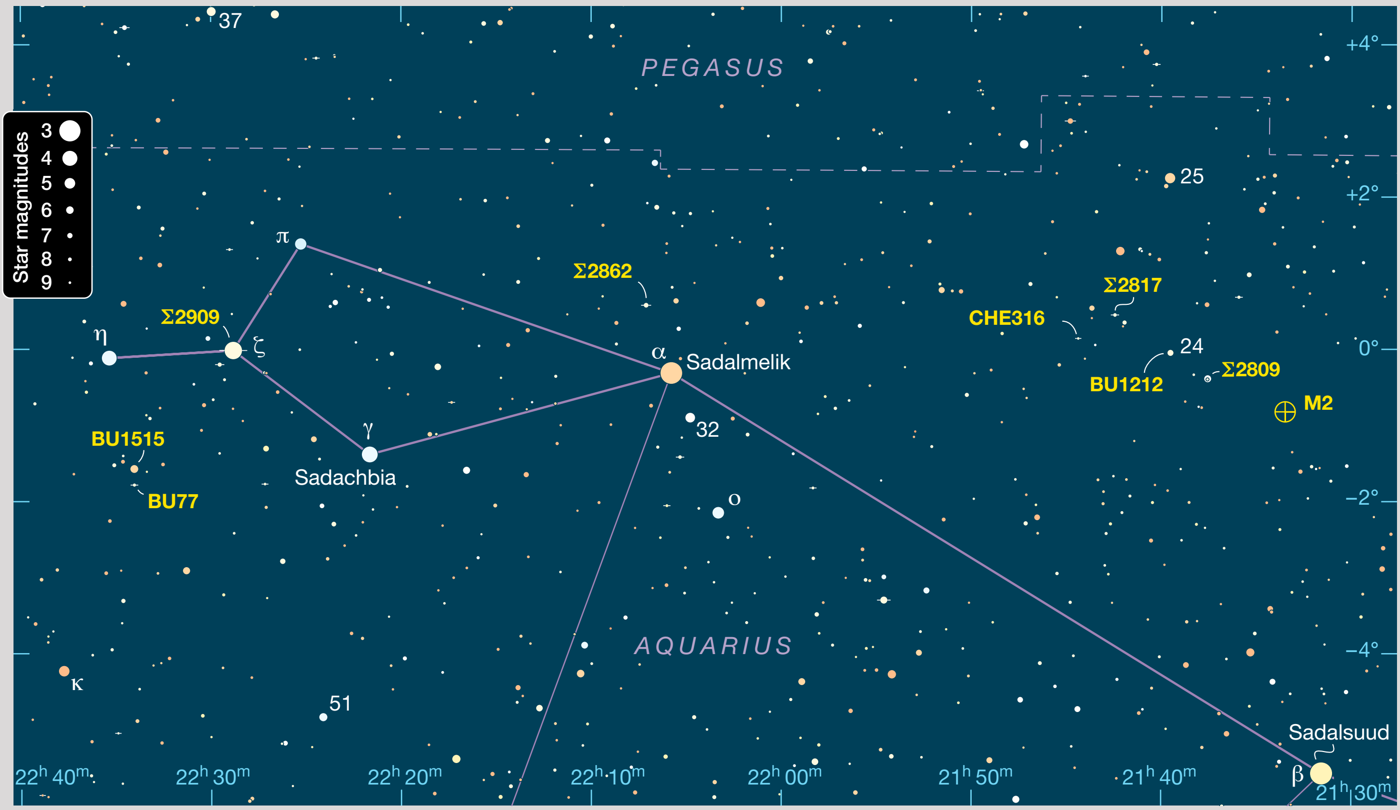
After Alpha & Co., I swept 8° west to **M2**. This showpiece globular cluster hangs farther south of the equator than Alpha, though not by much. If you're using an equatorial mount, simply place Alpha north of center in a low-power eyepiece, then shift westward in right ascension until you scoop up the 6.6-magnitude prize. This smooth move also works with an alt-az Dob, provided Alpha and M2 are near the meridian.

The Aquarius globular sits just inside a 17′-wide triangle formed by three 10th-magnitude stars. Two of them, 14′ apart, flank the cluster. Images show M2 almost bridging those flankers, but in my city-based optics at 48×, M2 is a diffuse, unresolved sphere that at best is 3′ across. No wonder — its leading members are magnitude 13.1, while most of the rest of the cluster's stars are at least three steps fainter. Regardless, the hazy hive invited a closer look.

Doubling to 96× produced a strongly concentrated, grainy ball. Its tenuous halo faded imperceptibly into space. I spotted a solitary sun immediately east of the halo, though in reality the cluster spreads well beyond that star. At 169×, M2 seemed slightly elliptical with a brilliant, distinctly grainy core. And I saw stars in the halo. Indeed, at 218× the halo was salted all over with pinpoints. The pale outskirts expanded when I again cupped my hands around the eyepiece and stared patiently using averted vision. M2 spanned 6′ — a captivating sight though still not quite half the object's full size.

I trained my smaller scopes on M2 and hoped for the best. In my 180-mm Mak-Cass at 84×, I beheld a respectable globular — obviously prominent, especially toward the center, and softly speckled at the edge. My adjacent solitary sun was also clearly visible. At 113× I detected starlike glints in the halo, and likewise, the cluster's broad middle was teasingly granular. The view exceeded my expectations.

M2 was a tougher challenge for my 120-mm apochromatic refractor. Working at 38×, the apo presented a luminous but minuscule object. The tiny-shiny blob demanded higher magnification, so I applied 129×. M2 morphed into a nebulous sphere that was impressively bright at its center, and my averted vision caught subtle mottling of the halo. I boldly upped the apo



▲ **WALKING THE LINE** A stroll along the celestial equator in Aquarius takes us from 3.6-magnitude Zeta Aquarii past 2.9-magnitude Alpha Aquarii to 6.6-magnitude globular cluster M2 — a span of 14°. Within that expanse are several interesting double stars and one of the sky's finest globulars.

to 200×, cupped my hands, and stared hard. That teased out a few halo stars.

The bottom line: Top-tier globulars like M2 fight the light!

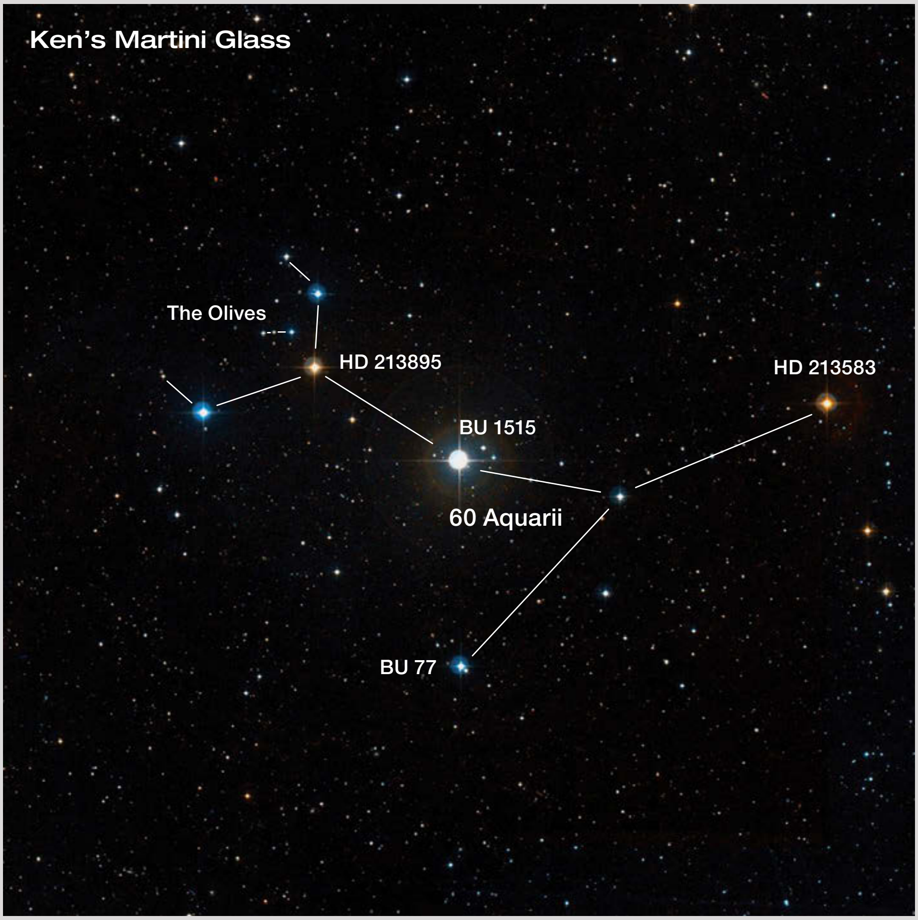
Extras, Anyone?

I powered the refractor down to 38× and headed northeast toward double star 24 Aquarii. Whoa — not so fast . . . I almost sailed past an easy duo, which I identified as **Σ2809**. Located 1.1° east-northeast of M2, Σ2809 displays 6.2- and 9.4-magnitude components, 31″ apart. Nudging the apo further brought me to 6.6-magnitude 24 Aquarii. Did something vanishingly faint lie beside it? I revved up to 200× again: Aha! An 11.8-magnitude attendant flickered weakly 36″ southward. The lopsided duo is listed as **BU1212**.

Given the novelty of a clear November night, I decided to do a little more exploring. Trolling at 38×, I quickly reeled in three doubles lined up in a ½°-long row about 1° northeast of 24 Aquarii. The first — not an official pair — is 7.7- and 9.5-magnitude stars separated by 3′. The second, comprising 8.9- and 9.2-magnitude mates 26″ apart, is **Σ2817**. The third, another unofficial set, exhibits 7.0- and 10.3-magnitude stars separated by 56″. These three wee ornaments modestly decorated my low-power field. A fourth little bauble, dubbed **CHE316**, beckoned ½° southeast of Σ2817. Its 9.2- and 10.5-magnitude components lie 38.4″ apart. CHE316 is no gem, but its proximity to the row-of-three made it hard to miss.

In total, I netted half a dozen doubles trending northeastward from M2 in a 3° sweep. Surveying this unexpected sextet wasn't immensely exciting, just cozily satisfying in a backyard astronomy kind of way. It's why I do this stuff. And best of all, I didn't get wet.

■ Contributing editor **KEN HEWITT-WHITE** praises the Water Jar every time he takes a shower.



▲ **MINI-MARTINI** Immediately southeast of the Water Jar, 5.9-magnitude 60 Aquarii dominates a Y-shaped asterism the author calls "the Martini Glass." In telescopes, 60 Aquarii sparkles with a slight yellowish hue, 7.9-magnitude HD 213895 shines more strongly yellow, and 8.1-magnitude HD 213583 glows yellow-orange.

POSS-II / STSCI / CALTECH / PALOMAR OBSERVATORY

Water Jar Wonders

Object	Type	Mag(v)	Size/Sep	RA	Dec.
Σ2909	Double star	4.3, 4.5	2.4″	22^h 28.8^m	−00° 01′
BU1515AB	Double star	6.0, 11.5	100.9″	22^h 34.0^m	−01° 34′
BU1515AC	Double star	6.0, 11.9	127.4″	22^h 34.0^m	−01° 34′
BU77	Double star	9.3, 9.9	2.8″	22^h 34.0^m	−01° 47′
Σ2862	Double star	8.0, 8.4	2.5″	22^h 07.1^m	+00° 34′
M2	Globular cluster	6.6	16′	21^h 33.5^m	−00° 49′
Σ2809	Double star	6.2, 9.4	31.1″	21^h 37.6^m	−00° 23′
BU1212	Double star	6.6, 11.8	36.2″	21^h 39.5^m	−00° 03′
Σ2817	Double star	8.9, 9.2	26.1″	21^h 42.4^m	+00° 27′
CHE316	Double star	9.2, 10.5	38.4″	21^h 44.4^m	+00° 08′

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

by Diana Hannikainen

Dings on the Moon

A coordinated global effort is dedicated to documenting flashes on the lunar surface.

FAVORABLE DATES

2021

Nov 19 Lunar eclipse
Dec 14 Geminids

2022

Apr 21 Lyrids
May 6 Eta Aquariids
May 16 Lunar eclipse
Oct 21 Orionids
Nov 8 Lunar eclipse
Dec 14 Geminids

▲ **CATCH A FLASH** Tom Nord of Tennessee captured this lunar impact flash during the total lunar eclipse in January 2019. November's partial eclipse should provide comparable circumstances.

We've all seen bits of comet dust self-immolate as they plow into Earth's atmosphere during meteor showers. But did you know that bits of dust ping the Moon as well? Meteoroids — to give them their official name — that hit the Moon have no medium in which to burn up and instead slam full-throttle into the lunar surface. In so doing, they carve out a small crater while emitting a very brief flash of light.

The Moon gets walloped. In November 1999, David Dunham (doyen of the International Occultation Timing Association) anticipated a particularly active Leonid meteor shower. He coordinated a network of observers armed with scopes and video cameras and instructed them to point at the Moon. Dunham himself observed at fellow astronomer George Varros's home in rural Maryland. Over in Texas, Brian Cudnik (of the Association of Lunar & Planetary Observers), sans recording equipment, participated by viewing through a 14-inch scope. During one of his stints at the eyepiece, he noticed a very brief, orange-yellow pointlike flash near the earthlit limb of the Moon. Cudnik relayed this info to Dunham who then carefully played back his tape. And there it was: an unmistakable pinpoint of light at the location and within one second of the time Cudnik reported.

Reports of *lunar transient phenomena*, as all manner of fleeting visual to-do's on the Moon are collectively known, go back centuries. But skepticism as to their existence prevailed . . . until that fateful night in November 1999. "This event spurred people to review their own tapes," Cudnik says, "and an additional five impact events were confirmed soon thereafter." And voilà, a new field of science flickered into being.

NASA gets in on the fun. Spurred on by amateur success, NASA (as well as other organizations around the world) established *lunar impact flash monitoring* programs to perform real-time observing of collisions in the solar system (e.g., Comet Shoemaker-Levy 9 plunging into Jupiter in 1994). They also strive to better understand the lunar environment for possible future bases. To this aim, NASA operates several telescopes at the Marshall Space Flight Center (**https://is.gd/nasa_lunar**). But, due to inclement weather and occasionally uncooperative mechanical bits and bobs, coverage isn't complete — and amateur contributions are essential for filling in the gaps.

How to look. You'll need a tracking telescope and a low-light astronomical video camera (the crucial element in the 1999 discovery). Use a scope with a field of view that can cover as much of the Moon's nightside as possible, while at the same time limiting glare from the dayside, recommends the British Astronomical Association's Tony Cook. (His lunar flash observation of January 2017 was the first confirmed event from the UK.) "Big aperture, small f/number," he advises. But you needn't go overboard: Cook himself uses an 8-inch Newtonian. You can find reasonably priced video equipment online, but avoid one-shot color cameras. A low-noise CMOS astrophotography camera, for example, would work well.

When to look. You'll want to see as much of the unlit Moon as possible. The waxing and waning crescent phases are optimal — specifically, from three days after the new Moon until two days after first quarter and two days before last quarter until three days before the new Moon. Heightened meteor activity will increase your chances of spotting a flash (see the table above). Lunar eclipses also make for favorable ding-watching, and this November's deep partial lunar eclipse on the 19th (see page 48) occurs just after the peak of the Leonid meteor shower. Even with a zenithal hourly rate of 10 (Cudnik normally recommends a ZHR of 20 for regular observations), it's worth pointing at the Moon.

Once you've recorded your lunar impact flash, head over to the ALPO (**https://is.gd/alpo_lunar**) or BAA (**https://is.gd/baa_lunar**) websites and follow their protocols for submitting your data. Cudnik, Cook, and a whole cohort of lunar impact flash enthusiasts are eager to hear from you!

■ **DIANA HANNIKAINEN** loves picturing meteoroids pinging the Moon.

 by Howard Banich

Arc of an Amateur

Many an observer may recognize themselves in this stroll down memory lane.

One of the beauties of astronomy as a hobby is that there's no one best way to do it. Like every other person who has been enticed to find out more about our universe, I've simply followed my curiosity and inclinations. But everyone's path turns out at least a little differently, and lately I've been thinking about how my past as a recreational observer, sketcher, and occasional amateur telescope maker might influence my future as an amateur astronomer. Perhaps you have, too.

I started my journey in astronomy when I was 11. The Space Race was in full swing, and I was completely caught up in the excitement of sending people into orbit and eventually to the Moon. I wanted to be an astronaut (still do!) and loved the imagination-expanding experience of reading science fiction. This meant I was like a zillion other kids my age, and I suspect a large number of amateur astronomers began their journey the same way. How I got from there to here, and where that might lead, is likely a path well-trod by many.

The Spark

I inadvertently found a way to travel through spacetime one early evening in the summer of 1966 when I saw the tiniest image of Saturn in what may have been the most user-unfriendly little scope ever made. However, the view it produced of Saturn was just large enough to see the rings as

separate from the globe of the planet, and I was electrified. That's the exact moment I became an amateur astronomer. I just had to see more!

My First Scope: 3-inch Tasco f/15 Refractor

Soon after I saw Saturn, my dad brought home a 3-inch f/15 Tasco refractor on a German equatorial mount (GEM). If he hadn't done so, that first spark for telescopic observing may have flickered out. The 3-inch was great for observing the Moon and planets and was unexpectedly exciting for exploring the deep sky, too.

The instructions that came with the scope were poorly translated from Japanese, and it took me a while to figure out which way to point the polar axis of the mount. In the photo below, I had the polar axis pointed at the Sun — I hadn't yet understood that it should point to the north celestial pole! But once I did, I not only gained insight into how the mount worked, but how the sky did, too. I was pretty proud of that.

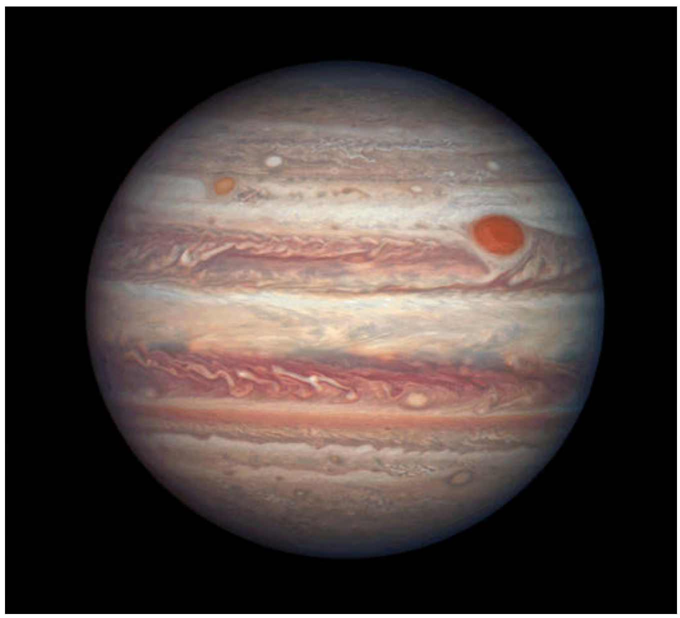
Motivated Novice: 8-inch f/4 Newtonian

Soon after the 3-inch arrived I started receiving the Edmund Scientific catalog, and I gradually convinced myself I could build an 8-inch Newtonian reflector. I turned 14 in July 1969 — just a week before Armstrong and Aldrin walked on the Moon. It was around then that I started working on my objective using an Edmund Scientific kit. I mounted the finished mirror in an aluminum tube my dad picked up at a scrap yard and was glad to find the scope was surprisingly useable for deep-sky observing. The first mount I made was a literal pain in the neck to use, but in 1974 I put it on a GEM with rotating rings. The scope then became much more comfortable to use, which made sketching at the eyepiece not only practical but enjoyable.

I'd always lived in the suburbs and had no idea how big a difference sky conditions make until I tried the 8-inch at a semi-dark site. The view of the Lagoon and Trifid nebulae embedded within the summer Milky Way blew me away almost as much as my first view of Saturn.

As I'm sure many of you have also found, my interests correlated with the strengths of the telescopes I used. The 3-inch f/15 refractor was really good on the Moon and planets, and the 8-inch f/4 was really good on deep-sky objects. Soon, I wanted an even larger scope to show me better views of everything.

▲ **LEARNING IS A PROCESS** I'm viewing a partial solar eclipse through my first scope, a 3-inch f/15 Tasco refractor. I'm still grappling with the mount at this stage. A cat wandered by in time for the photo — I have no idea where it came from.



▲ **BIG PLANET IN SMALL SCOPE** (*Top*) One of my first sketches of Jupiter shows three of the Galilean moons (arrowed). Jupiter is currently well placed in November skies: Look toward the south after sunset and you'll see the gas giant gleaming in Capricornus.

ALL PHOTOS AND SKETCHES BY HOWARD BANICH UNLESS OTHERWISE NOTED: ARCS AND TELESCOPE: *S&T* ILLUSTRATION; WITH TASCO: JAMES BANICH; JUPITER: NASA / ESA / A. SIMON (GSFC)

Seasoned Beginner: 12.5-inch f/7.8 Reflector

And so, in 1981, I built a 12.5-inch f/7.8 Dobsonian. A strong contender for the least attractive Dob ever made, it was nevertheless excellent at showing the Moon, planets, and deep-sky objects. At the time I thought it would complement the wide-field views of the 8-inch, but instead it effectively replaced the smaller reflector as my main scope.

During this phase of my life, though, things got busy, and astronomy became an even rarer pleasure. I used the 12.5-inch infrequently, but when I did, I was struck by how much relief observing provided from daily stresses — the larger perspective I got from those precious moments at the eyepiece helped me see problems as manageable obstacles. I did, however, compensate for the intermittency in my observing by subscribing to *Sky & Telescope*.

The Joys of Dobsonians, Naglers, Filters, and Friends

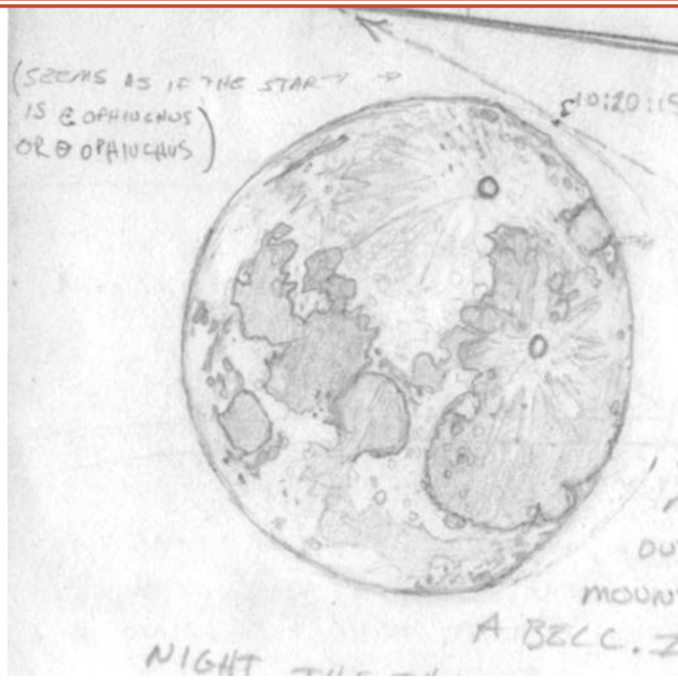
In the 1980s, Nagler eyepieces and narrowband nebula filters were becoming popular. They not only increased the capabilities of my scopes — heck, without Dobsonian technology even my 12.5-inch scope wouldn't have been possible — but filters made many deep-sky objects look as if I were observing under a much darker sky. The wide, well-corrected fields of view of the Naglers were simply astonishing and opened up new vistas. Even though I was still observing the planets at every opportunity, my passion began shifting toward the deep sky because of these innovations. I was ready to leave my backyard for darker skies and strike out more broadly into the *NGC* catalog.

▲ **EVOLUTION OF THE 8-INCH** At left is the first version of my Newtonian on a Modified English Yoke Mount, while the right-hand photo shows the current incarnation, a fixed-height-eyepiece Dobsonian.

And then 1991 rolled around. Big things happened in quick succession: I received an unexpected bonus from work, and so I ordered a 20-inch f/5 Obsession telescope; I went to the 1991 Oregon Star Party (OSP); and I joined the local astronomy club, the Rose City Astronomers (RCA).

I was 36 years old, and the OSP was the first star party I had attended. I'd never met another amateur astronomer, let alone a whole bunch of them. I was completely unprepared for how enjoyable it could be talking about observing and telescopes . . . without first having to explain why they're so incredibly fascinating. I'd found my people, many of whom became lifelong friends.

▲ **SIBLINGS OBSERVE, TOO** My sister Maryanne and I in 1974 chat beside the 8-inch f/4 Newtonian when it was on a commercial German equatorial mount.



▲ **FUN WITH LUNAR VIEWS** With my 8-inch, I observed a grazing occultation of a star by the Moon and sketched what I saw at the eyepiece. The Moon will undergo a deep partial eclipse on November 19th.

WITH THE 8-INCH: FRANCES BANICH

This was also the first time I observed under a truly dark sky. I took my 12.5-inch f/7.8 Dob because the 20-inch Obsession I'd ordered wouldn't arrive for another month. The star party was at 7,500 feet altitude in one of the most isolated — and darkest — locations in the U.S. This is when I understood that a great sky is at least as good as a bigger telescope. And this is where I met Chuck Dethloff.

Chuck and his wife Judy were codirectors of the OSP, and it was Chuck who checked me in for the star party. Later, when I got to look through his 24-inch f/5 Dob, I was blown away. Chuck also had this amazing ability to find everything in the sky without referring to a star atlas. We became observing buddies and great friends, and I know for sure that without meeting Chuck I would have ended up watching a lot more TV.

Experienced Observer: 20-inch f/5 Obsession

The 20-inch Obsession soon arrived, and a month later I had it under a dark sky. What a thrill! I saw more new objects that night than I had in the whole previous year, which highlighted the thinness of my observing experience. The only way to remedy that was to observe more, and that's what I set out to do.

Racing willy-nilly from one object to the next all night wasn't sustainable, and I soon realized I needed more stuff to support both the new telescope and observing: a more detailed star atlas, a sturdier observing ladder, more eyepieces and filters. Add to the list warmer clothes and boots, an adjustable observing chair, portable table, and a red light,

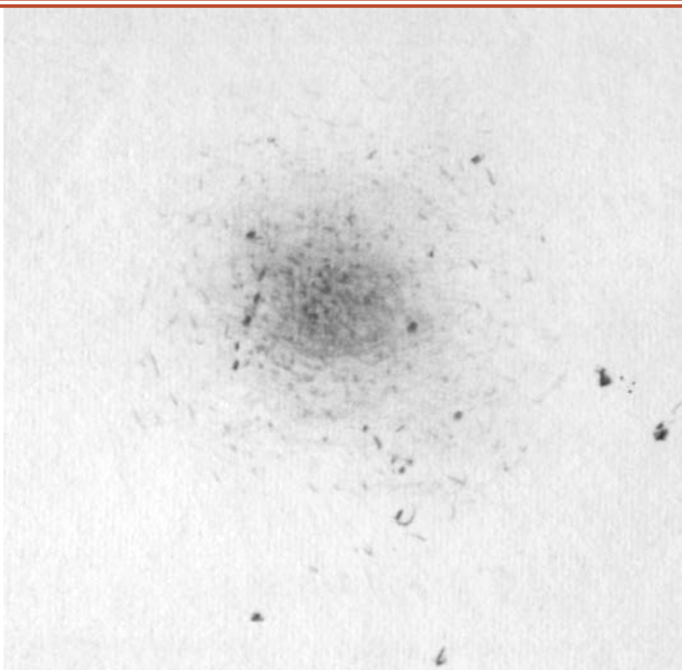
My experience was starting to catch up to my equipment: I was seeing a lot more now. And yet, I yearned for more.

too. I couldn't afford all this at once, but over time this stuff made my outings more enjoyable.

I also made an equatorial platform based on Tom Osypowski's design. Tom is one of the most talented, knowledgeable, and patient people I know. He's renowned for his platforms and telescopes, so his tips helped me a great deal. The platform worked like a dream. Now the 20-inch tracked for an hour before needing to be reset, which made sketching at the eyepiece much more pleasurable. A few years later I made a lightweight version, also based on Tom's design.

My first observing plan with the 20-inch was to complete the Messier list. I was embarrassed to admit I'd been an amateur astronomer for 25 years and hadn't yet observed all the Messiers, especially now that I had such a nice telescope. After finally accomplishing that goal, I tackled the Herschel I and II lists, and I also completed the Astronomical League's Galaxy Cluster program. My experience was starting to catch up to my equipment: I was seeing a lot more now.

And yet, I yearned for more. I began to realize what I could see with such a large instrument. I not only wanted to observe the faintest, most difficult targets, but I wanted to discern every possible detail in the brighter showpiece objects, too.



M13: STEFAN BINNEWIES / JOSEF PÖPSEL / CAPELLA OBSERVATORY

▲ **HIVE OF STARS** M13, the Great Globular Cluster in Hercules, teems with some 300,000 stars. The cluster was discovered by Edmond Halley, of comet fame, and cataloged some 50 years later by Charles Messier. The eyepiece sketch at left shows how I interpreted the view through my 8-inch. At this time of year, you can catch M13 in the early evening, low above the northwestern horizon.

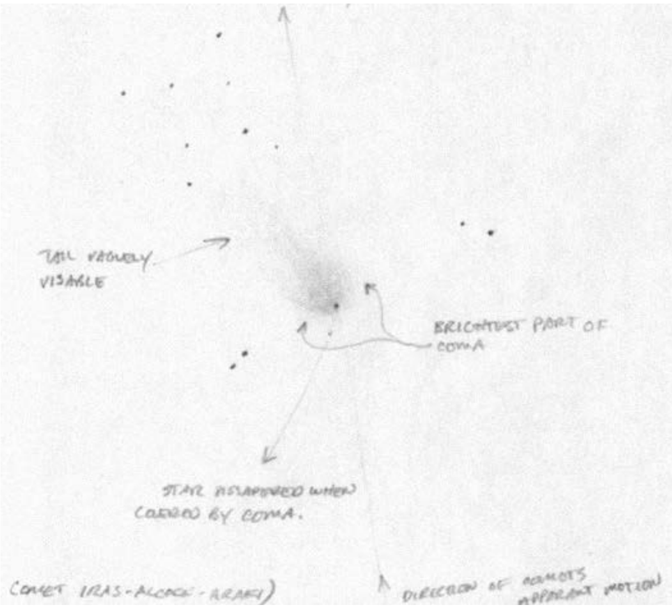
Increasingly Motivated Observer: 28-inch f/4 alt-az Newtonian

In 2003 I ordered a 28-inch f/4 mirror from Kennedy Optics, which was completed in early 2004. I financed the purchase of the mirror by reluctantly selling my 20-inch Obsession and its equatorial platform. I designed and constructed my current scope by combining the innovative designs of Tom Osypowski's Spica Eye telescopes and Dan Gray's 28-inch f/4.5 string telescope. Both were made entirely of metal — I wanted mine to be all aluminum to better withstand the damp observing conditions of western Oregon. First light was in May 2004, and the scope was fully functional a month later.

One of the best choices I made while designing the scope was accepting Dan's offer to test his brand-new Sidereal Technology telescope controller. I'd originally planned to make an equatorial platform for the 28-inch, but with Dan's system all I have to do is push the scope manually from object to object and let the controller track the sky. As a result, once I find an object the scope will keep it in the eyepiece until I'm ready to move on.

For me that's ideal — plus it makes the 28-inch easier to set up and take down than the 20-inch was with its equatorial platform. This ease of use and seamless tracking made sketching even easier, and my observing kicked up another notch because of it.

▼▶ SOLAR SYSTEM SPECIALS WITH THE 12.5-INCH I observed Comet IRAS-Araki-Alcock in 1983 and recorded the eyepiece view in the sketch shown below. The sketch at right shows how I saw Mars in 1988. The Red Planet will emerge at dawn in November — keep on eye on the east-southeastern horizon before sunrise toward the end of the month.



▲ TINKERING AWAY Above is the rebuilt 12.5-inch f/7.8 Dobsonian as it appeared after getting the 20-inch Obsession. The original was a basic but functional Dob built from bits and pieces of repurposed wood. It sported a long Sonotube optical tube painted green — which I apparently never photographed.

A Renewed Dedication to Sketching

In March 2009 I had a transformative experience with the 28-inch: an astonishingly detailed view of M51, the Whirlpool Galaxy. More importantly, that view sparked the idea that I needed to start sketching bright and detailed objects such as M51. When I first started drawing at the eyepiece in 1974, I focused on vivid and splashy objects. As my scopes got larger, the objects I sketched got smaller, fainter, and less detailed.

That may seem counterintuitive, but there are several reasons for this. First, small and faint objects are quick and easy to sketch, while bright, complex ones are multi-night projects. That's why I continued observing Abell planetary nebulae and Arp peculiar galaxies. Since M51 is also known as Arp 85, I knew I was going to have to sketch it at some point. That's when I decided to sketch every possible detail.

Properly motivated, I started to focus on M51 in earnest in June 2009. This was a return to my sketching roots, but now I was insanely well-equipped and with a ton more observing and drawing experience. I sent my sketch to *Sky & Telescope* for consideration in the Gallery section. A few months went by and I figured the magazine had no interest — after all, Gallery features astrophotos, not sketches.

Out of the blue I received an email from *S&T* inviting me to write an observing article about M51 featuring my sketch. No promises of publication, but just having a shot at it was tremendously exciting. After writing 176 observing articles for the Rose City Astronomers' newsletter, and reading *S&T* for three decades, the M51 article popped into my head nearly fully formed while on a long plane ride during a business trip. The M51 sketch led to my first article in this magazine (*S&T:* July 2011, p. 36), which is in the top five most astonishing events in my life as an amateur astronomer. I'm still excited, amazed, and grateful.

Before the M51 article, I'd already begun sketching the galaxies M33, M81, M82, and M101 to the same level of detail as M51, and was getting into the most enjoyable and rewarding observing groove yet. My experience had finally caught up with my equipment.

Each sketch took a ton of observing time because I wouldn't stop until I was certain I'd seen all I was capable of seeing. The process of sketching automatically encourages this kind of approach, and on multi-night projects I also found that as I became more familiar with the object, I could see fainter details more readily.

Almost as good as sketching, researching and writing about what I've observed has been highly rewarding. Reading professional research papers is a heavy lift at times — I have no formal training in astronomy — but the effort and resulting ad hoc education is always worth the effort.

I've continued with other observing projects, too, and now that I'm retired, I'm observing and sketching more than ever. I plan to continue along this path as long as I can, which brings me to the present and thoughts of the future.

Howard's Top Five Moments in Astronomy

1. Seeing Saturn for the first time.
2. The total solar eclipses of 1979 and 2017.
3. Observing M51 with the 90-inch Bok telescope on Kitt Peak.
4. My first article in *Sky & Telescope*.
5. Blinking the Crab Nebula pulsar with the 90-inch Bok.

What Next?

There are many directions I might go, and no certainties.

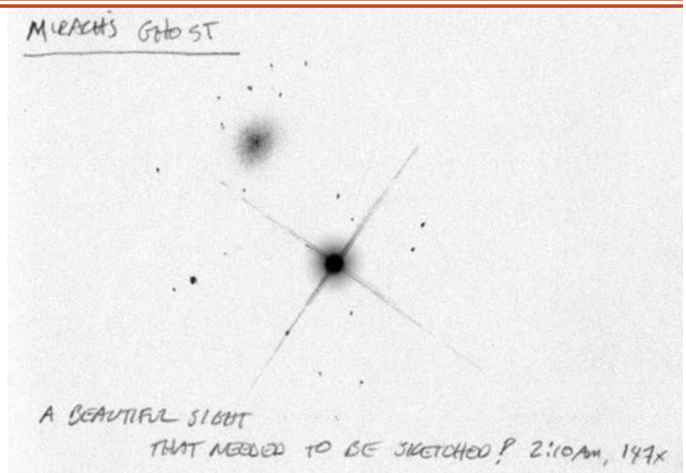
I've been fortunate to have used several scopes more powerful than my 28-inch, and aperture fever flares up each time. However, amateur astronomy is not just about telescopes. To quote the late computer scientist Edsger W. Dijkstra:

> *Computer Science is no more about computers than astronomy is about telescopes.*

▼ **A NIGHT AT STEENS MOUNTAIN** I'd only just started going to star parties two years prior to when this photo was taken of me in 1993 standing by the 20-inch f/5 Obsession. The scope is on the first of two homemade equatorial platforms I made for it.

▶ **STAR AND SPECTER** I observed Mirach, also known as Beta Andromedae, and its ghost, the elliptical galaxy NGC 404, in 2003 through my 20-inch scope. This ethereal pair is visible all night long, from dusk to dawn, throughout the winter.

WITH THE 20-INCH: CHUCK DETHLOFF; MIRACH: KENT WOOD



WONDROUS WHIRLPOOL The glorious spiral M51 graces the northern reaches of the constellation Canes Venatici, the Hunting Dogs. The smaller galaxy, NGC 5195, is gliding behind M51.

JOSEF PÖPSEL / STEFAN BINNEWIES / CAPELLA OBSERVATORY

Also, it's important to acknowledge that central as astronomy has been to my life, my family is much more important — as an amateur, this is a *hobby*. Along those lines, I've come to realize I don't need a bigger scope. My sketching campaign for the Cygnus Loop (*S&T:* Sept. 2021, p. 28) reminded me of how powerful an 8-inch scope is under a dark sky, so even if I end up having just that scope, I'll be OK. Sure, I'd welcome a telescope larger than the 28-inch if one came my way, but I'm not actively looking. I'll probably build an observatory for the 28-inch, though.

Chasing after an ever-bigger telescope isn't every observer's dream. Let's not forget binoculars — this magazine has a monthly column dedicated to exploring the sky with this most portable form of equipment. There are also other ways to explore the universe besides visual observing. The increasing accessibility of imaging and spectroscopy are becoming more tempting, as is double star speckle interferometry, an amazing way to accurately measure double stars.

I'm curious which paths I'll explore as I age. Knowing I could be hit by the proverbial bus tomorrow, I'm facing my mortality as a necessary planning tool because I want to enjoy this amazing hobby for as long as possible.

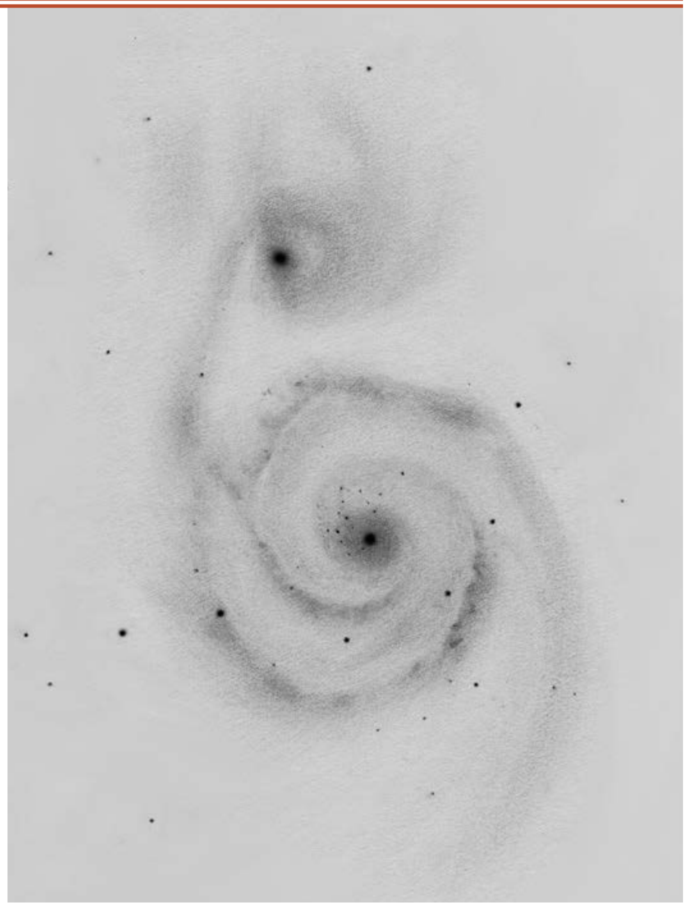
So, assuming the bus doesn't get me and my general health stays reasonably good, I'm absolutely positive I'll find ways to continue exploring the universe from this Pale Blue Dot, and perhaps that's the only certainty anyone needs.

Hauling the 28-inch

Before the 28-inch exceeds my physical abilities to roll it into the van, I'll build a motorized transporter that attaches to the scope so I can drive it into a trailer like Ed Allen does with his 24-inch Elvira telescope. See Ed's inspiring scope at **https://is.gd/ed_allen**.

■ A full-time optimist, **HOWARD BANICH** hopes his past *is* a good predictor of his future. Almost all the telescopes he's made — good, and not so good — along with more of his sketches and drawings are at **https://is.gd/howardbanich**.

▲ **MY VERY OWN BEHEMOTH** The homemade 28-inch f/4 alt-az Newtonian stands at nearly the same spot at Steens Mountain as the 20-inch more than two decades earlier. Although the scope has undergone extensive modifications since then, it still looks much the same. On the other hand, I'm much grayer now.



▲ **GLORIOUS VIEW** M51 is still my favorite. I observed it with my 28-inch at magnifications ranging from 253× to 710× and worked on this composite sketch from 2010 through 2011. For a shot at M51 this month, you'll have to stay up really late or get up very early to catch it as it climbs in the northeast before sunrise.

WITH THE 28-INCH: ROD SHEA

To Build or Buy?

A purely pragmatic look at the cost of doing it yourself

In the early days of amateur astronomy, if you wanted a telescope, you built it yourself. Commercially manufactured telescopes were few and far between, and those that were available were horribly expensive. Often, they had to be commissioned as one-off, hand-built items. Even when companies like Edmund Scientific started selling budget Newtonian reflectors, the cost was still well beyond most families' budgets.

On the other hand, the price of a glass blank and some grit was fairly reasonable, typically a few dollars for a 6-inch mirror. Once completed, the mirror could be chemically silvered (not aluminized) for a few dollars more. Adding a cardboard tube got you an optical tube assembly (OTA), some pipe fittings got you an equatorial mount, and with a Ramsden or Huygens eyepiece for a few dollars more you were in business.

John Dobson revolutionized both the size and ease of mounting homemade Newtonian telescopes, bringing scopes as large as 24 inches in diameter well into the realm of possibility for amateur telescope makers. But commercial telescopes remained wildly expensive: A 6-inch f/8 Newtonian went for $228 in 1971, which is $1,466 in today's dollars.

This situation persisted well into the 1970s, mostly because nobody could come up with a decent way to automate the mirror-making process. Paying someone in a telescope factory to grind a mirror was way more expensive than doing it yourself (assuming you worked for free).

Then the Coulter Optical Company came along and started selling medium-large (10″ and 13.1″) Dobsonian reflectors for only a few hundred dollars. Suddenly the equation flipped,

▶ **BUILT WITH CARE** A home-built 8-inch Dobsonian telescope can rival a commercial scope in quality, usability, and price.

BUILD: $???

and it became cheaper to buy than to build. Or nearly so, depending on how much scrounging of parts you were prepared to do.

Coulter's mirrors were hit-and-miss, though. Some were very high quality, others not so much. If you wanted a truly excellent mirror, you were still better off making it yourself.

However, Coulter opened the floodgates. By the turn of the 21st century, multiple other companies had joined the fray. Their increasing technical expertise raised the quality of their mirrors until nowadays it's relatively rare to get one that isn't at least quarter-wave accurate, what's often called "diffraction limited" (which means theoretically it can't get any better, although you could probably start a bar fight if you insisted that was true around more than a couple of other astronomers).

So, what's the story today? Can you buy a good telescope cheaper than you can build one?

▼ **DECISIONS, DECISIONS . . .** The price of a commercially manufactured telescope has never been more affordable. But is it still cheaper to build your own rather than purchase a scope outright?

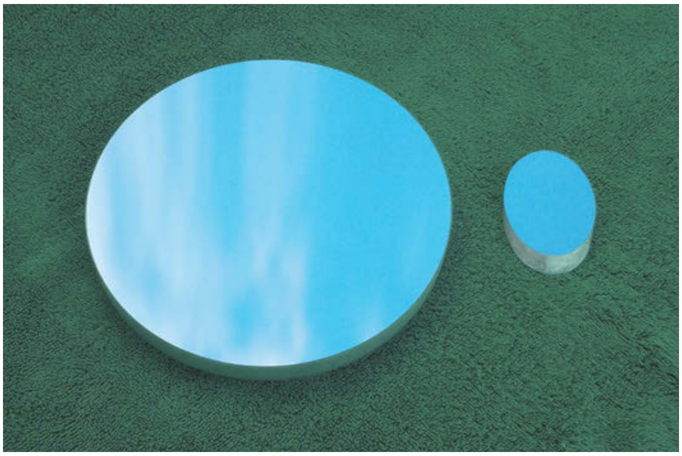
On page 74, I show you how you can make your own 80-mm refractor with a factory-made lens and focuser, some galvanized flashing, and an oatmeal canister. Total cost is about $60. That's considerably cheaper than what it would cost to buy a complete 80-mm refractor. But an 80-mm scope isn't really enough for a serious amateur astronomer. Most of us will quickly lust after something more.

The 8-inch Benchmark

An 8-inch Dobsonian is arguably one of the most versatile telescopes in existence. It's easy to transport, yet large enough to show you some serious eye candy. As I write this in June of 2021, Orion Telescopes & Binoculars (**telescope.com**), Sky-Watcher (**skywatcherusa.com**), Zhumell (**zhumell.com**), and several other companies will sell you a very good one for about $450. This is more than usual due to the surge in demand brought about by the stay-at-home orders during the Covid-19 pandemic, but it's still pretty reasonable. So $450 is our target. Can we make an 8″ scope for that? Let's have a look at the numbers.

◀ **STIFF COMPETITION** The Orion SkyQuest XT8 Dobsonian telescope is our benchmark. It's an economical model whose price is tough to equal, much less beat.

BUY: $450



▲ **NEWTONIAN ESSENTIALS** The primary and secondary mirrors are the heart of a reflector telescope.

The Primary Mirror

The heart of every reflecting telescope is its primary mirror. All else is, well, secondary. And it's pretty much a given that if you're going to make your own telescope from scratch, you'll want to grind your own primary.

To start with, you need a piece of glass. The cheapest blank I can find online is from Got Grit (**gotgrit.com**) and goes for $55 when it's in stock. That's for ¾″-thick plate glass, which is perfect for an 8″ mirror. In the old days the rule of thumb was that your glass should have a thickness of one-sixth of its diameter to avoid sagging due to gravity, but that has proven to be overly cautious; ¾″ is plenty for an 8-inch mirror.

An 8-inch grinding kit from Got Grit provides you with all the grit, pitch, and tool supplies you'll need, and it currently costs $64. So you're out $119 to get started.

Anywhere from 40 hours (if you've done this before or if you're lucky) to 100+ hours later (if you're fussy and/or overzealous in the final figuring like I am), you'll have a parabolized mirror ready to be coated. Several different companies offer vacuum-deposited aluminum coating services, which is the standard telescope mirror coating nowadays. (A list of companies that provide the service appears in our March 2019 issue, page 38.) Their prices for an 8-inch mirror average about $100. Shipping both ways is about $50 more. The adventurous might consider silvering their own mirror for a bit less (*S&T:* Jan. 2020, p. 74), but let's assume you're having yours aluminized. So now we're up to $269, and we have a shiny primary mirror in hand.

Interestingly enough: You can buy a completed 8″ f/5 mirror for about $240. Add in shipping costs and it's a wash. Arrgh!

The Secondary Mirror

I have a mirror-making friend who says he doesn't hate anyone enough to teach them how to make their own secondary mirror. Grinding and polishing a truly flat mirror is way harder than making a parabola. So, most amateur telescope makers simply buy them.

The size of the secondary depends upon the primary diameter and the focal ratio of the scope. F/5 is a very common focal ratio for an 8″ scope, so let's assume that's what we've ground our primary mirror to. The diameter of the secondary mirror is also heavily dependent upon how far from the optical axis your focuser sticks out, but it's common practice to add 3.5″ to the radius of the mirror (4″ in this case) to account for the focuser's average travel. A little math (secondary diameter = centerline-to-focal-plane distance divided by focal ratio) tells us we need a 1.5″ secondary mirror (3.5 + 4 / 5 = 1.5). You can buy secondary mirrors from many vendors. The average price I've found for a 1.5″ is about $40.

We're now at $309.

The Optical Tube Assembly

You need something to put these mirrors in. Most 8″ f/5 scopes go in tubes rather than in truss assemblies, because tubes of that size are easier to deal with, they protect the optics from dust when you cap the ends, and they provide excellent light baffling. The easiest way to get a tube is to buy a cardboard concrete form, often called a Sonotube (even if it's made by someone other than Sonotube). For an 8″ f/5 scope you'll need about 3.5 feet of tube. You'll most likely

▶ **OPTICAL TUBE ASSEMBLY** *Left:* Cardboard concrete forms make excellent, inexpensive telescope tubes. *Middle:* You can buy a secondary spider, but as John Dobson himself showed, you can easily make one from materials as basic as cedar shingles. *Right:* The primary mirror cell can be as simple as three bolts sticking up through a slab of plywood, padded with squares of Masonite held in place using cardboard from a cereal box.

have to settle for a 4-foot length of 10-inch-diameter tube, which will cost you about $11 at just about any home improvement store.

So now we're at $320.

You'll need something to hold the secondary mirror in the tube. That's called the "spider," and it's usually made of four vanes of metal and a 45°-angled mirror holder. You can make your own out of hacksaw blades, metal rulers, strips of galvanized tin, or even — harkening back to the days of Dobson's original sidewalk telescopes — cedar shingles (*S&T:* Apr. 2020, p. 36). I make mine out of wire nowadays.

You can also buy one. There are several vendors and the prices range pretty widely, but a spider for an 8″ scope will cost you about $40 to $100. To heck with that! Let's assume you've got some hacksaw blades or shingles and some ingenuity, so your spider will cost you a whopping $5.

That brings us up to $325.

You need something to hold the primary mirror at the bottom of the tube and let you collimate it. You can spend as much as you want to on a mirror cell, but with a ¾-inch-thick primary you can make your own out of plywood, some cork or hardboard padding, a triangle cut out of a cereal box, and three bolts (*S&T:* Apr. 2020, p. 72). Assuming you do it that way, your cost is only another $5.

We're now at $330.

Coming into Focus

You'll need a focuser, too. A good two-speed Crayford will set you back anywhere from $150 for the decent ones made by Guan Shen Optical (GSO), to you-don't-want-to-know for a precision high-end model. If you buy the GSO focuser, that puts your total cost at $480, which (*buzzzzzzzzzzzz!*) puts you over the cost of the commercial scope. So guess what: You're going to have to make your own focuser.

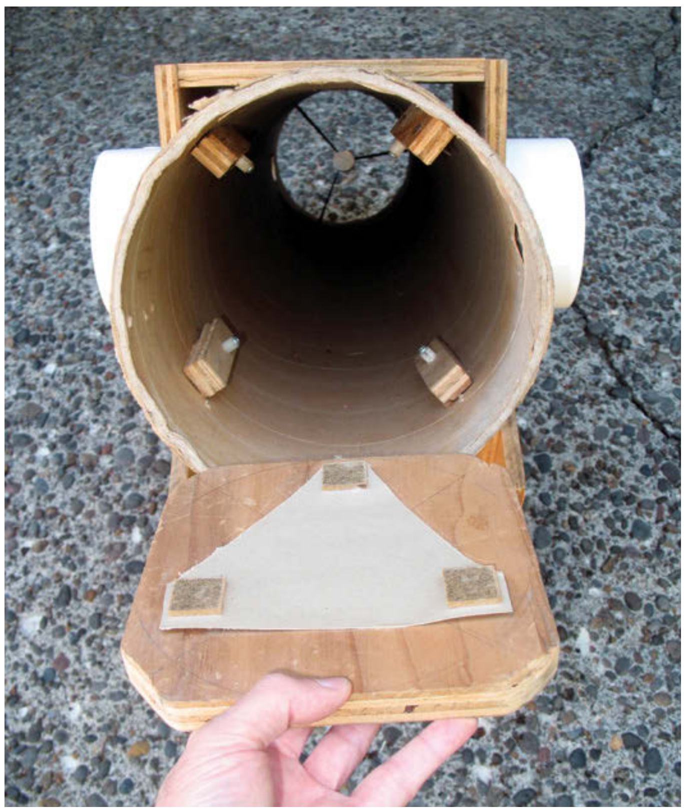
◀ **SCAVENGED OCULAR** A binocular eyepiece works just as well in a telescope as it does in binoculars.

Fortunately, I showed you how to do that in the February 2015 issue (page 68). Materials will cost you about $10, or a little less if you or your significant other knits and lets you repurpose a knitting needle to use as the focuser's pinion.

We're now at $340.

A commercial scope usually comes with at least one eyepiece — usually a 20- or 25-mm Plössl. You can buy one from Orion for about $40, or you can make your own like I described on page 74 of the September 2020 issue. That design used lenses from Surplus Shed (**surplusshed.com**), which cost $8.50. Then again, you can do as John Dobson did and buy a pair of binoculars at Goodwill and rob the eyepieces from that. That'll probably cost you about $10. So, let's go with the $10 figure, bringing us to $350.

Of course, a telescope of this size needs a finder. A Rigel QuikFinder would be really nifty, but that'll set you back $46 at Scopestuff (**scopestuff.com**) and even more elsewhere. Better build your own finder. I've described several different ways



▲ **SIMPLE BUT EFFECTIVE** *Left:* Commercial Crayford focusers, like the one at left, are nice, but you can build the one at right for practically nothing. *Right:* While unit-power finders by Telrad or Rigel are great (top left and right, respectively), you can make simple-yet-effective aiming devices using scrap wood or plywood left over from building your scope's mount.

to do that over the years (*S&T:* June 2013, p. 66, and June 2020, p. 72). Most of them can be made with scrap materials, so let's say the finder doesn't cost you anything other than time and effort.

The Dobsonian Mount

Now that the OTA is finished, it needs a mount. John Dobson designed his to use seven identical pieces of plywood, plus a couple of cradle boards cut from the same sheet. The cost of plywood has gone through the roof lately due to everyone doing home improvement projects when they're supposedly working from home, so this isn't as trivial an expense as it used to be, but it's still relatively cheap. You can buy a 4 × 8 sheet of A-D grade plywood for about $50, and you'll use about two-thirds of it for your mount, so call it $33.

You'll also need some Teflon for the mount's bearings, an old phonograph record for the azimuth bearing surface (no kidding), three feet for the scope to rest on, and some bolts, screws or nails, and glue. Let's add another $15 to cover that stuff. You can probably scrounge up some paint from the garage or basement for free, so we're at $48 for the mount.

You'll want a couple of shower caps for dust covers. Let's assume you can scrounge those for free at a motel or from your own stash.

Who Knew?

We're now at $398 for our finished homemade 8″ Dobsonian scope, as opposed to $450 to buy one ready-made. I'm sitting here in front of my keyboard with my mouth a bit agape, surprised at the outcome. I was prepared to say that you couldn't build your own 8″ Dob cheaper than you could buy one, but if you're willing to make the focuser, finder, mirror cell, and spider, you can just manage to squeak in under the commercial scope price.

▶ **OPTICAL CANON** The Dobsonian mount is simple to construct from plywood and miscellaneous hardware.

Larger Scopes

I chose an 8-inch as a good compromise between aperture and portability, so what about bigger ones? As the size of a scope increases, the cost also increases, but not in a linear fashion. The cheapest 16-inch Dob I can find is the Meade LightBridge Plus for $2,219. Without going through the above all over again, I've added up the cost of doing it yourself, and I've come up with a figure of about $1,500. You could afford to buy a commercial 2-speed focuser and a Rigel QuikFinder and still come out ahead.

The larger the aperture, the more sense it makes to build the scope yourself. But even an 8″ home-built scope can come in under the cost of a commercial version if you're willing to fabricate some of the subsystems and don't pay yourself a wage for your time. Also, you can grind the mirror to whatever focal length you desire, paint your custom scope any color you want, install setting circles, and so on.

And, of course, there's the incredible joy of using a scope you built literally from scratch. No camera will ever capture it, but I swear globular clusters look twice as nice in my homebuilt scopes as they do in a commercial scope of the same aperture.

■ Contributing Editor **JERRY OLTION** builds his own scopes for fun, not for economics.

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Explore Scientific's Observatory Tent

Here's a useful shelter for small-scope imagers and observers on the go.

◀▲ The Explore Scientific Two-Room Pop-Up Go Observatory Tent stands 1.8 meters (6 feet) tall at its highest point. In addition to the main observing room, the setup includes a second room of the same size. Both collapse into 69-centimeter disks (seen above).

Explore Scientific Two-Room Pop-Up Go Observatory Tent

U.S. Price from: $279.99

explorescientific.com

What We Like

Simple setup

Blocks light trespass

Perfect for imagers at star parties

What We Don't Like

Not enough stakes

Interior hot in sunlight

IF YOU'RE ANYTHING LIKE the amateur astronomer I am, you're constantly thinking of ways to squeeze more observing time from those infrequent periods of clear nights. Often good weather arrives on an evening when you have to work the next day, or perhaps there's a span of several clear nights on tap, but you don't have the time or energy to set up your equipment only to break it down in the morning again and again. A permanent backyard observatory would be ideal for some, though that can be costly and generally isn't an option for renters or city dwellers. The next best thing is a temporary shelter for your scope. That's where Explore Scientific's new two-room, Pop-Up Go Observatory Tent comes in.

I had the opportunity to use the Pop-Up Go Observatory last summer. The structure consists of two weather-resistant fabric rooms made of the same waterproof nylon fabric as a regular tent, framed with spring-steel loops. The rooms measure roughly 1½ meters-by-1½ meters (5 feet-by-5 feet) with a 1.8-meter (6-foot) peaked center serving as an additional windbreak. You can use the main room separately, or you can attach the second room to form single, two-room structure.

Both observatory rooms are in fact simply opaque walls — there's no floor or roof, though an included oversized rain fly (measuring 3-by-4½ meters) covers the entire tent and then some to protect your scope from rain or from the Sun during daylight hours.

Both room segments of the observatory "pop up" and don't require pole segments that need to be assembled.

▲ Each of the Pop-Up Go Observatory's two rooms can comfortably accommodate one observer with short, equatorially mounted telescopes of up to 6 inches aperture, or Dobsonians as large as 12 inches.

ALL PHOTOS BY THE AUTHOR

▲ Assembly of the Pop-Up Go Observatory is quick and easy — simply untwist each disk and they “pop” into shape. *Right:* The secondary room connects to the main structure with Velcro strips.

Instead, the tent walls are framed with large, flexible spring-steel rings that collapse into two convenient discs measuring just 0.7 meters (27 inches diameter) and roughly 4 inches thick. They literally spring into the shape of the wall panels when you untwist them. All you have to do next is place them in the desired location.

The main room has four walls with two large, zippered doors, while the second room has three walls and is attached to the main room using Velcro. Twelve tent stakes are included — six secure the structure at the base (or so I thought — more on this shortly), while the other six are used to anchor paracords attached to the top of the tent walls for added stability. Six additional paracords are included to secure the rain fly.

Setting up the Pop-Up Go Observatory for the first time took about 10 minutes, with most of that time taken up by attaching the paracords. After first use, I suggest leaving the cords attached, which cuts subsequent assembly times by about two-thirds.

Adding the rain fly for the first time proved to be a bit tricky, though the procedure became easier with the second attempt. The instructions (which can be downloaded from the company’s website) state that the stakes installed at the base of the tent are “optional” and should instead be used to secure the rain fly. I felt they were necessary, particularly when I set up the tent in a strong breeze. But that meant there was no way to secure the rain fly. Removing the base stakes for use with the rain fly worked, as the instructions note, though I suggest picking up a few extra stakes to avoid having to choose. After all, added stability is always a good thing with such a lightweight structure!

The 5-foot-square rooms are adequate for using a fast Newtonian of up to 6 inches aperture on a mid-sized equatorial mount, leaving just enough space to get around the instrument. There’s room for a larger Dobsonian (perhaps as big as 12 inches), but keep in mind that the closer the scope is to the ground, the more sky that will be blocked by the observatory’s walls. I was pretty comfortable using my 92-mm and 102-mm refractors on alt-az mounts, where I could raise the scope higher and see over the walls. My 12½-inch Dobsonian, however, was restricted to a large circle of sky around the zenith. Useable, but limiting.

The Go Observatory isn’t a structure designed to accommodate outreach or visitors. While it’s spacious enough for observing alone or when I invited my wife to have a look through the scope, things get pretty “intimate” when you have more than two people in the tent. This also isn’t a shelter for solar observers. Even with the top open to the sky, the interior of the tent became much hotter than the outside air — a byproduct of its black fabric, which quickly heats up in direct sunlight.

What this two-room temporary observatory *does* work well for is skygazing at star parties, where the unavoidable bright light from computer screens is forbidden on the observing field. One room can accommodate the imaging scope and mount, while the second room can house a table with your control computer. The walls do a good job keeping light from a laptop screen from bothering your neighbors.

I tended to set up the main room of the Go Observatory in my yard for several days at a time, often leaving my scope unattended. The tent held up well during some windy days with no more than a single paracord coming undone. The rain fly kept out the rain well, though users are encouraged to add an additional groundcloth tarp for even greater protection from moisture. Breaking down the tent took less than 5 minutes total, including folding up the rain fly. Collapsing the walls requires twisting the flattened panels into a sort of looping spiral and then tucking the loops together while pushing down.

The Pop-Up Go Observatory is great for solo observers or for imagers for whom light trespass is a concern. And while the tent isn’t meant to be a permanent home for your scope, it can allow you to keep your gear set up for days on end for those rare multi-night runs of good weather. And at less than $300, I consider it money well spent.

■ Associate Editor **SEAN WALKER** hopes to construct a new observatory before the end of 2021. Until then, the Go Observatory will suffice.

An oversized rain fly protects your gear and holds up quite well in a strong wind.

A Simple 80-mm Refractor

A millimeter for every year of Sky & Telescope*'s history*

An 80-mm refractor offers a fine — and inexpensive — view of the night sky. Use an erect-image diagonal (shown here), and it makes a great terrestrial scope, too.

IN HONOR OF OUR 80th anniversary, I thought this would be an appropriate month to describe how to build your own 80-mm refractor. Most homemade telescopes are reflectors, but small refractors are actually quite easy to make and very satisfying to use.

Just as 4.5-inch Newtonian reflectors make great introductory telescopes, 80-mm refractors provide a good entry point for those of us who prefer lenses to mirrors. They also make excellent grab-and-go scopes for quick outings, decent travel scopes, and even useful finderscopes for much larger telescopes.

I'd suggest grinding your own glass, but that's a huge undertaking, especially for a beginner. Fortunately, 80-mm achromatic doublets are available for next to nothing at one of my favorite outlets for telescope-making gear: Surplus Shed (**surplusshed.com**). They currently sell three versions: a 400-mm f/5, a 600-mm f/7.5, and a 900-mm f/11, all mounted in cells, for only $42 each. You couldn't buy the blanks and the grit for that.

They also sell an inexpensive but serviceable plastic focuser for $17.95. If you buy a lens and a focuser, all you need to do is put a tube in between them and you've got a telescope.

What to use for a tube? I made mine with galvanized flashing, the kind you find in rolls in hardware stores. I used the 400-mm focal-length lens, so my tube only had to be 177 mm (7 inches) long to put the focal point where the focuser was racked out about an inch. Note that this is with a diagonal between the focuser and eyepiece — if you prefer to look straight through, or if you choose one of the longer-focal-length objectives, you'll need to make a longer tube.

Making your own refractor requires the lens, the focuser, a tube to hold them the right distance apart, and a dew shield.

Gently roll the flashing into a cylinder of the right diameter. I overlapped the metal by about an inch and riveted it together. The focuser and the lens cell aren't exactly the same size, so it's tempting to make the tube slightly tapered, but that will cause problems later. Make it cylindrical to fit the lens cell and then simply shim the focuser with cardboard.

The lens cell has a curved flange around one end and a set of shallow fins down its length. It might seem that the obvious place to put your tube is over the finned section, but that would be using the lens backward. The telescope body goes inside the cell with the curved flange tapering down onto the tube; the dew shield goes over the outside.

The reason you don't taper the tube is because you want the end as perfectly square to the optical axis as possible. The lens cell has no collimation adjustments, so you have to do that when you attach it to the tube, and it's a lot easier if you start out square. (Mine required no adjustment beyond seating it flush in the tube.)

I attached the cell to the tube with three small screws. Be careful where you drill the holes so you don't hit the lens! Once the screws had tapped

ALL IMAGES COURTESY OF THE AUTHOR

▲ The body tube slips inside the lens cell. The dew shield slides over the top. Note how much of the focuser's drawtube I had to cut off to avoid vignetting the steep light cone from the f/5 objective lens.

themselves snugly into the sheet metal, I removed them and cut off the ends so they wouldn't stick into the light path.

You'll need three more screws to hold the tube to the focuser. No worries about encroaching on the light path there. You may need to cut off part of the focuser drawtube, though. On an f/5 scope, a long drawtube can vignette the steep light cone of the fast objective. You want the drawtube to let you see the entire lens, but not much of the tube itself when the fully assembled scope is at focus.

Make a dew shield out of more galvanized flashing or even just a cardboard tube. I used a Quaker Oats canister. Tart up the tube and dew shield to look pretty. I found some perfect contact paper to decorate mine.

For a mount, I ran metal straps around the tube and attached them to a wooden block. The block can have ¼ × 20 threads to connect it to a camera tripod, or a dovetail for an equatorial mount, or whatever works for you. I played with mine on a camera tripod for a while, then mounted it on my 20-inch scope to serve as a finder. It works great either way! It comes to a sharp focus, and since the lens is an achromatic doublet, color fringing is minimal even on bright objects.

For the adventurous, Surplus Shed sells a 127-mm (5-inch) achromatic doublet if you want to build a bigger scope. We'll detail how to do that in our November 2068 issue (our 127th anniversary).

■ Contributing Editor **JERRY OLTION** isn't a complete lens nut, but he's certainly a refractophile.

△ **NGC 5054**

Warren Keller and Mike Selby

Dark dust lanes and reddish star-forming regions intermingle in the arms of NGC 5054 in Virgo. Past interactions with another galaxy may have caused NGC 5054's unusual shape.

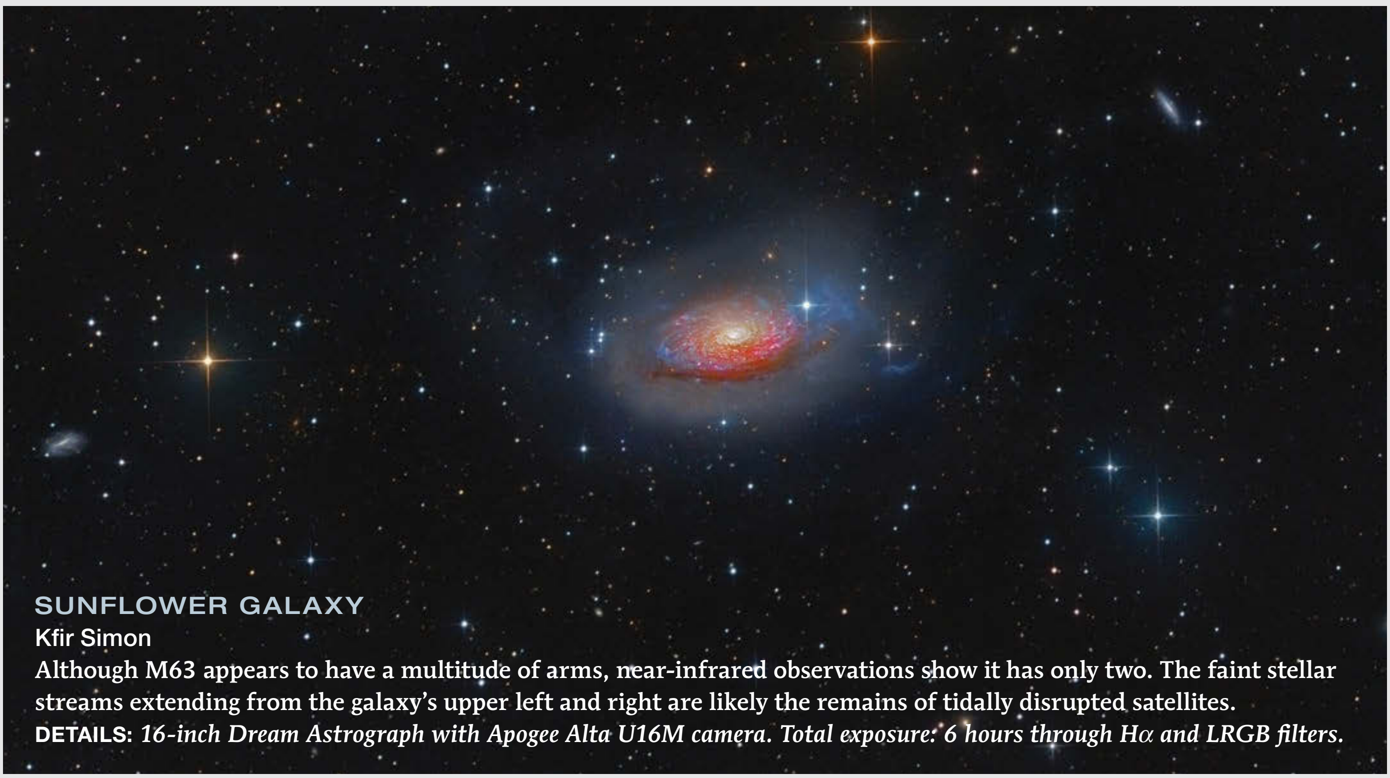
DETAILS: *PlaneWave CDK 1000 Dall-Kirkham telescope with FLI ProLine PL16803 camera. Total exposure: 23 hours through Chroma LRGB filters.*

△ **ONE-ARMED SPIRAL**

Chad Leader

A single, dusty spiral arm winds its way around the bright nucleus of NGC 4725 in Coma Berenices. This 10th-magnitude spiral galaxy lies about 40 million light-years away.

DETAILS: *Celestron EdgeHD 8-inch Schmidt-Cassegrain with ZWO ASI294MM Pro camera. Total exposure: 12½ hours through Antlia LRGB filters.*

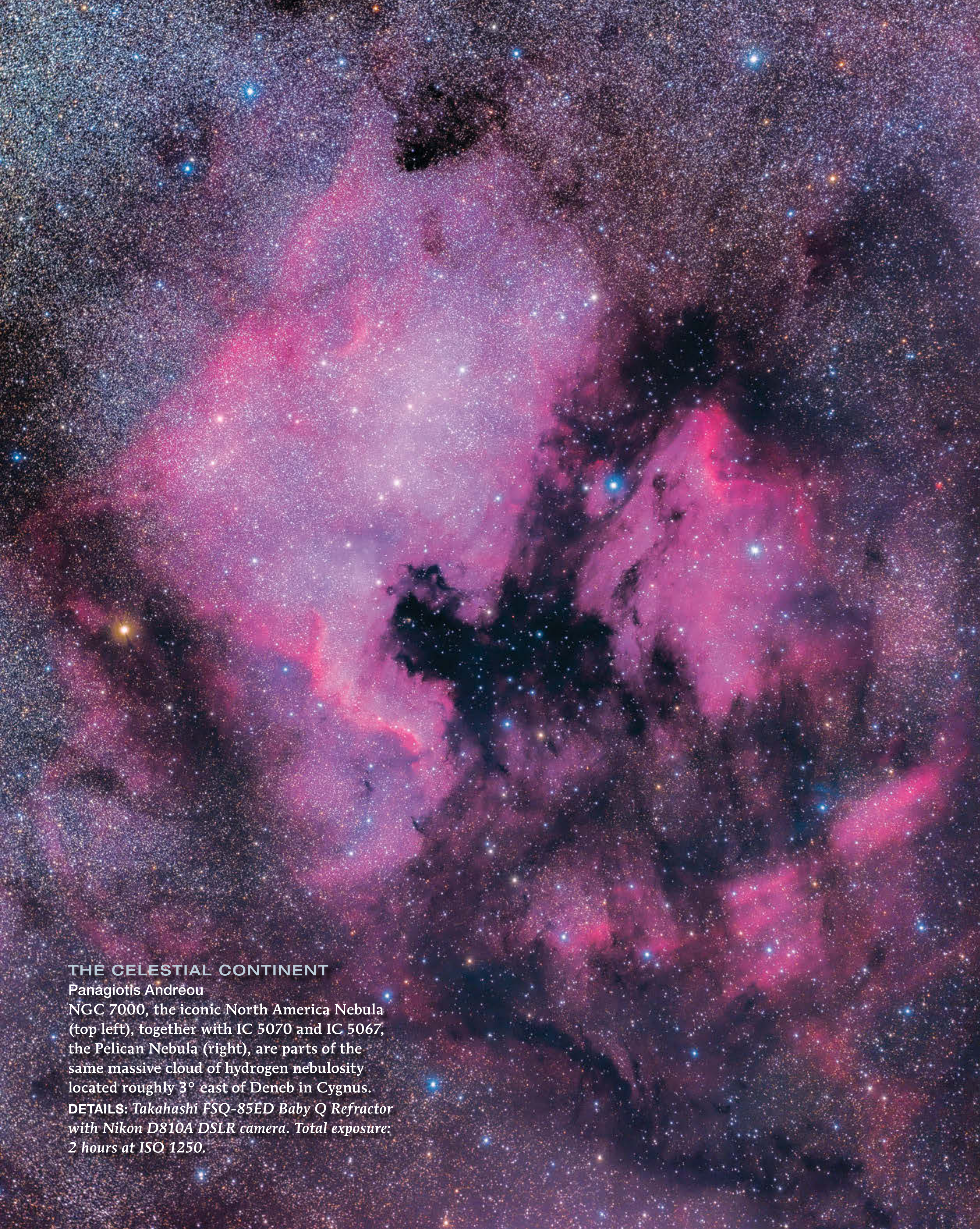


SUNFLOWER GALAXY

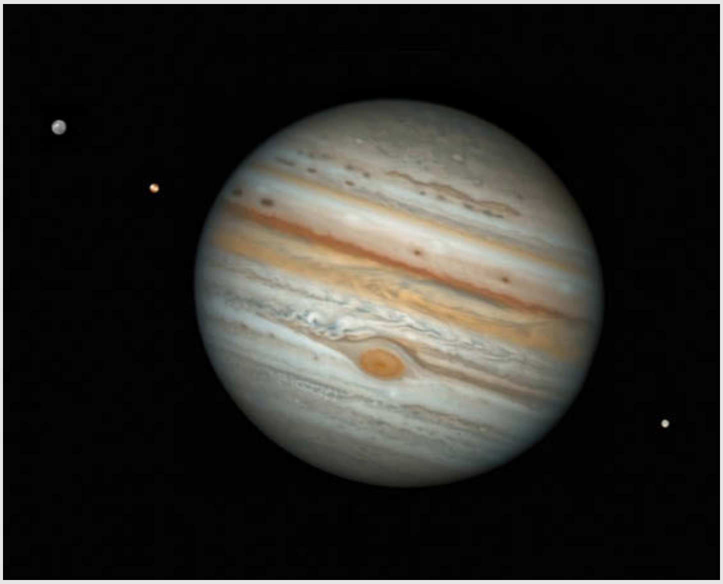
Kfir Simon

Although M63 appears to have a multitude of arms, near-infrared observations show it has only two. The faint stellar streams extending from the galaxy's upper left and right are likely the remains of tidally disrupted satellites.

DETAILS: *16-inch Dream Astrograph with Apogee Alta U16M camera. Total exposure: 6 hours through Hα and LRGB filters.*



THE CELESTIAL CONTINENT
Panagiotis Andreou
NGC 7000, the iconic North America Nebula (top left), together with IC 5070 and IC 5067, the Pelican Nebula (right), are parts of the same massive cloud of hydrogen nebulosity located roughly 3° east of Deneb in Cygnus.
DETAILS: *Takahashi FSQ-85ED Baby Q Refractor with Nikon D810A DSLR camera. Total exposure: 2 hours at ISO 1250.*



◁ JUPITER AND ITS ENTOURAGE

Damian Peach

Jupiter's ever-changing Great Red Spot (see page 52) transits the planet's central meridian. The Galilean moons Ganymede (far left), Io (left), and Europa (lower right) each display mottled surface details in this high-resolution image.

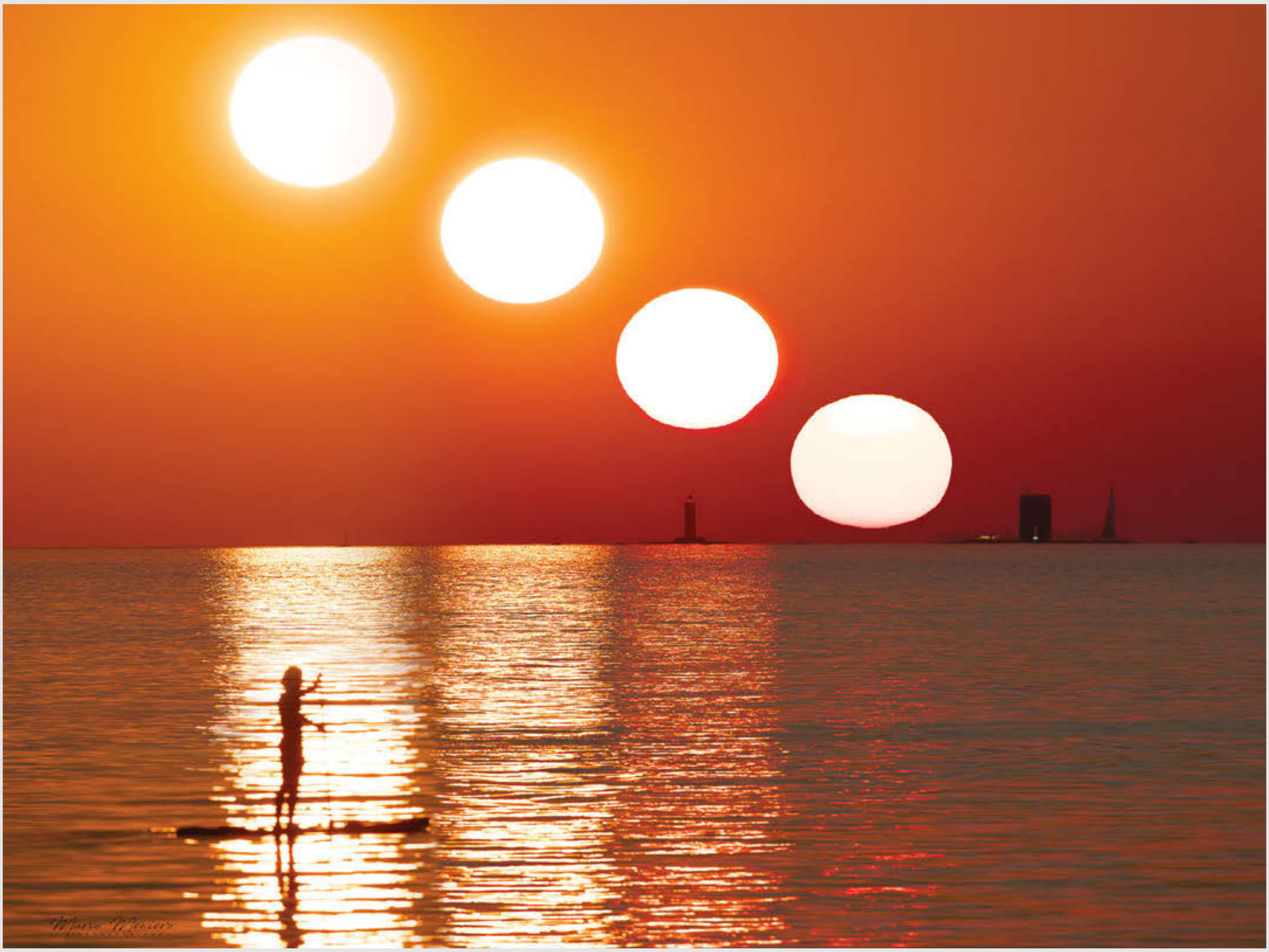
DETAILS: *ASA RC-1000 telescope with ZWO ASI290MM video camera. Stack of multiple video frames captured on August 5th at 3:57 UT through RGB filters.*

▽ SUNSET IN TUSCANY

Marco Meniero

Two elusive green flashes (caused by differential refraction in the atmosphere) are seen by the arch of Meloria Tower in Tuscany, Italy, at sunset on July 20th.

DETAILS: *Canon EOS-1D X Mark II with 400-mm EF DO IS II USM lens. Composite of five images taken at ISO 200.*



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Event Calendar

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

September 24–25
ASTRONOMY AT THE BEACH
Island Lake State Recreation Area, MI
glaac.org

September 29–October 3
ACADIA NIGHT SKY FESTIVAL
Mount Desert Island, ME
acadianightskyfestival.com

October 1–3
BLACK FOREST STAR PARTY
Cherry Springs State Park, PA
bfsp.org

October 1–9
OKIE-TEX STAR PARTY
Kenton, OK
okie-tex.com

October 2
ASTROASSEMBLY
North Scituate, RI
https://is.gd/AstroAssembly2021

October 2–10
PENNYRILE STARGAZE
Dawson Springs, KY
facebook.com/southstarparty

October 6–11
YORK COUNTY STAR PARTY
Susquehannock State Park, PA
yorkcountystarparty.org

October 7–10
HIDDEN HOLLOW ASTRONOMY CONFERENCE
Bellville, OH
wro.org/hidden-hollow-star-party

October 7–10
ILLINOIS DARK SKIES STAR PARTY
Chandlerville, IL
sas-sky.org/2021-idssp

October 9
ASTRONOMY DAY
Events across North America
https://is.gd/AstronomyDay

October 9
NOVAC STAR GAZE
C.M. Crockett Park, VA
novac.com/wp/outreach/stargaze

October 15–24
JASPER DARK SKY FESTIVAL
Jasper National Park, AB
jasperdarksky.travel

October 16
INTERNATIONAL OBSERVE THE MOON NIGHT
Everywhere!
https://is.gd/ObservetheMoon

October 31–November 7
PEACH STATE STAR GAZE
Deerlick Astronomy Village, GA
atlantaastronomy.org/pssg

November 1–6
ELDORADO STAR PARTY
Eldorado, TX
eldoradostarparty.org

November 2–7
DEEP SOUTH STAR GAZE
McComb, MS
dssg.boards.net

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

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Coming Full Circle

After nearly half a century of working for S&T, the author returns to where he began.

SOME YEARS AGO on my daily walk to lunch I paused at a construction site near the *Sky & Telescope* offices. A gruff-looking foreman approached me and questioned my interest.

"Just neighborhood curiosity," I said. "I'm a magazine editor and have worked in the building a couple of doors down for 35 years."

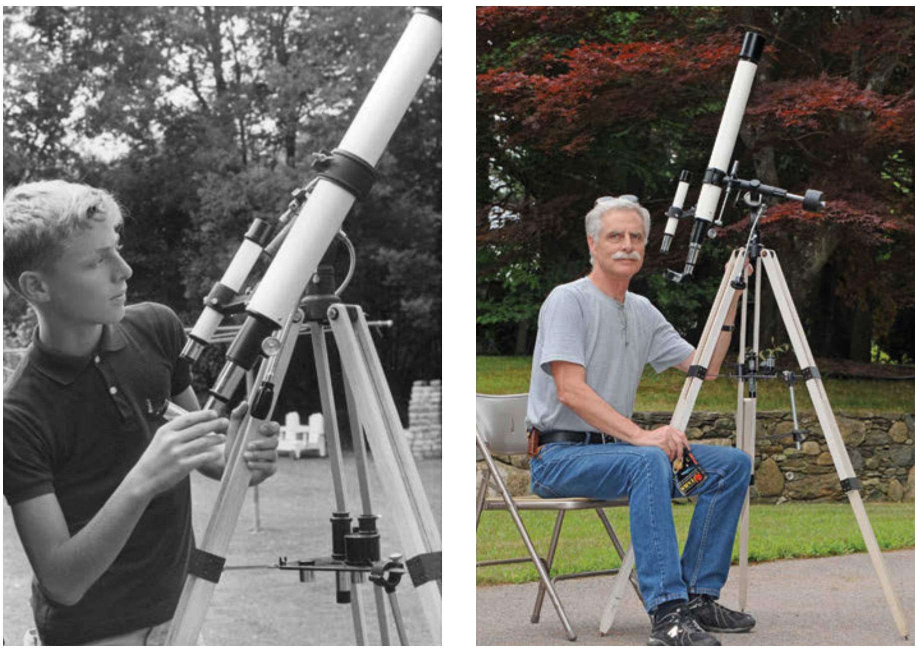
Tipping his head incredulously, he grunted, "Humph, 35 years? Sounds more like a prison sentence than a job."

I hadn't thought of it that way before, but I also hadn't thought about it being a job, either. To understand why requires a rewind to a late-summer afternoon in 1963 when my growing fascination with astronomy forever changed. That's when my first issue of *Sky & Telescope* arrived in the mailbox.

Suddenly, astronomy was no longer a static subject learned from aging library books. *S&T* featured stories, news, and events happening right now. There were things to see in the sky and reports on the activities of both other amateur stargazers and — of especial interest to me — other telescope makers. In short, the magazine became my monthly update on everything astronomical.

A few more years and a driver's license expanded my universe with access to astronomy clubs, conventions, and occasional stops at the *S&T* offices to say hi to editors I knew from various gatherings. Then came a fateful day in June 1974 when an impromptu visit ended with an offer to join the editorial staff. I said yes on the spot, thinking it would be something fun to do until I grew up and got a real job.

Thankfully, neither of those things ever happened! For the next 40-plus years I and my colleagues — virtually all of whom were *S&T* subscribers before joining the staff — focused on creating monthly issues. Each one was as much for us as it was for our readers, and our continual efforts to improve the publication benefited everyone. The



▲ The author in 1963 (left, with his 2.4-inch Lafayette refractor) and in 2013, 50 years to the day after he accidentally stumbled upon Saturn for the first time while using the same telescope

DENNIS DI CICCO (2)

> "Humph, 35 years? Sounds more like a prison sentence than a job."

work also kept us at the forefront of the science and the hobby of astronomy. As they evolved, so did the magazine.

For example, the rise in popularity of Schmidt-Cassegrain telescopes in the late '70s caused a surge in astrophotography. Readers began submitting beautiful color photos like never before, and that prompted a greater use of color illustrations in the magazine. When the Dobsonian revolution turned deep-sky observing into a mainstream pursuit, we responded with articles and regular columns devoted to the topic. As one might imagine, the rise of the internet in the late '90s had a huge impact on the magazine's evolving content.

A few years ago, semi-retirement weaned me from *S&T*'s day-to-day production, but I still regularly dropped by the office. That changed, however, when the staff began working remotely during the COVID-19 pandemic. Each issue now has more and more material I've not seen before it was printed.

That fact really struck me earlier this year when I caught myself standing by the mailbox flipping through the latest issue that had just arrived. It was as if I'd returned to that summer of '63 when I couldn't even wait to walk back to the house before paging through the magazine for its exciting new content.

S&T has changed a lot over the years, but so have I. What hasn't changed is how important each issue has been in helping fulfill my love of astronomy. I'm certain it will always be so.

■ Senior Contributing Editor **DENNIS DI CICCO** always takes his reading glasses along when he walks out to the mailbox.

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You can select among macOS, Windows, and the exceptionally stable Linux. Why paint yourself into a corner?

Apollo is designed and manufactured at our state-of-the-art factory in Golden, Colorado. Its high-grade metals are precision-machined to our uncommonly high tolerances. And our lead times for delivery are very reasonable.

If the agile and supremely capable Paramount Apollo meets your demanding requirements, place your order today!

Pictured PlaneWave Instruments CDK20 sold separately

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SOFTWARE BISQUE

Superior imaging solutions for astronomy and space applications.